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Modulation of the Alpha Oscillation Associated with Semantic and Somatic Self-referential Processing with Non-invasive Brain Stimulation

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Abstract

Who am I? What am I? While philosophers have pondered existential questions such as these for centuries, neuroscientists are beginning to reveal neural correlates that may partly underlie our semantic (verbal, psychological) and somatic (non-verbal, physical) senses of ourselves. Non-invasive brain stimulation (NIBS) can then introduce exogenous electric fields over brain regions to modulate a person's self-referential processing (SRP). Effective NIBS protocols can help establish causal connections between brain and self-experience, helping develop clinical interventions for mental health problems.

In this dissertation, I present a series of studies investigating the neuro-electrophysiology partially mediating SRP by combining electroencephalography (EEG) with NIBS. First, I present a systematic review of NIBS research seeking to modulate SRP as background for the current research. Then, two studies are presented that validate a novel experimental task for measuring the subjective and EEG responses during both semantic and somatic SRP in comparison with resting state and a simple external attention task; we demonstrated the significant role of alpha oscillations in distinguishing semantic and somatic SRP, both from each other and from internal (resting state) and external attention more generally. Next, three studies aimed to modulate alpha activity associated with SRP with either transcranial direct or alternating current stimulation (tDCS/tACS) over the medial prefrontal cortex (MPFC) or tACS over the bilateral inferior parietal lobule (IPL). Results showed that, compared to sham NIBS, significant changes in scalp-level alpha power occurred in all three experiments without any changes in self-reported mood or attention. Further, mPFC-tDCS and IPL-tACS modulated source-level alpha power and phase synchrony but not mPFC-tACS during somatic and semantic SRP, while only mPFC-tDCS modulated functional connectivity between posterior cingulate cortex and left IPL. Finally, we found that the effects of NIBS varied based on the order in which real vs. sham NIBS was conducted across two experimental sessions. Our findings provide insights into SRP's neuroscience and how NIBS may modify it.

Keywords

self-referential processing (SRP), bodily self-consciousness (BSC), non-invasive brain stimulation (NIBS), transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS), alpha electroencephalography (αEEG)

Summary for Lay Audience

Who am I? What am I? While philosophers have pondered existential questions such as these for centuries, neuroscientists are beginning to show that different brain waves may partly underlie the different ways we think about ourselves and feel within our bodies. Further, neuroscientists have developed ways of safely stimulating the brain with minimal amounts of electricity, which can help establish casual connections between brain waves and self-experience, helping develop clinical interventions for mental health problems.

In this dissertation, I present a series of studies that investigated the brain waves involved when people think about themselves and pay attention to feelings in their body, including before and after they received different kinds of transcranial electrical stimulation (tES) to the frontal and parietal lobes of their brain. In brief, we demonstrated the significant role of a specific type of brain wave called “alpha” - that was more or less active in different parts of the brain depending on whether a person was attending to how they feel about themselves in reference to various life roles (e.g., student, friend) or in reference to various body parts (e.g., legs, arms). We were also able to change the activity of alpha brain waves with different kinds of tES in various brain areas, although we could not change participants’ self-reported mood or attention. Our findings provide insights into the different brain waves that may partly underlie the different ways we mentally think about ourselves and physically feel in our body, as well as how these brain waves can be changed by safely electrically stimulating the brain.

Co-Authorship Statement

All projects were conceptualized, analyzed, and written by Zhongjie Bao and supervised by Dr. Paul Frewen. For the published manuscript in Chapter 2, while Mr. Belal Howidi drafted the framework and an initial version of the article, the principal author was Zhongjie Bao. Dr. Amer Burhan edited and offered suggestions on the articles in Chapter 2 and Chapter 4.

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First and foremost, I must express my deepest and sincerest gratitude to my doctoral supervisor, Dr. Paul Frewen, for your guidance throughout my academic journey, from the initial conceptualization of experiments to finalizing every manuscript for publication. Thank you, Paul, for your consistent insights, support, and compassion throughout the various challenges we encountered in the last five years, especially considering that I started at the beginning of the COVID pandemic and finished when the world had just recovered. It has been a heartwarming journey with you, and I simply cannot keep track of all of the academic, professional, and personal growth I have experienced in your lab.

I would also like to thank my mom for supporting me emotionally and financially throughout graduate school from the other side of the world. It is not easy to send your son to another side of the world and patiently listen to me talking about my experience and my research. I feel extremely lucky to have you as a consistent support throughout my life.

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Last, but not least, I would like to thank Dr. Darren Campbell, my undergraduate thesis supervisor, for igniting my passion for neuroscience and encouraging me to pursue graduate school. I would not have been where I am today without you.

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List of Abbreviations

ACC	Anterior cingulate cortex
ACW	Autocorrelation Window
AMT	Active motor threshold
ANOVA	Analysis of variance
BASS	Buddhist Affective State Scale
BOLD	Blood oxygen level dependent
BSC	Bodily self-consciousness
CPTSD	Complex post-traumatic stress disorder
DAN	Dorsal attention network
mDES	Modified Differential Emotions Scale
DLPFC	Dorsolateral prefrontal cortex
DMN	Default mode network
DMPFC	Dorsomedial frontal cortex
EBA	Extrastriate body area
ECG	Electrocardiogram/Electrocardiography
EEG	Electroencephalogram/Electroencephalography
FC	Functional connectivity
FDI	First dorsal interosseous muscle
FDR	False discovery rate
fNIRS	Functional near-infrared spectroscopy
GPS	Global psychotrauma screen
HBDT	Heartbeat detection task
HD-tDCS	High-definition transcranial direct current stimulation
HEP	Heartbeat-evoked potential
IA	Interoceptive awareness
IAF	Individual alpha frequency
ICA	Independent component analysis
ICSRLE	Inventory of college student recent life stress
IFG	Inferior frontal gyrus
IPL	Inferior parietal lobule
IPS	Inferior parietal sulcus
ITC	Inter-trial coherence
ITQ	International trauma questionnaire
LORETA	Low-resolution brain electromagnetic tomography
LTD	Long-term depression
LTP	Long-term potentiation
MEG	Magnetoencephalography
MEP	Motor-evoked potential
MFG	Middle frontal gyrus
MPFC	Medial prefrontal cortex

fMRI	Functional magnetic resonance imaging
MTL	Medial temporal lobe
NIBS	Non-invasive brain stimulation
V/NV-SRP	Verbal/Non-verbal self-referential processing
OM	Operational module
PCC	Posterior cingulate cortex
PCL	PTSD checklist for DSM-5
PD	Proprioceptive drift
PET	Positron emission tomography
PHQ	Patient health questionnaire
PMC	Premotor cortex
PPC	Posterior parietal cortex
PPG	Photoplethysmography
PTSD	Post-traumatic stress disorder
RHI	Rubber hand illusion
RMT	Resting motor threshold
ROI	Regions of interest
RT	Reaction time
SCL	Skin conductance level
SEB	Self enhancement bias
SMA	Supplementary motor area
SMG	Supramarginal gyrus
SOA	Supraorbital area
SODT	Self-other discrimination task
SPE	Self-processing effect
SRET	Self-referential encoding task
SRP	Self-referential processing
iTBS	Intermittent theta-burst stimulation
cTBS	Continuous theta-burst stimulation
tACS	Transcranial alternating current stimulation
tES	Transcranial electrical stimulation
tDCS	Transcranial direct current stimulation
TMS	Transcranial magnetic stimulation
rTMS	Repetitive transcranial magnetic stimulation
TPJ	Temporal parietal junction
TPO	Temporal–parietal–occipital
TRASC	Trauma-related altered states of consciousness
VLPFC	Ventrolateral prefrontal cortex
VMPFC	Ventromedial prefrontal cortex
VPMC	Ventral premotor cortex

Chapter 1

1 Introduction

1.1 Self-referential processing (SRP) in mind and body

What constitutes our sense of self? Philosophers, psychologists, and neuroscientists have postulated their models of the self from different perspectives. The question regarding the self can be dated back to Descartes' statement of *cogito, ergo sum* (I think, therefore I am), suggesting that self-awareness and reflections of one's existence may be at the core of the self. Then, Kant categorized the self into consciousness of oneself and one's psychological state (Wuerth et al., 2023).

Particularly influential to psychology and neuroscience has been William James' (1890) early subject-object framework that distinguished the experience of self-referential processing (SRP) into its task vs. stimulus aspects, with the content or stimuli of SRP further categorizable into corporal (physical, somatic, non-verbal) versus non-corporal (spiritual, semantic, verbal) referents, and positive versus negative emotional valences (see also Legrand and Ruby, 2009). This perspective bears significance not only in basic research conducted today toward understanding the nature of human experience but also in applied research seeking to develop treatments for people with psychological disorders of the self (Frewen et al., 2020).

Recent developments in neuroscience further stimulated discussions around selfhood as a neurobiological process and its importance in mental health, altered states of consciousness and disorders of consciousness (LeMoult et al., 2017; Lin et al., 2018; Yoon et al., 2019; Frewen et al., 2020). For example, the triumvirate selfhood model describes three aspects of the self, including the phenomenal agency represented in the frontal lobe (referred to as "self"), self-related emotional feelings which may be most represented in the right parietal lobe (referred to as "me"), and a reflective agency represented in the left parietal lobe (referred to as "I"; Fingelkurts & Fingelkurts, 2023). Then, a meta-analysis of fMRI studies on the self proposed a hierarchical three-level framework situating interoception (feelings in the inner body) at the core aspect of SRP, with exteroception (feelings in the outer body) as a middle layer and introspection (semantic SRP) as an outer later to include higher-order conscious processes (Qin et al., 2020). Other models have also focused on one or more aspects of SRP, lumping certain aspects of SRP together (e.g., somatic SRP may be considered inclusive of both exteroception and interoception) while expanding on other aspects (e.g., self-feelings; Damasio, 2003).

It appears that one common theme among the various philosophical, psychological, and neuroscience theories regarding SRP that are guiding empirical research today is the separation between a semantic and somatic sense of self. Semantic SRP involves conceptual elaboration and verbal description regarding different self-referential characteristics, while somatic SRP involves feelings and sensations in the absence of conceptual knowledge. Neuroimaging literature also provides a basis for distinguishing SRP into a semantic or verbal or “psychological” form of SRP (V-SRP) versus a somatic or non-verbal or “physical-bodily” form of SRP (NV-SRP) (Frewen et al., 2020). These semantic/verbal vs. somatic/non-verbal distinctions have been important in further investigations of the neuroscience of the self, discussed in the following section.

1.2 Neuroimaging of SRP

Methodologically, studies have imaged the neural correlates of SRP with fMRI and EEG. Briefly, fMRI measures participants’ blood-oxygen level-dependent (BOLD) signals that reflect metabolic changes in brain regions with high spatial resolution. In contrast, EEG measures participants’ neuro-electrophysiology with scalp-level electrodes, which is a more direct measurement of neural activity than fMRI with high temporal resolution but generally lacks spatial resolution compared to fMRI. In addition to localized neural activities, fMRI and EEG allow researchers to make inferences about the underlying neural networks that functionally organize distant brain regions. Therefore, the degree to which neural networks organize those regions is referred to as functional connectivity.

1.2.1 fMRI studies

Reviews of fMRI studies suggested that SRP in general, may be associated with activities in the default mode network (DMN) and its sub-systems. Within the DMN, a dorsomedial prefrontal cortex (DMPFC) subsystem consists of the DMPFC, inferior parietal lobule (IPL), the lateral temporal cortex, and the temporal poles. In comparison, a medial temporal lobe (MTL) subsystem consists of the ventromedial prefrontal cortex (VMPFC), posterior IPL, the retrosplenial cortex and the hippocampus. Finally, a midline core subsystem can be considered as the convergence of parts of the DMPFC and MTL subsystems (Andrews-Hanna et al., 2010; Wen et al., 2020).

However, neuroimaging findings in response to SRP tasks further differentiate responses among these regions of interest (ROI). For example, verbal or semantic (psychological) forms of SRP (i.e., V-SRP) are known to be at least partially mediated by DMN activity in the medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC), ventral precuneus, and the bilateral IPL (e.g., Araujo et al., 2015; Davey et al., 2016). However, the response to different kinds of meditation practices, which may also be considered tasks that engage or disengage from SRP in various ways, suggests that it may be particularly the left IPL more so than the right IPL that is associated with V-SRP (e.g., Fingelkurts et al., 2016; Fingelkurts et al., 2020). Further, both VMPFC and DMPFC may be important for valenced self-evaluation (Fingelkurts et al., 2016; Fingelkurts et al., 2020).

In contrast, non-verbal or somatic (physical) forms of SRP (i.e., NV-SRP) emanating from the inner body (i.e., interoception; e.g., heartbeat) or the outer body (i.e., exteroception; e.g., touch) is assessed during tasks that engage attention toward bodily self-consciousness (BSC) (reviewed by Park and Blanke, 2019). Although interoceptive BSC is typically associated with activity in the insula and cingulate cortex, exteroceptive BSC is typically associated with activity in the premotor cortex (PMC), intraparietal sulcus (IPS), and right IPL activity (Park and Blanke, 2019). Park and Blanke (2019) also suggested the existence of an integrated NV-SRP system centred in the IPS with the involvement of the PCC, IPL, PMC, and insula cortex.

1.2.2 EEG studies

In comparison with the abundant fMRI literature on SRP, the literature on EEG correlates is relatively scarce but has often supported the role of alpha EEG oscillations (8-12Hz) during SRP. For example, Mu and Han (2013) measured the degree of synchrony of several EEG bands in response to a V-SRP task; they found that self-evaluation was associated with desynchronization in the alpha, beta, and gamma bands. A review article published in the same year summarized the methods and findings of a number of other EEG studies on SRP (Knyazev et al., 2012) and suggested the crucial role of the alpha band, the DMN, and the MPFC in particularly V-SRP studies.

However, EEG studies investigating NV-SRP also found the crucial role of alpha oscillations in locating one's body in space, activating the sensorimotor and premotor cortices (Lenggenhager et al., 2011). Further, a more recent study that measured EEG while long-term meditators' attempted to manipulate different aspects of the self using various meditation practices further supported the involvement of alpha in both V-SRP and NV-SRP (Fingelkurts et al., 2020). We provide a more comprehensive review of prior EEG studies of SRP in Chapter 3.

1.2.3 Summary

Neuroimaging studies have contributed much to our understanding of the neuroscience of both semantic (or verbal) forms of SRP (V-SRP) and somatic (or non-verbal) forms of SRP (NV-SRP). However, although neuroimaging researchers draw correlational inferences between SRP and response in various brain regions, causal evidence remains lacking. Further, given the significance of SRP in mental health, researchers are seeking to design interventions to modulate SRP in a causal manner to provide symptom relief for mental disorders associated with negatively-valenced SRP. For example, Frewen et al. (2020) provided a theoretical basis for conceptualizing certain psychological disorders as self-related disorders, notably including depression, anxiety and post-traumatic stress disorder.

Let's consider Descartes', Kant's, and James' philosophies as among the first waves of studying the self through reflective theorizing alone and recent neuroimaging research as a second wave of studying the self through empirically measuring brain activities correlated to SRP. Efforts at modulating the self directly in a causal manner by seeking to alter underlying brain activity may be considered a third wave of investigating the self in the current age.

1.3 Non-invasive brain stimulation (NIBS) of SRP

One approach to arrive at causal evidence for the involvement of brain regions in both semantic or verbal SRP (V-SRP) and somatic or non-verbal SRP (NV-SRP) would be to seek to modulate the activity of different brain regions directly and assess the outcomes of doing so for SRP. Emerging literature has also investigated whether subjective and behavioural responses to SRP tasks can be modulated through non-invasive brain stimulation (NIBS) in the form of transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tES).

1.3.1 TMS methods

TMS involves stimulating a brain region with a powerful magnetic field for a short period using a magnetic coil to induce a current in the cortical neurons parallel to the coil (Hallett, 2000; Barker and Shields, 2017). TMS can be applied physically, using an event-related approach correlated to the presentation of discrete stimuli during an SRP task or repeatedly (rTMS) and tonically over an extended treatment session (e.g., measured in minutes). Typically, single or paired TMS pulses are applied within 500 milliseconds (ms) of stimulus onset during the event-related approach to affect the brain's response to that stimulus (Miniussi et al., 2013), whereas rTMS applied continuously can be used to affect task performance in general (Beynel et al., 2019), creating "carry-over" effects on neural excitability immediately during and after the stimulation session. As a rule of thumb, low-frequency (≤ 1Hz) rTMS reduces cortical excitability, whereas high-frequency (≥ 5Hz) rTMS increases cortical excitability (Beynel et al., 2019). However, it is important to note that increases or decreases in cortical excitability do not necessarily equate to the facilitation or inhibition of certain cognitive functions because the cascade of effects of cortical excitability is modulated by several factors before reaching the level of subjective or behavioural impacts (Bestmann et al., 2015).

1.3.2 tES methods

Whereas TMS induces magnetic fields surrounding the skull to influence target electrical currents within the brain indirectly, tES uses weak (typically ≤ 2.5 mA) currents either constantly applied (termed transcranial *direct* current stimulation or tDCS) or in an oscillating manner across time (typically measured on the Hertz scale, termed transcranial *alternating* current stimulation or tACS). Electrical currents are applied to either increase or decrease neuronal excitability depending on polarity. Both tDCS and tACS are almost always used tonically rather than physically as single pulses to discrete stimuli due to the weakness in current strength being unlikely to influence cognition in such a fashion. Anodal tDCS is often thought to increase the likelihood of reaching the threshold of the action potential, while cathodal tDCS is thought to inhibit neural activity in the stimulated area (Inukai et al., 2016); comparably, tACS varies the polarity at the Hertz scale. Depending on the distance between the electrodes used in various montages, the electrical field is increased either primarily under the cortex positioned between the sites or underneath both sites (Sadleir et al., 2010). Similar to TMS, tES does not always yield effects in the desired direction, and "paradoxical" non-linear effects have been described (e.g., Kuo et al., 2013). Moreover, continuous stimulation might influence the mechanism of neurophysiological homeostasis in addition to cortical excitability (Fricke et al., 2011), thus rendering the outcome of the stimulation further uncertain.

1.3.3 Prior reviews of TMS and tES of SRP

With these precautions in mind, a number of NIBS studies show impacts for rTMS and tES in cognitive processes and psychopathologies (reviewed by Brunoni and Vanderhasselt, 2014; Dedoncker et al., 2020), suggesting that NIBS might also be used to study SRP. However, NIBS studies on SRP have been relatively scarce. Accordingly, while Frewen et al. (2020) overviewed studies whereby NIBS was used to modulate both on-task SRP and spontaneous SRP as it occurs during resting state, they called for more research in this area.

Further, Chaieb et al. (2019) systematically reviewed the effects of neuromodulation on mind-wandering, which may be considered a form of spontaneous SRP during resting state due to the functional and anatomical overlap between the brain regions mediating mind-wandering and SRP (e.g., Qin and Northoff, 2011). In their review of the tDCS literature, Chaieb and colleagues (2019) identified the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex, the MPFC, and the right IPL as regions involved in mind-wandering and suggested that tDCS can potentially modulate activity within the MPFC and the right IPL, further suggesting possible applications of NIBS to SRP, although TMS studies were not included.

1.3.4 Summary

Two forms of NIBS have been applied in studies of SRP to date, which have different physical and physiological effects: TMS, which induces magnetic fields outside the skull to influence target electrical currents within the brain indirectly, and tES, encompassing both tDCS and tACS, which uses electrical currents to attempt to alter neuronal excitability in underlying brain tissue. A nascent literature has begun to explore whether these forms of NIBS might exhibit potential as means to modulate brain activities underlying SRP and related psychological functions in a causal manner, with possible downstream impacts on subjective and behavioural responses during SRP tasks.

However, more research is required, particularly for tES methods, before any firm conclusions can be drawn concerning the efficacy of NIBS for modulating SRP in a causal manner. Accordingly, while the next chapter systematically reviews the NIBS literature, including both TMS and tES studies, later chapters present our own new empirical research on the use of NIBS during SRP utilizing tES but not TMS.

1.4 Objectives and chapter overview

The primary aims of this dissertation are to investigate the potential effects of NIBS, and specifically tES methods, as a neuromodulatory tool for altering subjective experience and neuro-electrophysiology (EEG) during both semantic (verbal) and somatic (non-verbal) forms of SRP. A series of chapters lay out the results of my efforts to systematically review the literature (Chapter 2) and conduct new empirical investigations of the EEG outcomes of SRP, whether occurring in the absence of any NIBS (Chapter 3) or the context of tDCS (Chapter 4) and tACS (Chapter 5).

In the next chapter, I summarize what is already known about this topic by presenting the updated results of a systematic review of the literature I previously conducted and published in 2021 within *Frontiers in Neuroscience* on the effects of NIBS for on-task SRP that considered both TMS and tDCS studies and the theoretical differentiation between a semantic, conceptual, or verbal form of SRP (V-SRP) and a somatic, physical, and non-verbal form of SRP (NV-SRP) (Bao et al., 2021). Importantly, I also point out that no studies have yet utilized tACS to modulate either form of SRP. The systematic review summarizes past attempts at modulating SRP with NIBS and addresses the methodological issues of existing studies and gaps of knowledge. The published systematic review has been updated in the next chapter to include studies conducted since the original publication.

Then, to further our understanding of the effect of NIBS on SRP and address the limitations of previous research, I present a total of five empirical studies across chapters 3, 4, and 5. The first two experiments are reported in Chapter 3 and are designed to 1) establish a new experimental task that measures both V-SRP and NV-SRP and 2) measure the neural correlates of verbal and non-verbal SRP with EEG. In essence, Chapter 2 aims to investigate basic questions in neuroimaging research into SRP, such as the self-reports and neural correlates of semantic vs. somatic forms of SRP at a baseline level, in the absence of NIBS, before we seek to modulate them with NIBS in subsequent studies. To our knowledge, this was the largest EEG investigation of response to a structured SRP task that had been conducted to date. The primary results were published in the journal *Neuroscience of Consciousness* in 2022 but have been updated to include additional EEG analyses pertinent to the broader aims of this dissertation (Bao et al., 2022).

Specifically, we not only extend beyond the traditional spectral power analysis of continuous EEG data on the scalp to include eLORETA source localization analyses, but we have since further followed up with additional analyses, including cluster analysis of the eLORETA results, phase synchrony, and source-level functional connectivity analyses. Broadly speaking, we analyze the spectral power and connectivity metrics on both the scalp and source levels. These additional analyses allowed for a more thorough exploration of EEG data as measures of the neural correlates of semantic and somatic forms of SRP. To briefly define the EEG analytic metrics used in these investigations, eLORETA source analysis enables us to make inferences about the source of scalp-level EEG results obtained in the whole brain. Then, analysis of phase synchrony reveals differences or changes in EEG phase angle that are independent of changes in amplitude. Finally, functional connectivity analyses investigate the correlations between responses in different brain regions of interest (ROI) that may or may not be included within various neural networks, such as the DMN, that are known to be involved in SRP from prior neuroimaging literature (e.g., Frewen et al., 2020).

Subsequently, informed by the results of the studies reported in Chapter 3, I present two empirical investigations in Chapters 4 and 5, where we investigated the effects of two tES methods (both tDCS and tACS) at different sites (frontal and parietal). To our knowledge, these are the first tES investigations to examine the effects of NIBS for SRP not only on self-reports but also on EEG measures. Here, we used a repeated-measures (within-subjects) design to compare the response to each tES method to sham ("placebo") brain stimulation; participants were randomized either to receive NIBS during the first session and sham stimulation at the second session or vice versa. The tDCS study results reported in Chapter 4 are currently invited for re-submission for publication in the journal *Neuroscience*, while the tACS study results reported in Chapter 5 are planned for future submission.

Finally, in Chapter 6, I will discuss the overall implications of our findings for our understanding of the neuro-electrophysiology underlying semantic and somatic SRP and its susceptibility to modulation via NIBS. Outstanding questions that remain will also be highlighted for future exploration.

Chapter 2

2 A Systematic review of NIBS on SRP

This chapter presents a systematic review of the NIBS literature investigating its effects on SRP tasks. Studies using transcranial magnetic stimulation (TMS) or transcranial direct current stimulation (tDCS) as the stimulation method were included. This chapter reviews existing studies' findings and methodological issues to identify future directions for the current dissertation research.

The majority of the results of this systematic review have been published in *Frontiers in Neuroscience* (Bao et al., 2021). Since the published systematic review was conducted in 2021, I have updated the review in the current chapter to include studies conducted since the original publication.

2.1 Methods of the systematic review

We conducted a PsycInfo and PubMed search with the following terms in May 2024: (tDCS OR rTMS OR TMS OR tES) (self refer∗ OR self recog∗ OR self other OR rubber hand illusion), restricting our search to peer-reviewed journal articles with no restriction on publication time. This search yielded 281 results from PsycInfo and 491 results from PubMed, making a total of 772 results (Figure 2.1). After an initial screening of each article's abstract, 58 empirical studies were considered potentially relevant and thus were passed for full-text screening. The screening process and methodological quality evaluation were carried out by the primary author (ZB) and verified in consultation with the supervising author (PF), with discussions on each paper.

The 714 excluded articles were either 1) focused on tasks unrelated to SRP, 2) focused on clinical populations or 3) lacked inclusion of a behavioural task. After reading the full texts of the 58 studies, 30 qualified for the review because they featured at least one task requiring participants to explicitly attend to verbal or non-verbal (bodily) self-referential stimuli (i.e., involved on-task SRP). The 28 excluded studies either 1) did not include an SRP task condition or 2) only investigated spontaneous SRP without an explicit task (e.g., SRP occurring in the form of mind wandering during resting state). We decided not to include at-rest SRP studies because this literature was already recently reviewed by Chaieb et al. (2019).

For the current systematic review, we focus on SRP tasks that require internal attention directed toward oneself in the verbal (V-SRP) or non-verbal sense (NV-SRP) (see Frewen et al., 2020). Comparably, tasks that primarily required attention directed to other people (e.g., theory of mind tasks) or external stimuli were excluded. Finally, eight new studies from the reference lists of the 30 qualified articles were identified and added to the review, resulting in 38 studies in total (Figure 2.1). By comparison, the excluded studies are listed in Appendix Table 1.

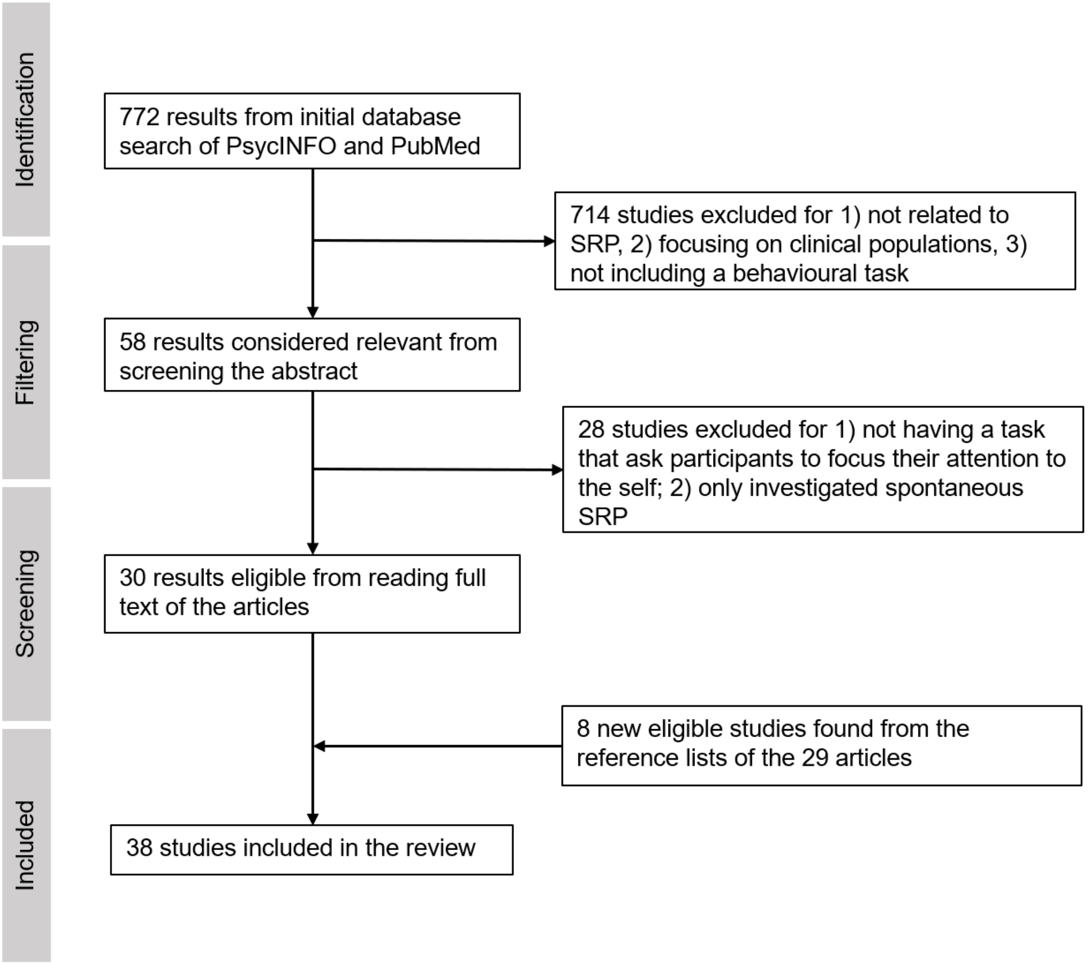

Figure 2.1. The process of article inclusion and exclusion of the systematic literature review.

From each article, we extracted the most relevant experimental variables, that is, the (1) study design (rTMS vs. single-pulse TMS vs. tDCS), (2) NIBS parameters (stimulation site, duration, timing and strength), (3) sample size, (4) type of SRP task administered, (5) measurement (Table 2.1, Table 2.2), and (6) findings (Table 2.3, Table 2.4), We followed the guidelines and used the Cochrane risk-of-bias tool (Higgins et al., 2019) to assess the quality of study methods (Table 2.5).

The included studies are subcategorized into V-SRP or NV-SRP studies based on the broad nature of the task and further categorized based on specific task types. Studies investigating responses to self-trait adjectives using self-referential encoding task (SRET) were considered within the V-SRP category. SRET studies were further subcategorized into those that used valenced words and therefore assessed the self-enhancement bias (SEB), defined as the tendency toward positive self-evaluation, or self-criticism, defined as the tendency toward negative self-evaluation, and those that selected primarily "neutral" trait adjectives and therefore assessed the self-processing effect (SPE), defined as one's tendency to process information differentially based on its degree of relevance toward oneself.

In comparison, studies that broadly involved tasks involving BSC were categorized into the NV-SRP category (for a definition of BSC, see Park and Blanke, 2019). These NV-SRP tasks were further subcategorized into tasks that investigated one of two forms of exteroceptive NV-SRP or BSC, specifically, (1) visual self-other discrimination task (SODT) or the (2) rubber hand illusion (RHI) or involved (3) interoception in the form of heart-beat detection task (HBDT) or breath counting. In the visual self-other discrimination tasks, participants' faces were digitally morphed into another face (close others or famous persons), and participants were asked to react to the change of identity during the morphing process. For RHI tasks, studies introduced visual-tactile illusions where participants' real hand is stroked with a brush in synchrony with a rubber hand to create illusory tactile sensations measured by proprioceptive drift and subjective reports of a sense of ownership of the rubber hand (Botvinick and Cohen, 1998). Finally, HBDT objectively measured heart rate and respiration rate and determined participants' accuracies in self-monitoring these measures over a specified time (Dale & Anderson, 1978; Schandry, 1981; Brener and Kluvitse, 1988; Brener and Ring, 2016).

Overall, we identified 14 studies investigating the effects of NIBS on V-SRP tasks, 8 being tDCS studies and 6 being TMS studies. Further, we identified 24 studies investigating the effects of NIBS on NV-SRP tasks, 7 being tDCS studies and 17 being TMS studies. The number of studies identified involving each of the sub-tasks is noted in Figure 2.2, further categorized as to the NIBS method employed.

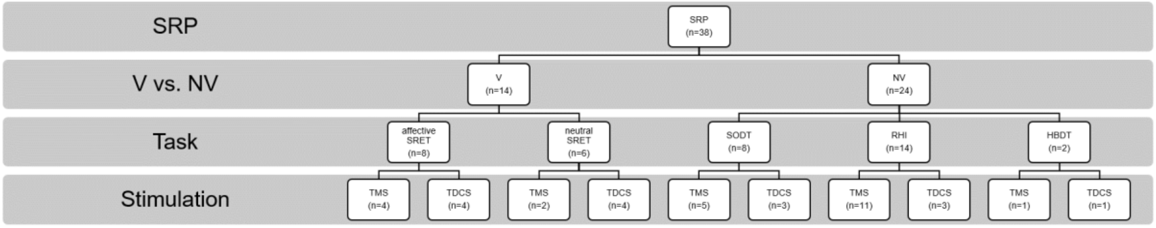

Figure 2.2 Summary of the included studies by type, task, and stimulation modality. SRP: self-referential processing; V: verbal SRP; NV: non-verbal SRP; SRET: self-referential encoding task; SPE: self-processing effect; SODT: self-other discrimination task; RHI: rubber hand illusion; HBDT, heartbeat detection task.

2.2 Results of the systematic review

As noted, among the 38 studies, 14 were classified as V-SRP studies, and 24 were NV-SRP studies. With regards to stimulation methods, 12 used single-pulse TMS (5 V-SRP, 7 NV-SRP), 11 used rTMS (1 V-SRP, 10 NV-SRP), and 15 used tDCS (8 V-SRP, 7 NV-SRP). The breakdown of the included studies by their method is summarized in Figure 2.2. The methodological details of each study are summarized in Table 2.1 and Table 2.2. Study findings are summarized in Table 2.3 for V-SRP and Table 2.4 for NV-SRP.
It should be noted that although our figures indicate the presence or absence of effects via coloured annotations, an indication of absence (grey) of effect does not mean a total lack of effect of NIBS. Rather, it only indicates a failure to reject the main null hypothesis. Readers should refer to Table 2.3 and Table 2.4 for a more detailed description of the results. Additionally, the studies excluded from this review are listed in Appendix Table 1. The results of the methodological quality evaluation are listed in Table 2.5. In brief,

the included studies have generally low levels of bias due to randomization, valid interventions, and appropriate use of missing data and outcome measurements. However, all studies received “some concerns” (SC) as the overall rating primarily due to the lack of pre-registered plans, albeit some of the papers were published before pre-registration policies were available or conventional (Table 2.5).

2.2.1 V-SRP

Among the six studies that assessed SPE, two TMS studies found that single-pulse TMS over the medial parietal region (Pz according to the 10-20 system) and the bilateral IPL reduced SPE (Lou et al., 2004, 2010; Figure 2.3). In comparison, neither study found the involvement of the MPFC during trait-assignment tasks. In addition to behavioural measures, Lou and colleagues (2004) obtained participants’ cerebral blood flow with PET scans and showed that TMS application over Pz at 160 ms post-stimulus decreased the cerebral blood flow in the left IPL more when the words presented were self-related rather than other-related (Lou et al., 2004).

Four studies investigated the effects of tDCS on V-SRP using memory tasks to examine SPE (Figure 2.3). Among the four tDCS studies, Yin et al. (2021) was the only study that observed a reduction of SPE and the only one among the four tDCS studies to investigate cathodal stimulation paired with the anode placed at an extracephalic area. Another study that presented participants with emotionally valenced words found non-valence-specific effects of tDCS, demonstrating SPE-like effects when the anode and cathode were placed at F3 and Fp2, respectively (Allaert et al., 2021).

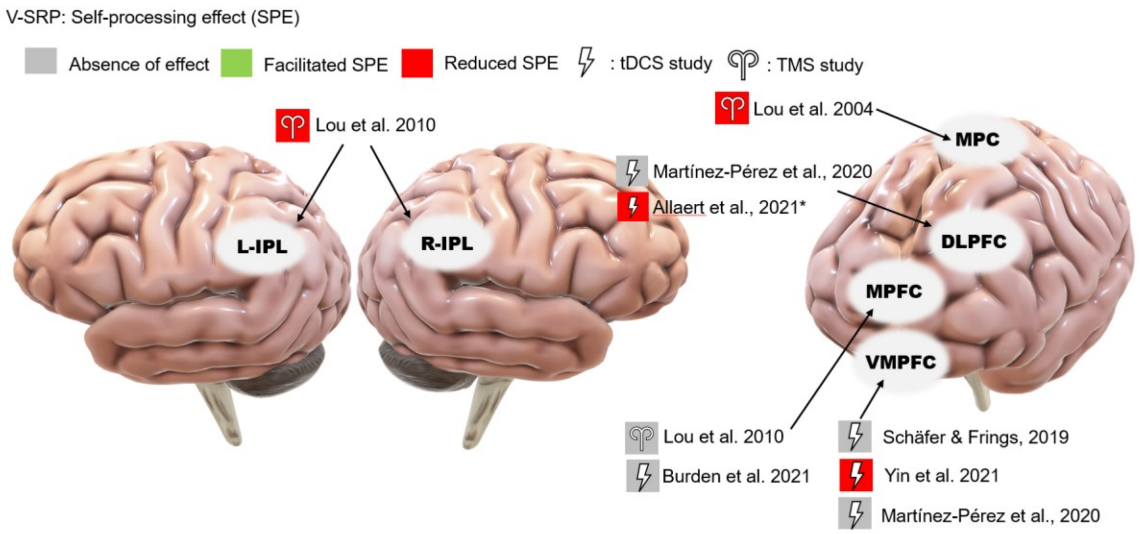

Figure 2.3 Results of the reviewed studies on neutral SRP with tasks involving self-processing effect (SPE). *For Allaert et al. (2021), although the task is valenced, The effects of tDCS were not valence-specific.

Among the studies that assessed SEB, four TMS studies consistently found that TMS over the MPFC reduced SEB, supporting the MPFC's role in emotional SRP (single pulse: Kwan et al., 2007; Barrios et al., 2008; Luber et al., 2012; rTMS: De Pisapia et al., 2019; Figure 2.4). Evaluating midline parietal cortex stimulation, Kwan et al. (2007) also found that stimulation applied to the Pz 10-20 EEG electrode site reduced SEB compared to TMS of the supplementary motor area (SMA). However, the effect of Pz stimulation was not significantly different from sham stimulation. This complicates interpretation since we cannot conclude that SMA stimulation improved SEB based on the non-significance between SMA stimulation and sham stimulation, albeit this trending result may help future studies in power calculation. Additionally, De Pisapia et al. (2019) reported an increased BOLD signal in the PCC in response to MPFC stimulation. However, no significant effect was found for left or right IPL stimulation on SEB (Luber et al., 2012).

Among the three tDCS studies that used emotionally valenced stimuli, two studies targeting the left DLPFC reduced negative self-evaluation (De Raedt et al., 2017; Dedoncker et al., 2019; Figure 2.4) and, in terms of associated mood changes, participants in both studies reported feeling less vigorous and less cheerful after the stimulation. Moreover, Dedoncker et al. (2019) found that the reduction in negative self-evaluation was associated with reduced functional connectivity between the DLPFC and the left posterior insula.

However, the two studies in this category that did not find an effect of NIBS on V-SRP are also tDCS studies. Mainz et al. (2020) targeted the MPFC and found no effect of offline tDCS on positive or negative self-evaluation. Further, Allaert et al. (2021) presented participants with social judgements (positive and negative trait adjectives). They found that the effects of tDCS over the left DLPFC were not specific to positive or negative judgments but observed a reduction of self-focused attention in general (Figure 2.3).

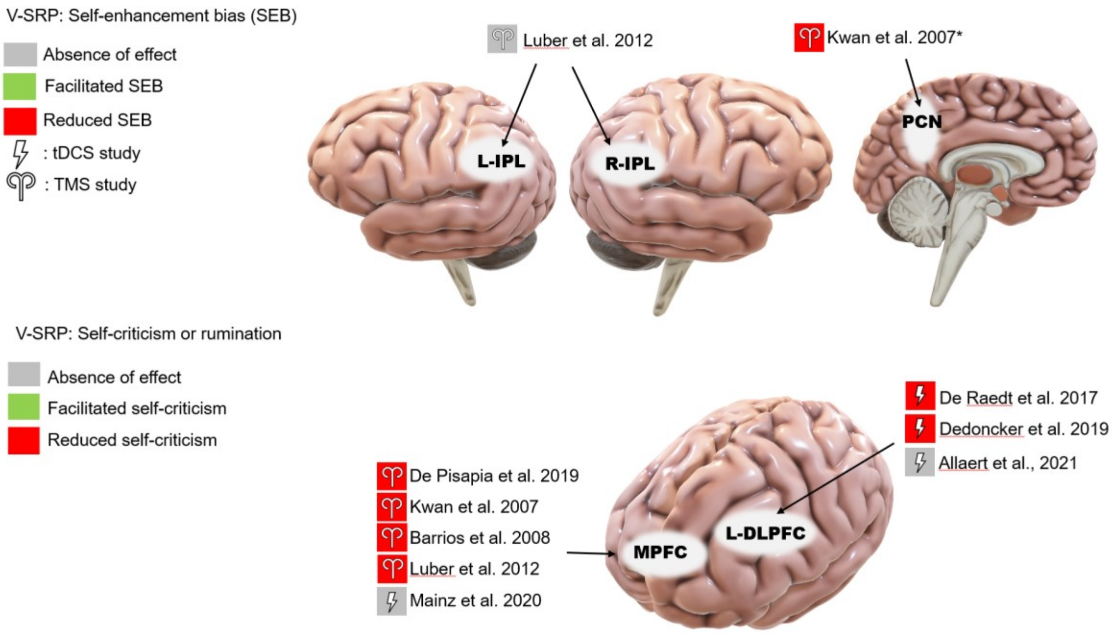

Figure 2.4 Results of the reviewed studies on emotional SRP with tasks involving self-enhancement bias (SEB) and self-criticism or rumination. *Note: This result was only significant compared to supplementary motor area stimulation.

2.2.2 NV-SRP

Among the studies that assessed self-other discrimination, neither study that targeted the left IPL found a significant effect of left IPL stimulation on self-other discrimination (Uddin et al., 2006; Heinisch et al., 2011). In comparison, three rTMS studies on self-other visual discrimination found that right IPL stimulation increased participants' propensity to judge ambiguous faces to be their own (Uddin et al., 2006; Heinisch et al., 2011; Heinisch et al., 2012; Figure 2.5).

However, other studies targeting the right IPL found null or contradictory results. For example, we identified a tDCS study on visual self-other discrimination that found that offline anodal stimulation to the right IPL increased the amount of self-face needed for self-recognition, effectively reducing participants' bias towards their face (Payne and Tsakiris, 2017; Figure 2.5). Another study found that tDCS reduced the reaction time and increased performance of a perspective-taking task, rather than in the emotional face self-other discrimination task (Weigand et al., 2021).

Other studies stimulated brain regions outside the IPL. For example, Bukowski et al. (2020) found no direct impact of TMS over the right SMG on self-other differentiation using a unique visual-tactile paradigm. However, they found that participants' trait empathy moderated the effects of TMS and that participants with low empathy activated their rSMG to a lesser degree, which was not observed in participants with high trait empathy. Pann et al. (2021) targeted the bilateral EBA with paired-pulse TMS and observed attenuated self-other differentiation in the hand discrimination task. Finally, Heinisch and colleagues (2011, 2012) found that rTMS over the right DLPFC reduced the judgment bias towards their faces in people who have negative attitudes toward their face, suggesting a role for valenced NV-SRP in the right DLPFC.

Given the differences in task design and stimulation parameters between studies, these results are inconclusive and potentially indicate that the effects of NIBS are sensitive to the stimulation type and location.

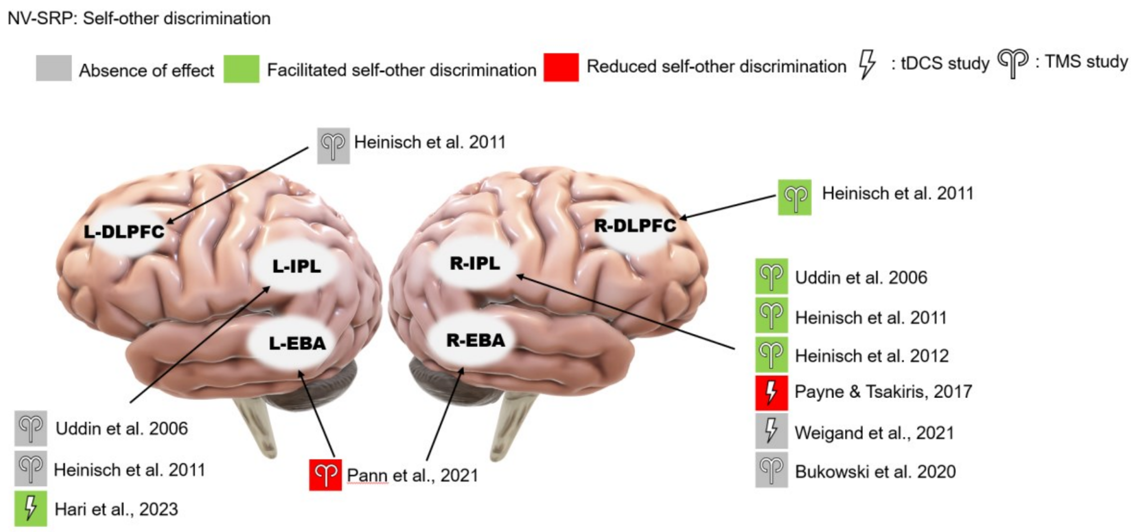

Figure 2.5 Results of the reviewed studies on NV-SRP with tasks involving self-other discrimination.

Among the studies that assessed the rubber hand illusion, two targeted the IPL and found that TMS reduced RHI-induced proprioceptive drift (single-pulse: Tsakiris et al., 2008; rTMS: Kammers et al., 2009; Figure 2.6), while one study targeting the extrastriate body area (EBA) found increased proprioceptive drift (rTMS: Wold et al., 2014). Another study using paired-pulse TMS targeting the anterior IPS and primary motor cortex (M1) found numerical but non-significant increases in proprioceptive drift when participants experienced agency and ownership over the rubber hand (Karabanov et al., 2017).

All but one study (Alaydin & Cengiz, 2021) that targeted the M1 with TMS found increases in RHI strength measured by increased proprioceptive drift, sense of ownership and embodiment (Figure 2.6). Further, note that Alaydin & Cengiz (2021) differed from the rest of the studies in this category in its control condition insofar as while the rest of the studies compared synchronous versus asynchronous stroking during RHI induction, Alaydin & Cengiz (2021) compared TMS-induced RHI with brush-stroke-induced RHI, which may explain the differences in results. Interestingly, other studies targeting different areas of the brain (L-IPL and VPMC) also found reduced proprioceptive drift, indicating that TMS can play an inhibitory role in RHI induction (Kammers et al., 2009; Peviani et al., 2018).

For tDCS, Convento et al. (2018) showed that anodal stimulation to both the right IPL and the right PMC increased proprioceptive drift (Figure 2.6). Interestingly, in their experiment, the effects of tDCS on the right PMC were indifferent to the synchrony of stroking. Moreover, another study found that online anodal tDCS over the posterior parietal cortex (PPC) but not the PMC facilitated proprioceptive drift and subjective ownership, further supporting the functional segregation between the parietal cortex and the PMC during RHI (Lira et al., 2018; Figure 2.6). Finally, a study found that online cathodal tDCS over the primary somatosensory cortex (S1) facilitated the subjective experience of RHI compared to the anodal group but not on proprioceptive drift (Hornburger et al., 2019). Interestingly, an iTBS study targeting the same region also found that increased motor cortical excitability decreased RHI intensity (Frey et al., 2023). These results may suggest that RHI intensity is associated with reduced activity in the S1 region of the brain.

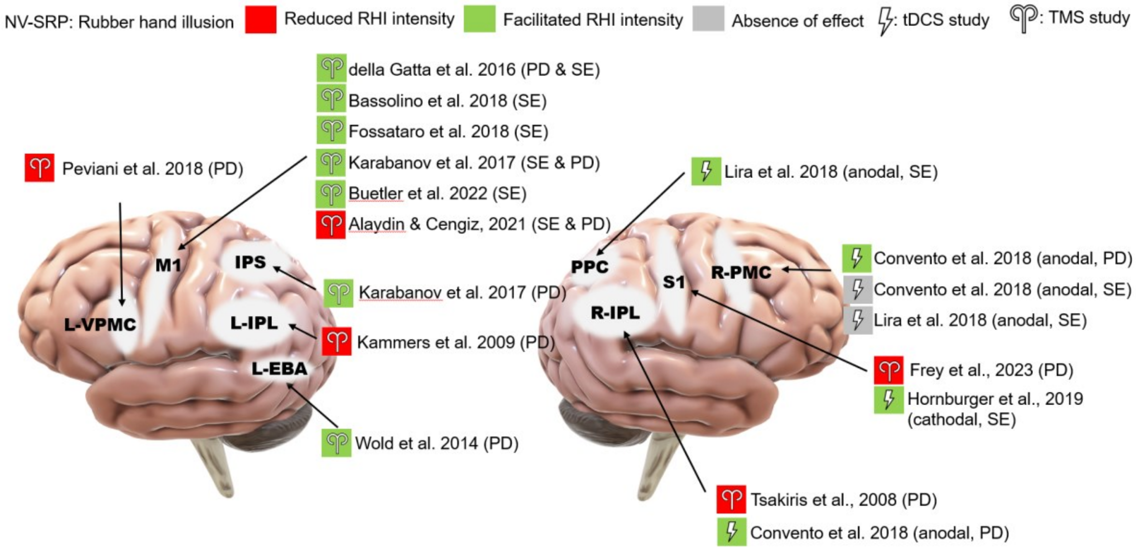

Figure 2.6 Results of NV-SRP studies on RHI. PD, proprioceptive drift; SE, the subjective embodiment of RHI.

Among the studies that assessed interoception, we identified only one TMS study that investigated the effects of offline continuous theta-burst stimulation (cTBS) on interoception, focusing on right insula and S1 stimulation in comparison to occipital cortex stimulation as a control (Pollatos et al., 2016; Figure 2.7). The researchers found that right insula and S1 stimulation reduced interoceptive accuracy (IAc), IAc confidence, and interoceptive sensibility. Specifically, cTBS over S1 reduced cardiac IAc, while cTBS over the right insula reduced both cardiac and respiratory IAc. Further, in terms of IAc confidence, right insula cTBS reduced confidence in respiration IAc compared specifically to occipital stimulation and reduced cardiac IAc confidence compared specifically to S1 stimulation. Additionally, both insula and S1 stimulation resulted in an increase in self-reported interoceptive sensibility compared to pre-stimulation. Note that one limitation of this study is that the cTBS targeting the insula would likely also have an impact on the overlying frontotemporal cortices, complicating interpretation.

We also identified only a single tDCS study that investigated interoception. Specifically, Sagliano et al. (2019) found no effect of offline anodal tDCS over the left and right insula on heartbeat counting accuracy with electrodes placed at F7, T3 for the left insula and F8, T4 for the right insula (Figure 2.7). However, sham tDCS was associated with counting accuracy when pre- and post-stimulation performances were compared. The authors suggested that this can be explained by real tDCS reducing the “practice effect” on interoceptive accuracy improvements, concluding that their study supports the role of the insula in IAc.

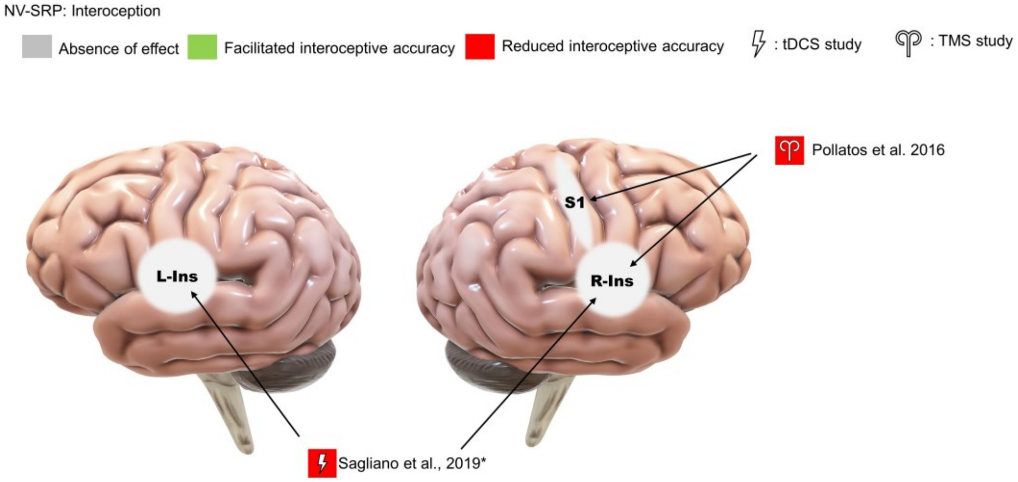

Figure 2.7 Results of NV-SRP studies on interoception. *Note: This study found that sham but not real stimulation improved interoceptive accuracy.

Table 2.1 Summary of experimental paradigms of V-SRP studies

Study	Task	Timing of Task	Design	Sham	Site of stimulation	*N (% females)*	Stimulation method, time and intensity	Dependent variable(s)
Schäfer & Frings, 2019	SRET - neutral	Offline	B	No	Anodal/cathodal VMPFC (Fpz), cathodal/anodal DLPFC (F3)	65 (72%)	0.5-mA tDCS for 20 min. Target electrodes are 9 cm^2, reference electrodes are 35 cm^2	Accuracy and RT
Lou et al., 2004	SRET - neutral	Online	W	No	Oz, Pz, and Fz	25 (54%)	Single-pulse TMS at 150% MEP of the feet, at 0~480 ms post-stimulus	Accuracy and RT
Lou et al., 2010	SRET - neutral	Online	W	No	MPFC, left IPL, right IPL	15 (39%)	Single-pulse TMS at 150% RMT, at 0~480 ms post-stimulus	Accuracy and RT
Burden et al., 2021	SRET - neutral	Online	B	Yes	Anodal Fz, cathodal right arm	28 (64%)	1.5-mA tDCS for 30mins. Target and reference	Accuracy

							electrodes are 10 cm^2	
Yin et al., 2021	SRET - neutral	Offline	B	Yes	Anode/cathode over the VMPFC and an extracephalic area	90 (50%)	1.5-mA tDCS for 15 mins. Target and reference electrodes are 9 cm^2	RT
Martínez-Pérez et al., 2020	SRET - neutral	Online	B	Yes	Anode/cathode VMPFC/DLPFC	90 (77%)	2-mA HD-tDCS for 11.5 mins. The average electric field magnitudes were .046 and .071 V/m in the VMPFC and DLPFC, respectively	Accuracy and RT
Barrios et al., 2008	SRET - affective	Online	B	Yes	MPFC, Pz, and SMA	10 (100%)	Single-pulse TMS at 90% RMT, 500 ms post-stimulus	Self-enhancement scores and RT
Mainz et al., 2020	SRET - affective	Offline	B	Yes	Anodal/cathodal Fpz (MPFC) and cathodal/anodal Oz (occipital)	75 (0%)	2-mA tDCS for 20 min. Target and reference electrodes are 35 cm^2	Self-enhancement scores
Dedoncker et al. 2019	SRET - affective	Offline	B	Yes	Anodal Left DLPFC, cathodal right supraorbital area	41 (100%)	1.5-mA tDCS or 20 mins. Target and reference electrodes are 25 cm^2	Perceived criticism, current mood, and resting FC
Kwan et al., 2007	SRET - affective	Online	W	Yes	MPFC, Pz, and SMA	12 (83%)	Single-pulse TMS at 90% RMT, 500 ms post-stimulus	Self-enhancement scores and RT
Luber et al., 2012	SRET - affective	Online	W	No	MPFC, left IPL, right IPL	18 (44%)	Single-pulse TMS at 150% RMT, 0~480 ms post-stimulus	Self-enhancement scores and RT

De Raedt et al., 2017	SRET - affective	Offline	W	Yes	Anodal Left DLPFC, cathodal right supraorbital area	32 (100%)	1.5-mA tDCS for 20 min. Target and reference electrodes are 35 cm^2	Ruminative thinking, current mood, implicit and explicit self-esteem
De Pisapia et al., 2018	SRET - affective	Offline	W	Yes	MPFC (Fpz)	14 (50%)	1-Hz rTMS for 14 min at 100% of RMT	RT and fMRI BOLD signal
Allaert et al., 2021	SRET - affective in a social evaluation task	Offline	B	Yes	Anode over F3 and cathode over Fp2.	74 (100%)	2-mA tDCS for 20 min. Target and reference electrodes are 35 cm^2	Gaze behaviour, SCL, Self-report measures

Abbreviations: within-subject design (W), between-subject design (B), resting motor threshold (RMT), reaction time (RT), transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), repetitive transcranial magnetic stimulation (rTMS), Continuous theta-burst stimulation (cTBS), medial prefrontal cortex (MPFC), ventromedial prefrontal cortex (VMPFC), dorsolateral prefrontal cortex (DLPFC), inferior parietal lobule (IPL), blood oxygen level dependant (BOLD), supplementary motor area (SMA), posterior parietal cortex (PPC), heartbeat-evoked potential (HEP), motor-evoked potential (MEP), extrastriate body area (EBA), anterior inferior parietal lobule (aIPS), primary motor cortex (M1), self-referential encoding task (SRET), rubber hand illusion (RHI), self-other discrimination task (SODT), heartbeat detection task (HBDT)

Table 2.2 Summary of experimental paradigms of NV-SRP studies.

Study	Experimental Task	Timing of Task	Design	Sham condition	Site of stimulation	*N(% females)*	Stimulation method, time and intensity	Type of measure
Payne & Tsakiris, 2017	SODT	Offline	B	Yes	Right IPL (CP6), reference electrode over the Vertex	60 (73%)	1-mA tDCS for 20 min. Target and reference electrodes are 3.5 cm^2	The proportion of morphing videos judged “self”
Uddin et al., 2006	SODT	Offline	W	No	Left and Right IPL	8 (75%)	1-Hz rTMS for 20 min at 100% RMT	The proportion of morphing pictures judged “self”

Heinisch et al., 2011	SODT	Offline	W	Yes	Left DLPFC (midpoint of triangle F3, F7, Fp1), right DLPFC (midpoint of triangle F4, F8, Fp2), left IPL (CP5), right IPL (CP6)	10 (50%)	1-Hz rTMS for 20 min at 100% RMT	The proportion of morphing video judged "self," self-reported valence of self-recognition
Heinisch et al., 2012	SODT	Offline	W	Yes	Right IPL (CP6)	10 (50%)	1-Hz rTMS for 20 min at 100% RMT	The proportion of morphing video that is judged to be the self, self-reported valence of self-recognition
Pann et al., 2021	SODT	Online	W	No	The bilateral extrastriate body area	16 (75%)	Paired-pulse TMS at 110% RMT	Accuracy and RT of self vs. other hand identity judgment
Weigand et al., 2021	SODT	Cognitive task online, emotional task offline	B	Yes	Anode over the right SMG, cathode over the contralateral supraorbital area	47 (60%)	1-mA tDCS for 20 mins. Anode was 35 cm^2, and cathode was 100 cm^2	RT and difference scores between ratings of self vs. other's emotions
Hari et al., 2023	SODT	Online	W	No	The left TPJ with a central electrode at CP5 for both anodal and cathodal stimulation	15 (47%)	2-mA HD-tDCS for 20 mins.	Accuracy and RT of the auditory intentional binding task
Bukowski et al., 2020	SODT	Offline	W	No	The right SMG and vertex	31 (100%)	cTBS for 40 sec at 80% AMT	Emotion rating discrepancy between self and other
Bassolino et al., 2018	RHI in Virtual reality	Online	Mixed design	No	M1, vertex, 80% RMT for subthreshold stimulation as the control	32 (50%)	Single-pulse TMS at 130% RMT	PD, MEP, subjective reports of body ownership

Convento et al., 2018	RHI	Online	B	Yes	Right PMC, right IPL	56 (95%)	1.5-mA tDCS for 10 min. Target and reference electrodes are 25 cm^2	PD, subjective reports of body ownership
della Gatta et al., 2016	RHI	Online	B	No	Left M1, right M1 as control	52 (64%)	Single-pulse TMS at 110% RMT	PD, MEP, subjective reports of body ownership
Tsakiris et al., 2008	RHI	Online	W	No	Right IPL, vertex	10 (60%)	Single-pulse TMS with varying intensity	PD
Kammers et al., 2009	RHI	Offline	W	Yes	Left IPL (TP3)	13 (100%)	1-Hz rTMS for 20 min at 80% RMT	PD, subjective reports of sensations
Wold et al., 2014	RHI	Offline	W	No	Left EBA, 40% RMT stimulation as the control	19 (58%)	1-Hz rTMS for 20 min at 80% RMT	PD, subjective reports of body ownership
Karabanov et al., 2017	RHI	Online	W	No	Anterior IPS, M1	28 (43%)	Single- and paired-pulse TMS at 100% RMT for M1, 90% RMT for aIPS	PD, MEP, subjective reports of body ownership
Fossataro et al., 2018	RHI	Offline	W	Yes	Left M1	48 (79%)	1-Hz rTMS for 20 min at 90% RMT and single-pulse TMS at 100% RMT	PD, MEP, subjective reports of body ownership
Hornburger et al., 2019	RHI	Online	W	Yes	Anodal/cathodal S1(C3), reference electrode over the right supraorbital region	30 (60%)	1-mA tDCS for 20 min. Target and reference electrodes are 35 cm^2	PD, subjective reports of body ownership

Lira et al., 2018	RHI	Online	W	Yes	Right PPC (35 cm^2, 2-mA, P4), right PMC (1-mA, fC4, 10-10 EEG system), reference electrode over the contralateral supraorbital region (35 cm^2)	160 (71%)	2- or 1-mA tDCS for 10 min. Target and reference electrodes are 35 or 21 cm^2	PD, subjective reports of body ownership
Peviani et al., 2018	RHI	Offline	W	No	PMC, vertex	24 (79%)	1-Hz rTMS for 20 min at 100% RMT	PD, subjective reports of body ownership
Frey et al., 2023	RHI	Online	W	Yes	S1 contralateral to the left FDI	17 (41%)	iTBS for 600 pulses in 200 seconds at 80% RMT	PD, subjective reports of ownership
Alaydin & Cengiz, 2021	RHI	Online	B	No	The right motor cortex's hand area and a peripheral electrical stimulation on the hand	21 (43%)	Single-pulse TMS to produce MEP of 200 µV	PD, subjective reports, and inhibition scores
Buetler et al., 2022	RHI in virtual reality	Online	W	No	Left M1	10 (50%)	Single-pulse TMS at 40-57% MEP	Movement metrics and subjective reports of embodiment
Sagliano et al. 2019	HBDT	Offline	W	Yes	Anodal Left insula (midpoint of F7 and T3), cathodal left frontal pole (Fp2); anodal right insula (midpoint of F8 and T4), cathodal right frontal pole (Fp1)	16 (56%)	1-mA tDCS for 15 min. Target electrode is 6.25 cm^2, reference electrode 25 cm^2	Heartbeat counting accuracy, self-reported state anxiety

Pollatos et al., 2016	HBDT	Offline	W	No	Right insula (FT8), somatosensory cortex (chest location, Cz), central occipital (Oz)	18 (0%)	5-Hz cTBS for 40 sec at 80% RMT	Heartbeat and respiratory counting accuracy and confidence in judging accuracy, self-reported state anxiety, HEP
Abbreviations: proprioceptive drift (PD), supramarginal gyrus (SMG), first dorsal interosseous (FDI), intermittent theta burst stimulation (iTBS), active motor threshold (AMT), rubber hand illusion (RHI), self-other discrimination task (SODT), heartbeat detection task (HBDT). See 'Abbreviations' under **Error! Reference source not found.** for missing abbreviations.								

Table 2.3. Summary of results of the included V-SRP studies.

Study	Task	Main Results	Other Results
TMS studies			
Neutral			
Lou et al., 2004	Rate the applicability of personality traits to self, best friend, and the Danish Queen. Then, indicate their previous choice as fast as they can	SPE was reduced by TMS to Pz applied 160ms post-stimulus (self > other)	No effect was found in the Fz stimulation condition
Lou et al., 2010	Same as Lou et al. 2004, but without the Danish Queen's condition	TMS reduced SPE to both left and right IPL applied 160ms, 240ms, and 480 ms post-stimulus. The left IPL had much stronger effects than the right IPL.	No effect was found in the Fz stimulation condition
Affective			
Kwan et al., 2007	Assign positive, neutral and negative adjectives to either the self or their best friend	real stimulation over the MPFC reduced SEB compared to sham	Precuneus stimulation was also found to reduce SEB but only compared to the Supplementary motor area stimulation
Barrios et al., 2008	Assign egotistic or moralistic adjectives that are either positive or negative to the self or best friend	TMS to the MPFC significantly reduced SEB but only for egotistic words	No self-enhancement effect was found among their all-female samples
Luber et al., 2012	Assign desirable and undesirable adjectives to either the self or their best friend	real stimulation over the MPFC reduced SEB compared to sham	TMS over the parietal cortex did not affect the self-enhancement effect
De Pisapia et al., 2018	Assign positive and negative adjectives to the self, close other, and the Eiffel Tower,	rTMS to the MPFC resulted in the inhibition of negative self-evaluation.	1) TMS reduced the BOLD signal in the MPFC in other conditions more than self; 2) TMS increased PCC BOLD signal in negative > positive; 3) TMS

	or count the number of syllables.		over the MPFC increased the BOLD signal in the bilateral IPL only for negative adjective assignment to the self
tDCS studies			
Neutral			
Schäfer & Frings, 2019	Recall previously learned word associations with the self, an other, and a neutral object	anodal VMPFC with cathodal DLPFC had no effect in all conditions	N/A
Burden et al., 2021	Participants encoded associations between objects and identity (self and other) and were then asked to retrieve the memory later. They also judged the pleasantness of the pairing.	Although SPE was present, tDCS did not influence memory retrieval compared to sham.	N/A
Yin et al., 2021	Participants encoded associations between objects and identity (self, stranger, and friend) and then asked to retrieve the memory later.	SPE was observed in both anodal and sham tDCS but attenuated in cathodal tDCS.	SPE was associated with increased functional connectivity between the VMPFC and frontoparietal regions related to working memory
Martínez-Pérez et al., 2020	Participants learned associations between geometric shapes and identity (self, stranger, and friend) and then asked to match the pairs later	Although SPE was present, tDCS did not influence memory retrieval compared to sham for matching pairs.	Cathodal stimulation over the DLPFC reduced accuracy only in non-matching pairs.
Affective			
De Raedt et al., 2017	Respond "true" or "false" to positive or negative statements related to the self. Then, they listened to the negative statements in audio format	anodal tDCS over the DLPFC with cathodal r-SOA reduced negative self-evaluation compared to sham	participants reported being more tired, less vigorous, and less cheerful after both real and sham tDCS
Dedoncker et al., 2019	Female participants listened to critical, neutral, and positive comments about them. Also reported their perceived level of criticism in their life.	Anodal left DLPFC stimulation reduced emotional responsiveness (measured by functional connectivity) towards criticisms in females with a high level of perceived criticism	Participants reported more fatigue, less vigour, and less cheerful after both real and sham tDCS; Participants reported more anger and more depressed after being criticized
Mainz et al., 2020	Indicate the descriptiveness of positive and negative adjectives related to the self. Then, they were asked	anodal MPFC with cathodal near Oz had no effect on both conditions	Participants exhibited self-enhancement biases towards positive words

	to recall the adjectives regardless of valence		
Allaert et al., 2021	Evaluate their photograph and receive positive and negative evaluations of their photograph	tDCS decreased self-focused attention compared to sham, and increased focus on others' photographs. The effects were not valence-specific	Slower fixation time (reduced self-focus) was correlated with smaller SCL only for participants receiving active tDCS
Abbreviations: Self-processing effect (SPE), self-enhancement bias (SEB), supraorbital area (SOA), posterior cingulate cortex (PCC). See 'Abbreviations' under Table 2.1 for missing abbreviations.			

Table 2.4 Summary of results of the included NV-SRP studies

Study	Task	Main Results	Other Results
TMS studies Self-other discrimination			
Uddin et al. 2006	Presented with pictures of their own face gradually morphed into a familiar other, then press a button to indicate a change of identity	rTMS over the right IPL increased propensity to judge faces to be one's own	No effect was found in the left IPL stimulation condition
Heinisch et al., 2011	Similar to Uddin et al. 2006, except 1) used video morphing instead of pictures. 2) Added an unfamiliar face condition. 3) A questionnaire on their perception of their own body was added.	rTMS over the right IPL and right DLPFC increased the propensity to detect self-faces emerging from famous faces but not unfamiliar faces.	rTMS over the right DLPFC reduced self-recognition sensitivity in people who have negative attitudes toward their own face
Heinisch et al., 2012	Similar to Heinisch et al. 2011, but measured attention during the task	Replicated Uddin et al. 2006 and Heinisch et al. 2011. But rTMS over the right IPL has no effect on other-other discrimination	Attention had no impact on the effect of the right IPL rTMS
Pann et al., 2021	Presented with pictures of their own hands vs. other's hands and asked to judge whether images indicated their own vs. others' hands	TMS over the bilateral EBA increased reaction time of self-other discrimination compared to vertex and no TMS	All TMS conditions (left, right EBA and vertex) reduced accuracy self-other hand discrimination compared to no TMS
Bukowski et al., 2020	Asked to rate their emotional response vs. other's emotional response in a tactile empathy task	cTBS did not result in significant changes in empathy ratings overall, but the degree of impact of cTBS was mediated by participants' dispositional empathy	Bias toward self-emotions was associated with a high BOLD signal in the rSMG, middle insula, and occipital cortex
Rubber hand illusion (RHI)			
Tsakiris, Constantini & Haggard, 2008	RHI, PD measurement	Single-pulse TMS over the r-IPL reduced PD when viewing the rubber hand but increased drifts when viewing the neutral object	N/A

Kammers et al., 2009	RHI, PD measurement, and a questionnaire about subjective RHI experience. Immediate and delayed effects were both measured	For immediate effects, rTMS over the left IPL reduced PD when viewing the rubber hand. No difference in subjective experience between real and sham TMS groups	No effect was found for delayed effects of rTMS
Wold et al., 2014	RHI with button clicking to indicate RHI onset, PD, subjective rating of RHI intensity	rTMS over the EBA increased PD during synchronous stroking compared to asynchronous stroking	No rTMS effect on subjective reports of body ownership
della Gatta et al., 2016	RHI, PD measurement, and a questionnaire about subjective ownership.	Single-pulse TMS over the M1 reduced MEP, increased PD, and increased sense of embodiment in the synchronous condition compared to the asynchronous condition	The reduction of MEP increased overtime
Karabanov et al., 2017	RHI procedure where the rubber hand can be anatomically implausible (ownership) and/or detached from the real hand (agency). PD, subjective rating of agency and ownership, and the effective connectivity between brain regions were measured.	Single-pulse TMS over the M1 increased PD and ownership. No change of PD and subjective rating induced by paired-pulse stimulation (M1-aIPS)	TMS over the aIPS inhibited motor-evoked potential (MEP) from TMS-induced signals from M1. Such effect is dampened during sensorimotor conflicts
Bassolino et al., 2018	RHI procedure in virtual reality with PD, ownership, and agency measurement	Pulses of supra-threshold TMS over the M1 increased the sense of ownership for synchronous stroking compared to asynchronous. Supra-threshold TMS over the M1 increased ownership and agency compared to sub-threshold for synchronous stroking	No effect was found for perceived agency, ownership, and location when comparing the two supra-threshold conditions
Fossataro et al., 2018	RHI procedure in virtual reality with PD and embodiment questionnaire	rTMS over the M1 increased sense of embodiment and disembodiment for synchronous stroking	N/A
Peviani et al., 2018	RHI procedure in virtual reality with PD and ownership questionnaire	rTMS over the VPMC reduced PD without influencing the sense of ownership	N/A
Alaydin & Cengiz, 2021	RHI induction and peripheral electrical stimulation on the hand with two types of TMS techniques	TMS reduced PD and subjective illusion intensity compared to brush stroke and passive movement	RHI increased short-latency afferent inhibition while reducing short-latency intracortical inhibition
Buetler et al., 2022	RHI induction in virtual reality with ownership and movement kinematic measurements	RHI strength was positively correlated with TMS-evoked potentials in the motor cortex	N/A

Frey et al., 2023	RHI induction, PD measurement, and a questionnaire about subjective ownership.	iTBS over S1 reduced PD compared to sham	iTBS did not have significant effects on subjective reports of RHI intensity
<u>Interoception</u>			
Pollatos et al., 2016	Heartbeat and respiration counting task with interoceptive sensibility questionnaire before and after the task	cTBS over the S1 reduced cardiac IAc compared to occipital stimulation cTBS over the right insula reduced cardiac and respiratory IAc compared to occipital stimulation	Stimulation over the right insula reduced confidence in cardiac IAc compared to occipital stimulation Stimulation over the right insula reduced confidence in respiration IAc compared to S1 stimulation
tDCS studies			
<u>Self-other discrimination</u>			
Payne & Tsakiris, 2017	Similar to Heinisch et al. 2011, without the attention task	Anodal stimulation at CP6 with the cathode at the vertex decreased the propensity to judge faces to be one's own	N/A
Weigand et al., 2021	Presented with emotionally ambiguous situations and asked to judge their own experienced emotions vs. others' emotions	tDCS did not affect participants' emotional egocentric biases. No difference in bias was observed between positive vs. negative emotions	tDCS increased task performance accuracy during a perspective-switching task
Hari et al., 2023	Learned associations between auditory stimulus and identity (Self vs. other), then tested on their memory accuracy of RT	Anodal stimulation reduced reaction time for both self and other conditions, whereas cathodal stimulation only reduced RT for the self condition.	HD-tDCS did not have a main effect on self vs. other-associated stimuli
<u>Rubber hand illusion (RHI)</u>			
Convento et al., 2018	RHI, PD measurement, and questionnaire about subjective RHI experience with an additional experiment with no stroking	Anodal stimulation over the right IPL increased PD in synchronous stroking compared to asynchronous stroking, while the effects of anodal right PMC stimulation on PD were indifferent to synchrony	Stimulation to the right IPL, not the right PMC, induced the subjective feeling of "illusory touch" Anodal tDCS to the right IPL and right PMC increased PD even without stroking
Hornburger et al., 2019	RHI procedure where the location of the rubber hand became increasingly anatomically implausible, PD, and subjective questionnaire measurements	Cathodal tDCS facilitated the subjective experience but not PD during RHI compared to the anodal group	Regardless of stimulation, RHI strength and PD exhibited gradual decreases as the rubber hand moved further away from the real hand

Lira et al., 2018	RHI, PD measurement, and questionnaire about subjective RHI experience	anodal tDCS over the PPC but not the PMC facilitated of RHI and subjective reports, regardless of synchrony.	PPC tDCS's strength of effect in PD is higher in synchronous conditions compared to the asynchronous condition
Interoception			
Sagliano et al., 2019	Heartbeat counting task with ECG recordings before and after tDCS	sham tDCS over the left and right insula improved the counting accuracy of heartbeats but not real stimulation.	No effect of tDCS on state anxiety
Abbreviations: premotor cortex (PMC), ventral premotor cortex (VPMC), the primary somatosensory cortex (S1), proprioception drift (PD), electrocardiogram (ECG), interoceptive accuracy (IAc), see 'Abbreviations' under Table 2.1 for missing abbreviations.			

Table 2.5. Summary of methodological qualities of the included studies

Study	Bias arising from the randomization process	Bias due to deviations from intended interventions	Bias due to missing outcome data	Bias in the measurement of the outcome	Bias in the selection of the reported result	Overall risk-of-bias judgement
V-SRP						
Lou et al., 2004 (TMS portion)	L	SC	L	SC	SC	SC
Lou et al., 2010	L	L	SC	L	SC	SC
Schäfer & Frings, 2019	L	L	SC	L	SC	SC
Kwan et al., 2007	L	L	L	L	SC	SC
Barrios et al., 2008	L	L	L	SC	SC	SC
Luber et al., 2012	L	L	SC	L	SC	SC
Mainz et al., 2020	L	L	L	L	SC	SC
De Raedt et al., 2017	L	L	L	L	SC	SC
Dedoncker et al., 2019	L	L	L	SC	SC	SC
De Pisapia et al., 2018	L	L	L	L	SC	SC
Burden et al., 2021	L	L	L	L	SC	SC
Yin et al., 2021	L	SC	L	L	SC	SC
Martínez-Pérez et al., 2020	L	L	L	L	SC	SC
NV-SRP						
Uddin, et al., 2006	L	L	L	L	SC	SC

Heinisch et al., 2011	L	L	L	L	SC	SC
Heinisch, Krüger & Brüne, 2012	L	L	L	L	SC	SC
Payne & Tsakiris, 2017	L	L	L	L	SC	SC
Tsakiris, Constantini & Haggard, 2008	L	SC	L	L	SC	SC
Kammers et al. 2009	L	L	L	L	SC	SC
Wold et al., 2014	L	L	SC	L	SC	SC
Karabanov et al., 2017	L	SC	L	L	SC	SC
Convento et al., 2018	L	L	L	L	SC	SC
Bassolino et al. 2018	L	L	L	L	SC	SC
della Gatta et al., 2016	L	SC	L	L	SC	SC
Fossataro et al., 2018	L	L	L	L	SC	SC
Hornburger et al., 2019	L	L	L	L	SC	SC
Lira et al., 2018	L	L	L	L	SC	SC
Peviani et al., 2018	L	SC	L	L	SC	SC
Sagliano et al. 2019	L	L	L	L	SC	SC
Pollatos et al., 2016	L	L	L	L	SC	SC
Alaydin & Cengiz, 2021	L	SC	L	L	SC	SC
Pann et al., 2021	L	SC	L	L	SC	SC
Weigand et al., 2021	L	L	L	L	SC	SC
Bukowski et al., 2020	L	SC	L	L	SC	SC
Hari et al., 2023	L	SC	L	L	SC	SC
Buetler et al., 2022	SC	SC	L	L	SC	SC
Allaert et al., 2021	L	L	L	L	SC	SC
Frey et al., 2023	L	L	SC	L	SC	SC
Abbreviations: L = Low; H = High, SC = Some Concerns						

2.3 Discussion

We systematically reviewed 38 studies that investigated the effect of NIBS on SRP, separated by verbal (V-SRP) vs. non-verbal (NV-SRP) domains. Within the context of V-SRP, studies examined neutral (SPE) vs. emotionally salient (SEB) trait characteristics with SRETs. As described in Tables 1 and 3 referring to V-SRP, and Tables 2 and 4 referring to NV-SRP, the studies described in this review used diverse methods, particularly in stimulation type (repetitive: rTMS or event-related: single or pair-pulse TMS) and strength (TMS strength and tDCS current density). In terms of experimental tasks, studies involved either self vs. non-self stimulus discrimination (V-SRP and NV-SRP), response to the rubber hand illusion (NV-SRP), or interoception (NV-SRP). Overall, the methodological quality of the reviewed studies exhibited generally low biases but revealed some concerns, such as lack of sham control and pre-registration. Despite such differences in methods, the results of the reviewed studies revealed some consistencies, albeit with some caveats.

2.3.1 V-SRP

Self-Processing Effect

The results of NIBS on V-SRP were relatively consistent across the 14 reviewed studies in demonstrating a likely role for the cortical midline structures and particularly the left IPL in the self-processing effect (SPE), which, as a task involving self-endorsement responses to relatively neutral adjectives, negates the relevance of emotional valence (Figure 2.3). Moreover, although Lou et al. (2010) found that TMS to both the left and right IPL resulted in a reduction in SPE, the effect of left IPL stimulation was found to be greater than right IPL, which is in line with fMRI studies on V-SRP such as that of Davey et al. (2016) who found the involvement of the bilateral IPL in V-SRP with the left IPL showing increases in BOLD signal more than the right IPL. However, so far only two TMS studies have investigated the effects of IPL stimulation on V-SRP tasks, and therefore more studies are needed for further validation.

Self-Enhancement Bias

Further, whereas the IPL has been implicated in neutral V-SRP or the SPE, the MPFC demonstrates significance when studies consider emotional valence as a variable (Figure 2.4). In our review, three single-pulse TMS studies found that MPFC stimulation reduces self-enhancement bias (SEB), although one tDCS study failed to provide corroborative evidence. Additionally, other regions of interest (ROI), such as the precuneus and bilateral IPL, received weak support (Kwan et al., 2007; Luber et al., 2012; De Pisapia et al., 2019). The effects of MPFC stimulation on SEB seem to be self-specific and egotistic, referring to an inflated sense of self-worth, status, and power, indicative of an increased SEB (Barrios et al., 2008). Importantly, six out of eight studies found that rTMS or anodal tDCS over the MPFC or the DLPFC also reduced negative self-evaluation (self-criticism), suggesting that activation of the prefrontal cortex could have resulted in an overall dampening of emotional response to V-SRP (Figure 2.4). Meanwhile, five out of eight studies that attempted to modulate V-SRP with tDCS over the prefrontal cortex in our review resulted in null findings, suggesting the exact protocol to modulate V-SRP consistently with PFC-tDCS is still unclear.

Summary

Considering the V-SRP studies together, a pattern of functional segregation seems to emerge between the left IPL and the MPFC. Results suggest that the left IPL may be involved in determining the self-relevance of verbal information as primarily tested by the neutral V-SRP studies of SPE (Figure 2.3), while the MPFC might be more so involved in the affective evaluation of such information as tested primarily by the emotional SRP studies of SEB (Figure 2.4), consistent with several functional network models of SRP (Fingelkurts et al., 2016, 2020; Frewen et al., 2020). Further, considering the midline posterior cortex, Lou et al. (2004) and Kwan et al. (2007) applied TMS over the midline parietal cortex (Pz electrode site) and found smaller degrees of impact on V-SRP compared to the MPFC, while De Pisapia et al. (2019) found that MPFC had an impact on both the PCC and the bilateral IPL BOLD signals during emotional V-SRP. Interestingly, the dynamic causal modelling conducted by Davey et al. (2016) suggested that the PCC may be the main driver for self-related processes with the MPFC as the moderator. This supports the notion that although the PCC might be the drive for SRP in general, V-SRP may be more closely related to the MPFC, especially when V-SRP is emotionally significant.

2.3.2 NV-SRP

Self-Other Discrimination Task

Given our affinity to faces even from infancy, distinguishing one's face from others' faces can be considered a basic form of NV-SRP, measured by SODTs. In this review, three TMS studies and one tDCS study supported the right IPL's causal role in self-other face discrimination (Figure 2.5), confirming the correlational findings from neuroimaging studies (Uddin et al., 2006; Heinisch et al., 2011, 2012; Payne and Tsakiris, 2017).

Interestingly, although stimulation over the left IPL did not yield any significant change in visual self-recognition in two studies, Hari et al. (2023) successfully facilitated the self-bias in a tone-matching task. Their finding may suggest that modulation of self-other discrimination could be specific to certain sensory modalities. Given that most SODT studies use visual stimuli, future studies may incorporate other sensory modalities to test this hypothesis.

Although right hemisphere lateralization in self-other discrimination has been observed, our review suggests that the left-right separation of V-SRP and NV-SRP may not be as clear-cut. For example, one of the reviewed studies also found involvement of the right IPL in V-SRP, which suggests that the right IPL may be involved in both V-SRP and NV-SRP (Lou et al., 2010). Interestingly, Heinisch et al. (2011) found that stimulation over the right DLPFC reduced visual self-recognition but only in people who have pre-existing negative attitudes toward their own face, effectively reducing their negative self-evaluation. Therefore, there might be some degree of laterality in NV-SRP in the right hemisphere, although contrary evidence also exists (Weigand et al., 2021; Bukowski et al., 2020).

It is possible that NV-SRP is associated with multiple processes and, therefore, is primarily affected by stimulation to the right IPL and other regions, such as the left IPL and the DLPFC, to some degree. Considering the right IPL as part of the MTL subsystem of the DMN, one might postulate that NV-SRP partially overlaps with the functions of the MTL subsystem and interacts with affective processes in the PFC, which may explain the results of Heinisch et al. (2011). Given that most studies on emotional SRP have focused on V-SRP instead of NV-SRP, future studies could also investigate the effect of NIBS on emotional NV-SRP with MPFC stimulation, for example, in response to facial displays of emotion or using a priming methodology (Frewen et al., 2013, 2017, 2020).

Rubber Hand Illusion (RHI)

Contrary to the possible right hemisphere dominance in visual self-other discrimination, NIBS over both the left and right hemispheres altered the effects of RHI for the contralateral hand (Figure 2.6). It is important to note that RHI strength has two dimensions: the change in perceived hand position measured by proprioceptive drift and the change in subjective experiences such as embodiment and ownership of the rubber hand. As illustrated in Figure 2.6, stimulation over different areas had a differential impact on proprioceptive drift and subjective experience. We found that TMS over the M1 and the EBA facilitated subjective experience, whereas TMS over the left IPL and the left PMC reduced proprioceptive drift. Additionally, anodal tDCS over the right PMC and the right IPL facilitated proprioceptive drift, and cathodal tDCS over the S1 facilitated subjective experience (Figure 2.6).

These results may offer support for hierarchical processing in the RHI wherein low-level somatosensory processing might be relayed to high-level multisensory integration to form feelings of ownership and agency over the body (Apps and Tsakiris, 2014). Consistent with this interpretation, paired-pulse TMS over the aIPS reduced the motor-evoked potentials from M1 (Karabanov et al., 2017) that was dampened by sensorimotor conflict, supporting the “comparator” mechanism that processes incoming sensory and proprioceptive inputs as proposed by Tsakiris (2010). In our review, areas shown to affect proprioceptive drift include the left VPMC, IPL, EBA, M1, and right IPL for proprioceptive drift, while areas shown to affect subjective experience included left M1, right PMC, S1, and the PPC. According to the hierarchical theory, the right IPL and the PPC might act as the integration areas for proprioceptive drift and subjective experience, respectively, but such assumptions need to be validated by further evidence.

Interoception

As compared to the RHI, which involves the processing of one of the bodily extremities, interoception can be measured from a sensory perspective toward internal bodily sensations by IAc of heartbeat or respiration and a subjective perspective by interoceptive sensibility and IAc accuracy. With regards to accuracy, both of the reviewed NIBS studies supported the causal role of the left and right insula in both cardiac and respiratory interoception (Figure 2.7; for the right insula: Pollatos et al., 2016; and for the left and right insula: Sagliano et al., 2019). Further, with regards to subjective experience, Pollatos et al. (2016) found the involvement of the right S1 in both IAc and the awareness associated with IAc, suggesting that S1 may also be part of a neural system that links interoceptive sensory signals with awareness of such signals. These results provided support for the existence of Park and Blanke's (2019) integrative BSC system connecting multiple interoceptive sensory areas.

Referring to meta-awareness as measured by IAc confidence, Pollatos et al. (2016) also argued that the decline might be related to disturbance of the sensory integrative processes in the anterior insula, resulting in mismatching between beliefs and sensory input. However, a more comprehensive picture of the brain areas involved still requires further evidence, as the NIBS literature on IAc and awareness is scarce.

Summary

Overall, our review provides causal support for brain regions discovered by neuroimaging studies in NV-SRP in the parietal cortex (including the IPL and PPC), the insula, and sensorimotor cortical areas (including the M1, S1, PMC, and EBA). More importantly, both interoception and BSC (observed in RHI studies) were able to show that stimulation to NV-SRP-related areas can induce changes in participants' perception of internal or external stimuli such as proprioceptive drift or IAc, and they can also alter participants' subjective experiences measured by self-reports, supporting the existence of a common NV-SRP system proposed by Park and Blanke (2019).

In their theory, self-identification is associated with a PMC-IPS-insula network, whereas self-location is associated with a PCC-IPS network (Park & Blanke, 2019). While a number of NIBS studies investigating the response to the RHI were able to alter self-location by stimulating the IPL, no reviewed NIBS studies on self-identification have chosen the PMC or the insula as the stimulation target, which can be of interest for future studies.

Moreover, most of our reviewed NV-SRP NIBS studies have targeted the sensorimotor areas, which may be lower within the hierarchy of processes producing the subjective experiences associated with NV-SRP. In the study conducted by Karabanov et al. (2017), paired-pulse TMS was used to investigate the modulatory role of a higher-order integrative area (e.g., aIPS) toward the M1; future NIBS studies may use similar experimental paradigms to investigate the modulatory relationships between ROIs in NV-SRP.

However, compared to the mixed results in self-other discrimination studies, RHI studies exhibited a higher consistency wherein modulations of subjective reports of RHI and proprioceptive drift were reported in 15 of the included 17 studies (Figure 2.6). One explanation is that self-other discrimination tasks are more simplistic than RHI, requiring more precise NIBS interventions to modulate performance. In comparison, RHI tasks would seem to involve multiple processes, from raw sensorimotor processing and proprioception of one-sided bodily stimuli (e.g., left or right hand) to a higher-level integration into subjective experiences and BSC as a whole. On the contrary, the differences in RT and accuracy between self and not-self-related stimuli are often measured in milliseconds and outside of the participants' subjective awareness. Finally, the success of modulating interoception with NIBS should be treated with caution, given only two NIBS studies were found in the interoception category, one of which showed a bilateral response in the insula (Figure 2.7; Sagliano et al., 2019).

Future SRP studies may approach the effect of NIBS from a hierarchical perspective, given that meta-analyses have recently suggested that V-SRP and NV-SRP are potentially nested processes where higher-level processing of self-relevant information such as traits rely on lower-level interceptive and exteroceptive sensory processing (Qin et al., 2020; Frewen et al., 2020). For example, according to the three-level model of the self proposed by Qin et al. (2020), NIBS targeting the insula may not only have impacts on NV-SRP, but the changes in bodily sensations may potentially affect sensory integration and regions of the brain associated with V-SRP. From this perspective, future NIBS studies should expand beyond self-reports and behavioural measures to incorporate neuroimaging measures to understand NIBS's impact comprehensively. Further, outcomes for both V-SRP and NV-SRP could be measured in tandem.

2.3.3 Limitations and future directions

A quantitative meta-analysis was not possible for this review due to the large variability of study designs; thus, we relied on a qualitative and descriptive approach. Another limitation is that the quality of methodology utilized was judged to have some concerns for several of the included studies in this review; future studies are encouraged to utilize stronger methodology, ideally pre-registering their study and including double-blinded designs, including both sham and active stimulation controls. Moreover, sample sizes in many studies were small and underpowered, and participant samples were frequently not well described, such as for demographic characteristics, a problem that also requires attention in future studies. Finally, to limit the scope of the current review, we excluded studies that investigated the effect of NIBS on resting-state and focused only on structured SRP tasks, despite the fact that SRP frequently occurs during resting state.

In addition to the small number of NIBS studies that have investigated SRP, most reviewed studies have only investigated the effect of NIBS on subjective and behavioural outcomes. From a practical perspective, self-report and behavioural measures can have direct clinical applications, although the underlying brain mechanisms of NIBS on SRP remain a "black box" until the effects of NIBS are routinely simultaneously investigated not only for phenomenological and behavioural outcomes but also for neurobiological outcomes (e.g., EEG, fMRI). Moreover, the experimental tasks used in NIBS studies exhibit a clear verbal vs. non-verbal split between studies, while no studies have so far compared the response to both V-SRP and NV-SRP in the same study. Therefore, future studies may comparatively investigate both verbal and non-verbal aspects of SRP under one experimental design.

It will also be important for future studies to compare the effects of different stimulation sites, for example, inter-hemispherically within the IPL or the insula or between posterior (e.g., IPL, PCC) and anterior (e.g., MPFC) sites, as well as by stimulation method (e.g., TMS vs. tDCS), including investigating additional methods of NIBS of SRP such as transcranial alternating current stimulation (tACS) that, to our knowledge, has not yet been investigated. Moreover, in so far as it is well known that many psychiatric and neurological disorders are associated with disturbances in SRP (e.g., reviewed by Frewen et al., 2020), it will be important to evaluate whether NIBS during SRP tasks would have any clinical significance in treatment, for example, for reducing self-criticism associated with affective disorders such as depression and posttraumatic stress. At the least, studies may investigate the immediate effects of NIBS on participants' mood following the completion of SRP tasks that draw self-focused attention to mental and bodily aspects of themselves.

Chapter 3

3 Self-report and EEG correlates of semantic and somatic SRP

3.1 The neural correlates of SRP

It has long been known from phenomenological inquiry that self-referential processing (SRP) can occur via “introspection” upon semantic references (e.g. “Who am I?”) as well as via “interoception” upon somatic references (e.g. “How do I feel?”) (e.g. James 1890). However, it was not until only recently that neuroimaging studies contributed to our understanding of the brain bases of our semantic vs. somatic senses of self[1] (Frewen et al. 2020; Qin et al. 2020), the latter also often termed “bodily self-consciousness” in recent literature (e.g. Park and Blanke 2019). Introspective SRP of semantic content is associated with responses within the frontal hub of the default mode network (DMN), particularly the medial prefrontal cortex (MPFC), the orbitofrontal cortex, and the anterior cingulate cortex (ACC), whereas interoceptive SRP of somatic content is associated with the premotor cortex, the inferior parietal sulcus, the ventrolateral prefrontal cortex (VLPFC, including the inferior frontal gyrus, IFG), the temporoparietal junction (TPJ), and the insula (Araujo et al. 2015; Davey et al. 2016; Lutz et al. 2016; Salvato et al. 2020). Additionally, a meta-analysis using the Neurosynth database (Yarkoni et al. 2011) of 166 semantic and 81 somatic SRP studies found that semantic SRP may also be associated with the posterior cingulate cortex (PCC), the ventral precuneus, bilateral posterior TPJ, and temporal poles, while somatic SRP may also be associated with the ventral MPFC and frontal operculum (Frewen et al. 2020). This suggests that while semantic and somatic forms of SRP were associated with different sub-networks of the DMN (van Buuren et al. 2010), there may also be considerable degrees of overlap between the two forms of SRP. Another recent meta-analytic review comparing semantic and somatic SRP proposed a three-layer model that placed the insula

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[1] We previously referred semantic SRP as verbal SRP (V-SRP), and somatic SRP as non-verbal SRP (NV-SRP). Herein we use these terms interchangeably.

as the core layer of the self, playing a part in introspection, interoception, and exteroception (Qin et al. 2020).

Most of the neuroimaging of SRP literature comes from analysis of the BOLD signal using fMRI, while comparably little is known about the underlying neuroelectrophysiology involved in SRP such as can be assessed by electroencephalography (EEG), which affords a direct measurement of the electrophysiological activity of the brain from scalp recordings. Only a few EEG studies have investigated semantic SRP during structured periods when participants are explicitly instructed to perform "on-task" SRP such as during self-referential encoding tasks (SRETs, e.g. Mu and Han 2013) or SRP that occurs spontaneously during unstructured periods of "resting state" (Knyazev et al. 2012; Bocharov et al. 2019). Although resting-state EEG studies found the involvement of all EEG bands, among the existing SRP studies, different results in SRP compared to non-SRP conditions were most frequently observed in the alpha and theta bands. For example, Bocharov et al. (2019) found that frontal alpha and theta band power exhibited decreases while participants were experiencing spontaneously arising self-referential thoughts as compared to when they were experiencing non-self-referential thoughts during resting state. Comparably, Knyazev et al. (2012) asked participants to complete the Spontaneous Thought Questionnaire after recordings of resting-state EEG that were analyzed with the exact low-resolution electromagnetic tomography (eLORETA) and found that the frequency of self-reported self-referential thoughts during resting state was best predicted by higher alpha activity within the DMN, followed by lower theta activity in the frontal cortex. Finally, in a topographical on-task EEG study, participants were asked to complete a SRET requiring them to evaluate whether trait adjectives (e.g. "extroverted") described themselves on certain trials or to evaluate the font of the adjective (bold vs. light) during other trials (Mu and Han 2010) and found that, compared to font-judgment, trait-judgment (semantic SRP) induced decreased theta over the posterior-occipital electrodes and increased theta over the left frontal–central electrodes, and further that trait-judgment induced decreases in alpha band over the frontocentral and posterior electrodes (Mu and Han 2010). Taken together, the few EEG studies of SRP that have so far been conducted have yielded heterogenous findings suggesting that frontal alpha and theta oscillations play a particularly crucial role in semantic SRP, although the directionality of effects remains unclear.

Unfortunately, studies directly comparing the EEG correlates of semantic to somatic SRP are even scarcer. In somatic SRP tasks, participants are typically instructed to focus attention on their momentary bodily sensations from either within the body (i.e., interoception, such as heartbeat) or the external environment (i.e., exteroception, such as touch). The interoception vs. exteroception comparison is rarely made in existing tasks that measure somatic SRP. As an example of interoception, Rodriguez-Larios et al. (2020) compared participants' EEG during mind-wandering vs. attention toward breathing and found that focusing on breathing was associated with higher alpha and lower theta band power across the whole brain. As an example of interoception, Fingelkurts et al. (2020) induced somatic SRP by asking eight experienced meditators to focus on "sensing yourself centred in the body from which you are experiencing the world" (p.6). Fingelkurts et al. (2020) showed when experienced meditators "up-regulate" the somatic self, alpha band synchrony within the right posterior cortex exhibited significant increases compared to the down-regulated state (Fingelkurts et al. 2020). Overall, previous EEG studies comparing semantic and somatic SRP implicate alpha and theta oscillations, albeit the directionality of responses has varied across studies.

The findings of Fingelkurts et al. (2020) and several other studies also illustrated the significance of analyzing phase synchrony in SRP, which refers to the degree of uniformity of phase angle observed in brain oscillations. For example, Mu and Han (2013) reported that self-evaluation of personality traits and orienting one's attention towards the self decreased phase synchrony in the alpha band between electrodes in the left hemisphere. A more recent study measured both epileptic patients' responses to autobiographical memory recall through intracranial EEG (Stieger et al., 2023) and found that activities in the hippocampus were driving increased low-frequency (1-30 Hz) coherence in the anterior thalamus, the posterior cingulate and the prefrontal cortex during autobiographical memory recall compared to arithmetic statements. Prior research also established that the brain exhibits higher phase synchrony within the DMN at rest and higher phase synchrony on task within a task-specific brain network (Kirschner et al., 2012). While studies have investigated the phase synchrony associated with both semantic SRP and resting state, phase synchrony associated with somatic SRP remains unexplored.

Several limitations in the current literature are hindering drawing conclusions regarding the EEG correlates of semantic vs. somatic SRP. Regarding experimental design and task, there is a lack of a standardized SRP task for both behavioural and neuroimaging studies to measure both semantic and somatic SRP. Then, among existing SRP tasks, discrepancies in the choice of control conditions may contribute to the heterogeneity of results. While some studies chose to control for the effect of referential target by comparing SRP with other-referential processing (e.g. assigning traits to a friend; Mu and Han 2013), other studies used resting state as the control condition (Bocharov et al. 2019; Rodriguez-Larios et al. 2020). Moreover, emotional valence is an important aspect of SRP with implications regarding self-esteem and mental health, but few existing SRP tasks measured emotional valence with some exceptions (e.g. Mu and Han 2010; Frewen et al. 2013). Studies that differentiated positive vs. negative SRP did not measure participants' psychological well-being outside of their SRP task. Regarding neuroimaging during SRP, most studies only analyzed the scalp topographic EEG activity or used dipole source localization, thus limited by assumptions such as the perpendicularity of cortical pyramidal neurons and the fixed number of dipoles (Grech et al. 2008). As a result, EEG studies of SRP tend to report the activity of EEG bands across large surface areas on the scalp instead of making observations on specific regions of the brain, and future studies might be better to implement EEG analytics utilizing distributed source localization methods that do not make assumptions on the orientation of pyramidal neurons and the number of dipoles, such as eLORETA used in Knyazev et al. (2012). Additionally, although past fMRI studies have documented the BOLD functional connectivity associated with SRP within the DMN, the functional connectivity of EEG oscillations within the DMN and other regions of interest relevant to SRP has not been explored. Moreover, existing studies only measured SRP valence with self-reports of emotional states and not psychophysiological responses that provide objective indicators of arousal. Finally, past task-based studies typically have small sample sizes, therefore limiting the sensitivity of statistical analyses.

3.2 Aims of the current chapter

Given the paucity and diversity of results regarding existing EEG studies investigating SRP, the current chapter aims to address the limitations of previous studies with two experiments.

In study 1, I present participants' responses to a new SRP task that I developed under the supervision of Dr. Frewen. The new SRP task is similar to the tasks used by Simmons et al. (2013) and Lutz et al. (2016), where participants are asked to focus on semantic and somatic stimuli in different trials. However, our new task also includes sustained periods of resting state, during which participants were without any specific task and thus were free to allow their minds to wander, as well as a counting letters task to compare the internal, self-focused attention that occurred in response to the semantic and somatic self-referential stimuli to a similarly simple but externally and non-self-focused task.

To assess subjective experience in terms of emotional valence and arousal in response to these tasks, participants provided self-report ratings of feelings of pleasantness. At the same time, participants also rated how well they were able to maintain their attention in response to task conditions. Further, to assess individual differences and the potential clinical significance of the SRP task, we also correlated participants' responses to the SRP task with other measures they completed about their level of psychological well-being. Specifically, based on the relevance of negatively-valenced SRP for understanding responses to life stress and psychological trauma (e.g., Lin et al., 2018; Lanius et al., 2020), we predicted that participants' experience of pleasantness and attentiveness would negatively correlate with variability in psychological and trauma- and stressor-related mental health problems.

Study 1 was conducted online with a sample of 304 student volunteers. The study included a singular semantic SRP task, in which participants self-evaluated themselves in reference to different life roles (e.g., *"How do I feel about myself as… a student? … as a* *friend?"*) and two SRP tasks involving bodily self-consciousness (BSC), referring specifically to "inner" aspects of their body such as organ systems (e.g., *"How do you feel right now in your stomach?"*), or to "outer" aspects of their body such as extremities (e.g., *"How do you feel right now ... in your arms? ... in your legs?"*). The results of Study 1 are planned for submission for publication in a peer-reviewed psychology journal.

In study 2, I then present an investigation of the EEG oscillatory patterns underlying response to the SRP task, focusing on alpha EEG (αEEG) and theta EEG (θEEG) frequencies in 50 student volunteers. To our knowledge, the study is the largest experimental study of EEG responses to a structured SRP task that has been conducted so far. Here, we modified the SRP task for offline EEG recording and adjusted the task conditions based on the results of Study 1 to focus attention only toward the "outer" (while not the "inner") BSC (i.e., somatic SRP). In addition to eLORETA source-level measurements of alpha (αEEG) and theta (θEEG) spectral power, we also surveyed participants' mood ratings before and after the task and included secondary physiological measures of autonomic arousal throughout the task, specifically, skin conductance level (SCL) and photoplethysmography (PPG) metrics measured from the non-dominant hand. The results of this investigation were published in 2022 in the journal *Neuroscience of Consciousness*.

Importantly, the results presented in Study 2 update those reported in the 2022 journal article to include scalp-level αEEG spectral power and phase synchrony, as well as functional connectivity analyses within brain regions of interest specified in the supervisor's prior review (Frewen et al., 2020). We measured phase synchrony by calculating the inter-trial coherence (ITC) between different operational modules (OMs), which were defined slightly differently by Fingelkurt et al. (2020). Based on the few fMRI studies that directly compared response to semantic and somatic SRP (Simmons et al. 2013; Araujo et al. 2015; Lutz et al. 2016) and the limited prior EEG literature, we predicted that, compared to the resting state and external attention control conditions, both semantic and somatic SRP would induce lower alpha (αEEG) and either lower or higher theta (θEEG) in the frontal lobe (Mu and Han 2013; Bocharov et al. 2019;

Rodriguez-Larios et al. 2020), while increased alpha (αEEG) oscillations were expected in the left and right parietal cortex for semantic and somatic SRP, respectively (Fingelkurts et al. 2020). Additionally, we directly compare the EEG correlates of semantic and somatic SRP in an exploratory fashion.

3.3 Study 1 methods

3.3.1 Description of the SRP Task

We designed our task based on the task used in two previous SRP studies (Araujo et al., 2015; Simmons et al., 2013). Our task addresses SRP by asking participants to reflect on attend to how they feel about themselves in each of three experimental conditions as reference points: 1) their life roles (student, citizen, consumer, child, friend, and employee); 2) their inner body (gums, stomach, heart, lungs, throat, and bladder); and 3) their outer body (arms, shoulders, legs, feet, head, and hands). For the external attention control condition, we asked participants to count the number of times the letter "X" was stated in a string of six letters. Stimuli in each category were randomized within blocks. The words were chosen based on their universal applicability and the short number of syllables, ensuring the task was relatively easy to complete.

We constructed this task using the Gorilla Experiment Builder (www.gorilla.sc) and distributed the task online via the Department of Psychology's student research volunteer system. The SRP task began with instructions and was prefaced by one round of practice. Since the contents of the entire task were presented in audio format, participants were instructed to keep their eyes closed for the entire task except during short breaks arranged between each of the three rounds of the task.

During the task, participants were presented with six words in audio form arranged in blocks, with each word appearing for 5s, making 30s total for each block. During the "life roles" block, which comprised the semantic or verbal SRP condition, they were instructed to evaluate themselves in reference to each life role. For example, when a participant hears "student," they were to evaluate themselves as a student (e.g., "How do I feel about myself as a student?"). During the body-focused blocks (inner body and outer body referents), participants were to focus on the sensations in that body part (e.g., "How do I feel in my stomach?"); these two related tasks comprised the somatic or non-verbal SRP condition. Finally, during letter counting blocks, participants heard six letters for 5s each with varying numbers of the letter "X" from 1 to 5. Within each block, the order of words or letters was randomly shuffled, as was the order of the blocks themselves within each of the three runs of the task, with each condition presented a single time within each run. The graphical illustration of the SRP task can be found in Figure 3.1.

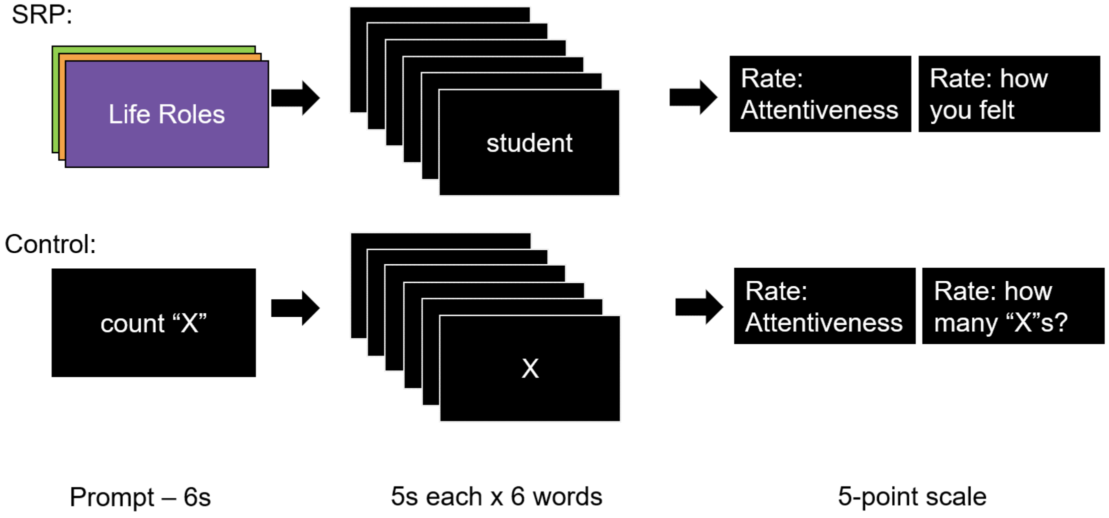


Figure 3.1 Graphical illustration of the SRP task. For the SRP conditions, different colours represent the three SRP conditions presented in different trials, including Life Roles, Outer Body, and Inner Body.

After each block of SRP or counting letters, participants were asked to give two ratings with their mouse. The first rating asks participants to rate their self-assessed degree of attentiveness during the task with the following options: "very inattentive," "inattentive," "neutral," "attentive," "very attentive," which were scored from 1 to 5, while they also had the option to select "choose not to answer" for ethical purposes. The second rating asks participants how they felt during different task blocks, with the following options: "very unpleasant," "unpleasant," "neutral," "pleasant," or "very pleasant," which were again scored from 1 to 5, while they again had the option to select "choose not to answer." Note that while participants were asked about their attentiveness after the external attention control trial, they were not asked about pleasantness. Instead, they were asked to indicate the number of “X”’s that they had heard as a means to assess the accuracy and thereby an objective measure of attention, with answers ranging from 1 to 6.

3.3.2 Participants and procedures

We collected data from 304 undergraduate participants for study 1 recruited from the SONA research participation system (SONA) portal at Western University. There were no specific exclusion criteria for this study. Our sample consisted of 67% females, with nearly all students (98%) reporting that they were between the ages of 17 and 22. Regarding ethnical background, 41% identified as Caucasian, 46% identified as Asian, 7% identified as “Mixed,” 3% identified as “Other,” and 2% identified as Black.

Upon entering the online experiment, all recruited participants were first asked to complete a Qualtrics online survey on demographics, followed by sliding-scale evaluations on how they felt in reference to each of the 18 self-referential words that were also used in the SRP task. These ratings were given from 0 to 100, where 0 refers to “Very Negative/Bad” and 100 refers to “Very Positive/Good”. Thus, the 18 words comprised the semantic SRP stimuli (i.e., 6 words referring to “life roles”), and the two sets of 6 words referred to inner- and outer-body parts, comprising the somatic SRP stimuli. In short, the rating task mirrored the words that were also used during the SRP task, conducted later.

For measures to correlate with SRP task performance, we also administered a battery of additional surveys via the Qualtrics online survey. One of these, the Inventory of College Student Recent Life Events (ICSRLE, Kohn et al., 1990), was administered to all university students. Comparably, participants were randomly assigned to complete one of two subsequent sets of related survey measures to reduce attentional burden. Group 1 completed the International Trauma Questionnaire (ITQ-12, Cloitre et al., 2018), the Global Psychotrauma Screen (GPS-17, Frewen et al., 2021), and the Patient Health Questionnaire (PHQ-9, Löwe et al., 2004). In comparison, Group 2 completed the PTSD checklist for DSM-5 (PCL-5, Bovin et al., 2016) and the trauma-related altered states of consciousness survey (TRASC, Frewen et al., 2015). The questionnaires are chosen based on the relevance of negatively-valenced SRP in psychological well-being and response to stress and psychological trauma (Lin et al., 2018; Lanius et al., 2020). We separated participants into two groups due to the consideration of the length of the experiment and the potential effect of fatigue on their responses. After the Qualtrics surveys, participants were directed to the SRP task on the Gorilla platform. Participants received course credits upon completion of the study.

3.3.3 Data analysis

The collected data were analyzed using the R package 'rstatix' for analysis of variance (ANOVA) and correlation analyses. The ratings of pleasantness and attentiveness are encoded ordinally from 1 to 5, with 1 indicating "very unpleasant" or "very inattentive" and 5 indicating "very pleasant" and "very attentive."

In order to assess the effects of SRP task condition on the attentiveness and pleasantness ratings, a within-subject repeated measures ANOVA test was conducted. In the case of attentiveness, there were four experimental conditions: Life Roles, Outer Body, Inner Body, and External Attention). Comparably, for pleasantness ratings, only 3 of those 4 conditions were to be compared (excluding External Attention). Based on the ordinal nature of the SRP task data, we also conducted Spearman's correlations to determine whether there were any associations between participants' ratings during the SRP tasks and their sliding-scale self-reported feelings of pleasantness and mental health measures.

Multiple comparisons were corrected with the false-discovery rate (FDR) method for the ANOVA and post hoc analyses. Due to the number of questionnaires and the correlation analysis's exploratory nature, results were considered statistically significant with $p < 0.01$ (uncorrected).

3.3.4 Results

We only included participants with no missing data in statistical analyses for each group. As a result, a total of 197 participants had complete slider + ICSRLE data, 139 participants had complete Group 1 data (GPS-17, ITQ-12, PHQ-9), and 165 participants had complete Group 2 data (PCL-5, TRASC survey).

The ANOVA showed no significant differences between participants' reports of pleasantness across all three SRP conditions. The means of the pleasantness responses are life roles = 3.6 (SD = 0.8), outer body = 3.5 (SD = 0.8), and inner body = 3.5 (SD = 0.8). Participants also mostly correctly responded to the letter counting question, with mean deviation from the correct answer = 0.1, SD = 0.5.

Comparably, the ANOVA on participants' levels of attentiveness showed that participants paid more attention during the external attention letter counting task (M = 4.1) than all of the other three SRP conditions at p.adj < 0.001. However, no significant differences were observed between the three SRP conditions (means: life roles = 3.7, outer body = 3.8, and inner body = 3.7).
Correlation analyses revealed that participants' ratings of pleasantness were positively correlated with slider pleasantness ratings in reference to the measures for life role (r = 0.25, p < 0.001), outer body (r = 0.31, p < 0.001), and inner body (r = 0.26, p < 0.001). The full correlations between SRP task measures are listed in Table 3.1 and Table 3.2.

Then, the correlations between SRP task responses and mental health surveys are listed in Table 3.3. Participants' responses in ICSRLE (i.e., student life stress) were negatively correlated with life role attentiveness (r=-0.22, p = 0.002). Further, for Group 1, participants' outer body pleasantness was negatively correlated with PHQ-9 (i.e., depressive symptom severity) scores (r = -0.26, p = 0.002). Finally, for Group 2, participants' scores in PCL-5 (i.e., PTSD symptom severity) were negatively correlated with the pleasantness of life roles (r = -0.20, p = 0.009) and outer body (r = -0.22, p = 0.005).

Table 3.1 Correlations between pleasantness and attentiveness ratings during the SRP task

	Life Roles pleasantness	Outer Body pleasantness	Inner Body pleasantness	Life Roles attentiveness	Outer Body attentiveness	Inner Body attentiveness	Letter Counting attentiveness
Life Roles pleasantness	-						
Outer Body pleasantness	0.40***	-					
Inner Body pleasantness	0.37***	0.51***	-				
Life Roles attentiveness	0.39***	0.24**	0.26***	-			
Outer Body attentiveness	0.24**	0.32***	0.25***	0.56***	-		
Inner Body attentiveness	0.18	0.23**	0.33***	0.46***	0.42***	-	
Letter Counting attentiveness	0.18	0.09	0.10	0.41***	0.34***	0.45***	-
Note: Only results with p < 0.01 are considered significant. **: p < 0.01; ***: p < 0.001							

Table 3.2 Correlations between SRP task and slider measurements

	Life Roles slider	Outer Body slider	Inner Body slider
Life Roles pleasantness	0.25***	0.19**	0.18
Outer Body pleasantness	0.26***	0.31***	0.30***
Inner Body pleasantness	0.18	0.19**	0.26***
Life Roles attentiveness	0.20	0.15	0.11
Outer Body attentiveness	0.10	0.12	0.09
Inner Body attentiveness	0.13	0.11	0.08
Letter Counting attentiveness	0.12	0.10	0.05
Note: Only results with p < 0.01 are considered significant. **: p < 0.01; ***: p < 0.001.			

Table 3.3 Correlations between SRP task responses and mental health surveys

	ICSRLE	GPS-17	PHQ-9	ITQ-12 PTSD	ITQ-12 CPTSD	PCL-5	TRASC
Life Roles pleasantness	-0.15	-0.12	-0.15	-0.10	-0.12	-0.20**	-0.15
Outer Body pleasantness	-0.10	-0.18	-0.26**	-0.15	-0.13	-0.22**	-0.09
Inner Body pleasantness	-0.08	-0.04	-0.11	0.06	-0.05	-0.13	-0.05
Life Roles attentiveness	-0.22**	-0.11	-0.10	-0.07	-0.10	-0.10	-0.07
Outer Body attentiveness	-0.10	-0.07	-0.10	-0.01	-0.05	-0.01	0.03
Inner Body attentiveness	-0.17	-0.04	-0.07	-0.05	-0.06	-0.02	0.07
Letter Counting attentiveness	-0.08	-0.10	-0.06	-0.09	-0.06	0.05	0.06

Note: Only results with $p < 0.01$ are considered significant. **: $p < 0.01$; ***: $p < 0.001$. Abbreviations: Inventory of College Student Recent Life Event (ICSRLE), International Trauma Questionnaire (ITQ-12) split into PTSD items and complex PTSD (CPTSD) items, Global Psychotrauma Screen (GPS-17), Patient Health Questionnaire (PHQ-9). PTSD checklist for DSM-5 (PCL-5), trauma-related altered states of consciousness survey (TRASC).

3.3.5 Discussion

The goal of Study 1 was to address the limitations of previous experimental tasks by introducing a new SRP task. Our task is novel insofar as it measured multiple categories of SRP, specifically, differentiating between semantic and somatic aspects, as well as across two forms of the latter (i.e., “inner” vs. “outer” body), which has been considered a relevant distinction within the neuroscience of BSC (e.g., Park & Blanke, 2019). Thus, our SRP task included 1) both semantic and somatic conditions, 2) an external attention control condition, and 3) measures for emotional valence during SRP. Additionally, we measured the correlations between individual differences in stress and associated mental health problems and participants’ reports of pleasantness and attentiveness during the SRP task to further explore the potential clinical significance of SRP task performance.

First, we found that pleasantness reports were relatively equated across the three SRP conditions, with means approximating 3.5, suggesting that participants found completing the SRP task to be slightly pleasant overall. Such an outcome may serve as a baseline measure for future neuroscience experiments comparing semantic and somatic SRP and give a basis for the assumption that doing so would not be inherently confounded by intrinsic differences in the experienced pleasantness of different experimental conditions. Further, participants’ reports of the pleasantness of various conditions were positively correlated. Evidently, if a participant tended to feel that one part of the SRP task was more or less pleasant, they tended to feel that other parts of the task were similar. The self-reported pleasantness ratings on the slider scale were also correlated with their reports of pleasantness in response to the structured SRP task, providing convergent validity for each measurement form.

Second, participants reported paying more attention during the letter counting task (external attention) than all SRP conditions (internal attention). Given that all of the experimental conditions should have been decidedly easy to complete, this suggests a possible qualitative difference between internally self-focused attention, on the one hand, and externally non-self-focused attention, on the other.

Past research comparing the performance of structured, attentional tasks to unstructured periods of mind-wandering suggested that attentiveness correlates negatively with DMN activity (Scheibner et al., 2017). Specifically, Scheibner et al. found that internally focused attention was associated with increased activity in the PCC, whereas external attention was associated with increased activity in the left IFG. Therefore, our findings regarding attentiveness may provide indirect evidence that participants' DMN may have been more active during SRP conditions than the external attention condition, which would certainly be consistent with much prior evidence (e.g., Frewen et al., 2020; Knyazev et al., 2020).

Regarding correlations between experiences of pleasantness and attentiveness within the SRP task, we observed that participants' ratings of pleasantness during the SRP task exhibited low positive correlations with their ratings of attentiveness for the same SRP condition, suggesting that increased task-focused attention was associated with increased pleasantness. Further, in five of the remaining six cases, attentiveness and pleasantness ratings were also correlated across *different* experimental conditions, whereas pleasantness experienced in response to SRP was not correlated with reported attention levels in response to the letter-counting task. These discrepant findings again imply a possible meaningful dissociation between the subjective experience and neural networks that may be active during internally self-focused attention, be it at a semantic or somatic level, and the kinds of externally directed, non-self-focused attention participants were involved with when letter counting.

In the few circumstances in which correlations were non-significant between pleasantness and attentiveness levels across different forms of SRP, these discrepancies always implicated a slightly lower correlation between semantic SRP, on the one hand, and the "inner" form of somatic SRP, on the other. This pattern of results may be interpretable from the three-level self model proposed by Qin et al. (2020). In their model, interoception lies in the bottom layer of SRP, representing the most basic form of SRP. Then, exteroception lays in the middle layer between interoception and introspection (i.e., semantic SRP), based on the relative recruitment of overlapping sets of brain regions and neural networks. Their framework potentially explains why self-report measures acquired in response to both the SRP task and standard slider survey, pleasantness and attentiveness during semantic and somatic SRP were significantly correlated in all cases except in specific correlations involving semantic SRP and "inner" BSC (Table 3.1, Table 3.2).

We also found that the relative pleasantness of feelings in response to SRP of life roles (semantic) and "outer" body (somatic) correlated with certain (albeit not all) measures of stress and mental health problems, which is broadly consistent with the established link between valenced SRP and mental health (e.g., Frewen et al., 2020). Comparably, attentiveness levels did not correlate with such outcomes, nor did the pleasantness of orienting to "inner" BSC. These findings suggest that should the task be reduced in length; the clinical significance of a shortened version might be best to retain each of the semantic and "outer" body somatic conditions in favour of retention of the "inner" body condition for ease of subsequent interpretation of results.

3.3.6 Limitations and conclusions

Despite its contributions, the current study had several limitations. First, our sample came from strictly a university student population in their early adulthood, limiting the generalizability of our findings. Second, our sample exhibited an unusually high dropout rate (~29%). We suspect it is due to the technical difficulties in switching between three online research participation platforms. Third, studies have shown the mediating effect of culture and values on SRP (Knyazev et al., 2021; Salvador et al., 2022), which were not considered in the current study. Fourth, while the SRP task measures participants' momentary feelings regarding their sense of self, it does not capture participants' trait self-concept and bodily self-consciousness. Therefore, future studies may further validate the study of SRP by extending our current findings to other populations and including established scales to investigate the possible relationships between state and trait differences in SRP better.

However, in the context of this dissertation, the SRP task appears to be suitable for measurement in future neuro-electrophysiological investigations involving EEG and NIBS. Therefore, in Study 2, I extend the results of a published EEG study using only the semantic and "outer" body somatic SRP task described in Study 1, with a few modifications as were necessary to further investigate the EEG correlates of SRP (Bao & Frewen, 2022).

3.4 Study 2 Methods

3.4.1 Participants

Fifty undergraduate students were recruited from the SONA research participation system at Western University. Participants' ages ranged between 18 and 22, and 52% were female. In addition to being students, 73% indicated that they were employed part-time. Participants identified as White (31%), Chinese (22%), South Asian (19%), or "Other" (28%).

3.4.2 Procedures and materials

Upon entering the experiment and providing informed consent, participants completed a 30-item questionnaire on their current mood state, including the 20-item Modified Differential Emotions Scale (mDES; Fredrickson et al. 2003) and the 10-item Buddhist Affective State Scale (BASS; Zhu et al. 2019). The mDES consists of 10 positive affect items such as "Grateful, appreciative, thankful" and ten negative affect items such as "Sad, downhearted, unhappy." The BASS was modelled after the mDES but assessed affective states associated with Buddhist psychology that are not included in the latter, such as “Oneness, unity, connectedness” and “Sacredness, reverence, spiritual.” All items were rated on an 11-point scale with increments of 10 (0 = “Not at all” and 100 = “Very much more than usual”).

Then, participants practiced one run of the SRP task before EEG data collection was initiated to ensure task familiarity and reduce novelty during EEG recordings. As described in Study 1, the SRP task required participants to evaluate how they feel about themselves in different life roles during the semantic SRP condition and how they feel in different parts of their “outer” body during the somatic SRP condition. The “inner” body condition from Study 1 was removed from the EEG version of the task to limit the scope and complexity of the current experimental design and due to its lower correlation with the other already mentioned conditions and various mental health surveys that were administered in Study 1. Therefore, herein, we refer to somatic SRP as interchangeable with exteroception (“outer” BSC) instead of an umbrella term to describe both interoception (“inner” BSC) and exteroception. Comparably, during an external attention condition, participants were again asked to count the number of times they heard the letter “X” in a string of six letters.

Furthermore, for the EEG version of the task, we added a resting state condition where participants were instructed simply to wait until further instructed, thus allowing their attention to wander during the intervening period (Figure 3.2). The resting state condition serves not only as a control condition for the structured SRP tasks, given that internal, self-focused attention often predominates during the resting state, but also as an SRP state of interest unto its own, as compared with the externally focused letter counting condition, given its degrees of overlap with SRP.

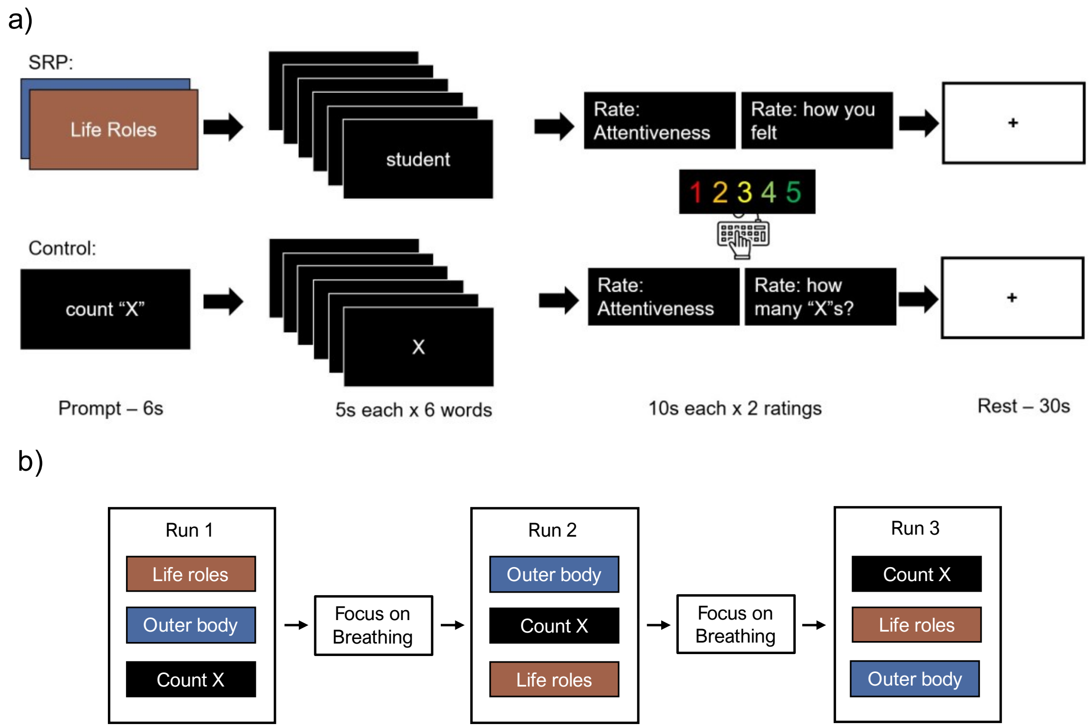


Figure 3.2 Graphical illustration of the experimental design and SRP task. Note: (a) example of life roles and counting letter conditions of the SRP task and (b) the overall structure of the SRP task used in the EEG experiment

At the end of each block, participants were asked to rate their level of attentiveness on a 1–5 scale similar to Study 1. Instead of using a mouse to respond, participants pressed number keys on a keyboard, with 1 referring to "very inattentive" and 5 "very attentive." Additionally, following the semantic and somatic SRP tasks, participants were asked to rate how pleasantly they experienced the task on a 1–5 scale, with 1 referring to "very unpleasant" and 5 "very pleasant." Pleasantness was not rated in response to the external attention (letter counting) task, after which participants were instead asked to report the number of "X"s they heard from 1 to 5 to assess accuracy. Each individual stimulus (word or letter) was presented for 5 s, making each experimental block last 30 s, while the resting state condition [i.e. inter-block interval (IBI)] was also 30 s. Participants were presented with three blocks of each task condition (cumulatively 90 s), while the cumulative resting state acquired was 270 s (3 × 3 × 30 s). Between each run of SRP tasks, for 7.5 min, participants completed a brief meditation. Participants were asked to focus their attention on the sensations of breathing and to bring their attention back from mind-wandering to breathing when they noticed mind-wandering. During the 7.5-minute meditation, participants heard three bell sounds at 1-minute intervals as reminders to bring their attention back to breathing. These 7.5-minute meditations essentially acted as structured resting state sessions since the degree of mind-wandering does not differ appreciably between resting state and breath-focusing meditation among novice meditators (Rodriguez-Larios & Alaerts 2021). The SRP task and the experimental procedure are described in Figure 3.2. After the SRP task, participants completed the same 30-item mood state questionnaire once again before exiting the study. The study was approved by the institutional research ethics board of Western University, Canada.

3.4.3 EEG data acquisition and peripherals

EEG data were recorded with the Nexus-32 system (www.mindmedia.com) and the Biotrace+ software at 512 Hz sampling rate with standard 19-channel (Fp1, Fp2, F3, F4, Fz, F7, F8, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, and O2) caps under the international 10–20 system. We also measured PPG (128 Hz) and SCL (32 Hz) from the fingers of the non-dominant hand.

3.4.4 EEG and peripheral data preprocessing

EEG data was preprocessed using custom-made EEGLAB code (Delorme and Makeig 2004) under the MATLAB environment. EEG preprocessing steps in sequence included: (1) importing raw data and events; (2) bandpass filter between 1 and 50 Hz; (3) reconstructing artifacts with the Riemannian method of Artifact Subspace Reconstruction (Blum et al. 2019); (4) interpolate rejected data channels; (5) decompose data using Picard independent component analysis (ICA), chosen based on its balance in accuracy and processing speed (Ablin et al. 2018); (6) accept ICA components using IClabel (Pion-Tonachini et al. 2019) based on at least 70% probability on the “brain” category; and (7) epoch data and export for the subsequent eLORETA and phase synchrony analyses.

We selected eLORETA as the method of source localization because it has been used in prior SRP research Knyazev et al. (2012). The eLORETA is also a validated source-localization approach with the merits of low localization errors and reduced computational time among other source localization methods (Jatoi et al., 2014). While the spatial resolution of source localization depends on the number of EEG channels, 19-channel EEG montages with eLORETA have been shown to be an acceptable method to identify changes in brain networks (Miraglia et al., 2021).

Preprocessing of PPG data in millivolts was conducted with the Kubios Premium Software (Tarvainen et al. 2013), which automatically rejects noisy data segments and calculates heart rate (HR) variability metrics. We included HR, standard deviation of the NN intervals, and root mean square of successive RR interval differences as time-domain metrics and normalized low (LF) and high-frequency (HF) power as well as LF–HF ratio (LF/HF) as frequency-domain metrics. SCL data in microsiemens were preprocessed using a fourth-order Butterworth bandpass filter of [0.05, 0.3] Hz and normalized with log-transformation for the subsequent data analysis (Cacioppo et al. 2007).

3.4.5 Statistical analysis

3.4.5.1 Self-reports

We used the R package 'rstatix' for statistical analyses of 1) their self-reported ratings of attentiveness and pleasantness during the SRP task, 2) their mood ratings, and 3) participants' log-transformed mean 10 Hz ITC. 4) PPG metrics, and 5) SCL signals using t-tests with the Holm–Bonferroni method to adjust for multiple comparisons. Outliers above [Q1 + 1.5 × (Q3 − Q1)] and below [Q1–1.5 × (Q3 − Q1)] were removed and replaced with the group median prior to analysis. We detected one outlier in the life roles condition for the pleasantness rating and one outlier in both the outer body and letter-counting conditions for the attentiveness rating.

3.4.5.2 EEG source power

We used the LORETA-KEY software package for EEG source localization (www.uzh.ch/keyinst/loreta, Pascual-Marqui et al. 1999). First, electrode names were converted to Talairach coordinates to create eLORETA transformation matrices. The cross-spectra for each subject was then computed and tapered with the Hann window function (mean-corrected) for both alpha (8–12 Hz) and theta (4–8 Hz) bands.1 Given the cross-spectra, eLORETA was used to estimate the current density, reported on the MNI152 template (Maintz and Viergever 1998). For reporting results, the MNI coordinates were converted to Talairach space (Brett et al. 2002) and labelled by the Talairch Daemon (Lancaster et al. 1997). Only unambiguous gray matter voxels within the brain compartment were retained in the process.

Statistical analyses were also performed within the LORETA-KEY package (http://www.uzh.ch/keyinst/loreta). Subject-wise normalizations were performed on the processed data to correct for global sources of variability. Two-tailed paired group comparisons on the logarithm of F-ratios were conducted with the Statistical non-Parametric Mapping (SnPM) methodology, which corrects for multiple comparisons with 5000 non-parametric randomizations using maximum statistics without assuming normality (Nichols and Holmes 2001). Results of the exceedance proportions test (Friston et al. 1990, 1991) indicating statistically significant supra-threshold clusters with $P \leq 0.05$ were accepted and reported herein. When the SnPM analysis yielded a choice of multiple significant thresholds, we selected the lowest threshold to maximize specificity. Brain structures with the log of F-ratio > 0.1 are reported in the text, while all statistically significant results are reported in tables. Additionally, we conducted regression analyses to determine the mediating effects of attentiveness and pleasantness on EEG spectral power using the LORETA-KEY program.

3.4.5.3 EEG Functional Connectivity

Finally, we also investigated the functional connectivity as post hoc analyses of differences between SRP conditions that showed statistical significance in source power using the LORETA-KEY software package. First, we generated a list of ROIs and their coordinates a priori based on the SRP review conducted by Frewen et al. (2020), specifically, the ventral PCC, the precuneus, bilateral IPL, bilateral insula, perigenual ACC, dorsomedial ACC, ventral MPFC, middle MPFC, dorsal MPFC, and frontal eye fields (coordinates listed in Appendix Table 2). We defined the ROIs as all voxels within a 15 mm radius of the seed. Second, the linear lagged connectivity for the significant bands was calculated for each eLORETA file with the Hann window function selected as the mean-corrected discrete Fourier transform taper. Third, the connectivity matrix files were entered into the statistics program from the LORETA-KEY package for Wilcoxon signed-rank tests using SnPM with 5000 randomizations. Significant W-thresholds with $p \leq 0.05$ were then entered into the 'connectivity viewer' to visualize the significant connectivity results after FDR correction.

3.4.5.4 Inter-trial Coherence (ITC) as a Measure of Phase Synchrony

Calculations of ITC were conducted in MATLAB with the EEGLAB function newtimef() with frequency set to 8-12 Hz. First, 30-second epochs are extracted from each channel that corresponds with the SRP task conditions. Then, newtimef() calculates the ITC between two 30-second epochs by averaging the ITC by randomly sampling 200 time points within each epoch.

We then calculated participants' ITC between and within three operational modules (OM) adapted from Fingelkurts et al. (2020) during each category of SRP. In their study, different modalities of SRP are associated with the alpha oscillation represented on the scalp as the frontal OM (including F3, FZ, and F4), left-posterior OM (including T5, P3, O1), and the right-posterior OM (including T6, P4, and O2). We slightly modified their definitions of the left and right posterior OM to match the peak of simulated current density described in Chapters 4 and 5 to ensure that the findings across all three studies are comparable. We defined the frontal OM to include FP1, FZ, and FP2; left-posterior OM to C3, P3, and T5; right-posterior OM to C4, P4, and T6. For between-OM synchrony, the ITC between FZ and P3 was calculated as the synchrony between frontal and left-posterior OMs, the ITC between FZ and P4 was calculated as the synchrony between frontal and right-posterior OMs, and the ITC between P3 and P4 were calculated as the synchrony between left and right-posterior OMs. The channel locations FZ, P3, and P4 were selected for between-OM calculations also based on their vicinity to the peak current density. As a result, we produced six dependent variables from ITC calculations for further statistical analysis, including three within-OM synchrony values and three between-OM values. Since Fingelkurts et al. (2020) suggested the crucial role of alpha in all three OMs, we also restrict the analysis of phase synchrony to the alpha band.

3.4.6 Results

3.4.6.1 Ratings of mood states, pleasantness and attentiveness

After the experiment, participants reported statistically significant increases in joy [$\Delta M = 6.4$, $t(50) = 3.47$, $p.adj = 0.03$], awe [$\Delta M = 9.6$, $t(50) = 3.31$, $p.adj = 0.05$], gratefulness [$\Delta M = 9.0$, $t(50) = 3.93$, $p.adj = 0.007$], serenity [$\Delta M = 16.6$, $t(50) = 5.25$, $p.adj < 0.001$], insightfulness [$\Delta M = 9.2$, $t(50) = 5.23$, $p.adj < 0.001$], and oneness [$\Delta M = 12.0$, $t(50) = 5.72$, $p.adj < 0.0001$]. Participants also reported decreased sadness [$\Delta M = 5.6$, $t(50) = -3.35$, $p.adj = 0.05$], confusion [$\Delta M = 8.2$, $t(50) = -3.21$, $p.adj = 0.05$], embarrassment [$\Delta M = 8.0$, $t(50) = -3.40$, $p.adj = 0.03$], and stress [$\Delta M = 10.4$, $t(50) = -4.66$, $p.adj < 0.001$).

Participants rated their levels of pleasantness during the SRP task to be slightly positive overall on the 1–5 rating scale and significantly different between life roles and outer body with $t(49) = 2.84$, $p.adj = 0.007$, Cohen's $d = 0.40$. Descriptive statistics were, for life roles, $M = 3.65$, $SD = 0.54$, min/max = 2.7/4.7, and for outer body, $M = 3.83$, $SD = 0.56$, min/max = 3.00/5.00.

Given that the mean occurrences of the letter "X" were objectively accurate at 3, participants made very few mistakes in the counting letters task (before outlier removal: $M = 3.00$, $SD = 0.16$, min/max = 2.33/3.50). Participants' self-reported levels of attentiveness were also qualitatively high in response to the letter-counting task, with $M = 4.66$, $SD = 0.50$, min/max = 3.33/5.00. Self-reported attention was also qualitatively high in response to the life roles task, $M = 4.19$, $SD = 0.66$, min/max = 2.33/5.00, and the outer body task, $M = 4.29$, $SD = 0.53$, min/max = 3.00/5.00. Nevertheless, participants reported that they paid significantly more attention during the letter-counting task when compared to both the life roles condition, $t(49) = 3.58$, $p.adj < 0.001$, Cohen's $d = 0.51$, and the outer body condition, $t(49) = 3.41$, $p.adj = 0.001$, Cohen's $d = 0.48$; self-rated attentiveness was not significantly different between the two SRP conditions with t(49) = 1.23, ns.

3.4.6.2 Skin Conductance Levels and Photoplethysmography

No statistically significant differences were found between conditions from the PPG metrics indicative of average HR or its variability. Analysis of SCL signals revealed that SCL was lower during resting state (M = 0.81, SD = 0.85, min/max = −1.01/2.44) than during semantic SRP (evaluation of life roles) (M = 0.90, SD = 0.86, min/max = −0.76/2.46, Padj = 0.002), or somatic SRP (attention to outer body) (M = 0.90, SD = 0.85, min/max = −0.90/2.44, Padj = 0.006), or the external attention control task (counting letters) (M = 0.92, SD = 0.85, min/max = −1.1/2.44, Padj = 0.002).

3.4.6.3 Phase Synchrony Measured by ITC

Analysis of alpha phase synchrony showed a main effect of SRP Condition on ITC within the left-posterior OM (F(3, 147) = 4.72, p.adj = 0.012) and the right-posterior OM (F(3, 147) = 4.77, p.adj = 0.012) depicted in Figure 3.3. For the left-posterior OM, the post hoc analysis indicated that the ITC associated with life role was higher than both outer body (ΔM = 0.003, t(49) = 2.73, p.adj = 0.024) and external attention (ΔM = 0.003, t(49) = 2.92, p.adj = 0.024). Then, ITC associated with the resting state was also higher than both outer body (ΔM = 0.003, t(49) = 2.26, p.adj = 0.042) and external attention (ΔM = 0.003, t(49) = 2.63, p.adj = 0.024). For the Right-posterior OM, post-hoc analysis indicated that the ITC associated with life role was higher than outer body (ΔM = 0.003, t(49) = 2.63, p.adj = 0.024), resting state (ΔM = 0.002, t(49) = 2.93, p.adj = 0.015), and external attention (ΔM = 0.003, t(49) = 3.55, p.adj = 0.005).

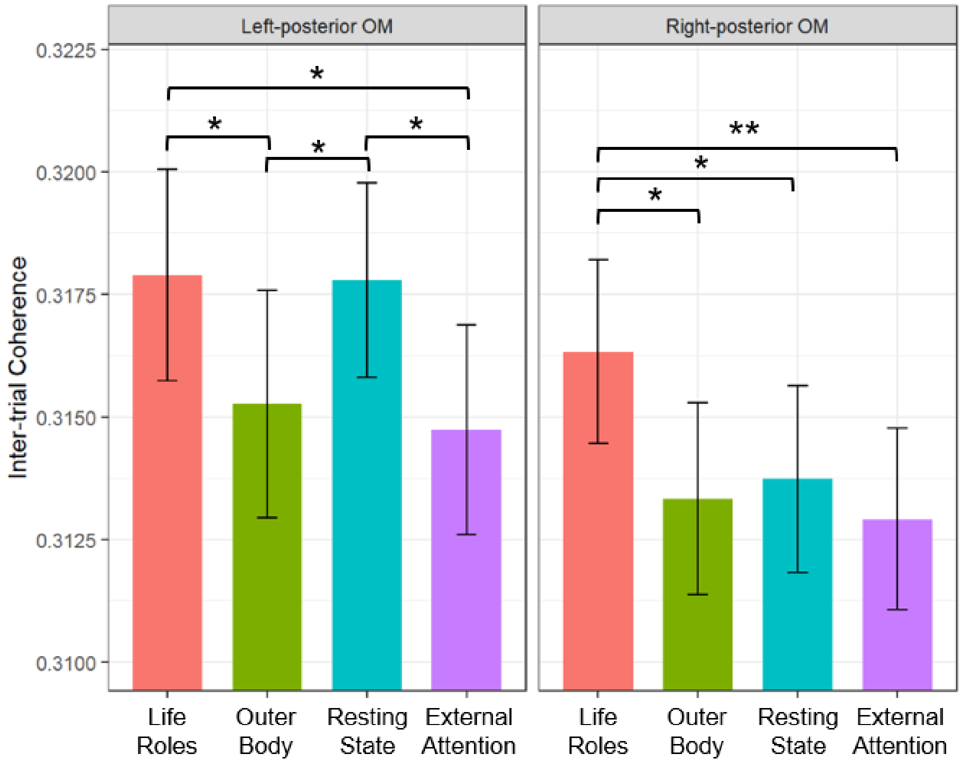


Figure 3.3 Significant differences between SRP conditions in phase synchrony measured by inter-trial coherence (ITC). *: p.adj < 0.05, **: p.adj < 0.01.

3.4.6.4 eLORETA results

Source analyses of differences between SRP conditions reveal significant differences in spectral power in the alpha and theta bands, but no differences in functional connectivity were observed. Figures 2.3-2.5 and Appendix Tables 2-4 show the eLORETA contrasts in the alpha and theta bands between semantic SRP (life roles) and somatic SRP (outer body) in comparison to the external attention (letter counting) task and the resting state IBI.

SRP and resting state vs. external attention

Semantic SRP vs. external attention. The exceedance proportion tests comparing semantic SRP and external attention showed significance in the alpha band with the two-tailed log of F-threshold = 0.017 (P = 0.006). Semantic SRP induced higher alpha in the bilateral insula, frontal, and ACC, with maximum activation in the left IFG. Brain structures with log of F-ratios higher than 0.1 include the bilateral IFG, the bilateral precentral gyrus, the bilateral cingulate gyrus, the bilateral ACC, and the left middle frontal gyrus (MFG). Additionally, semantic SRP induced lower alpha in a posterior cluster with maximum deactivation in the precuneus (Appendix Table 3, **Error! Reference source not found.**)

Somatic SRP vs. external attention. Our results also showed significant two-tailed contrasts between somatic SRP and external attention with log of F-threshold = 0.017 ($P = 0.026$) in the alpha band. Somatic SRP also induced higher alpha in the bilateral insula and the right frontotemporal cortex, with the maximum activation in the right insula and the right IFG. Brain structures with log of F-ratio higher than 0.1 include the right IFG, the right insula, the bilateral precentral gyrus, the bilateral MFG, and the left ACC. Somatic SRP induced lower alpha activity in a temporoparietal cluster with maximum deactivation in the temporal gyri and the parahippocampal gyrus (Appendix Table 3, **Error! Reference source not found.**).

Resting state vs. external attention. The exceedance proportion tests comparing resting state and external attention showed significance in the alpha band with a two-tailed log of F-threshold = 0.019 ($P < 0.001$). The resting state induced higher alpha in the bilateral insula and the frontal cortex with maximum activation in the right IFG and right insula. Brain structures with log of F-ratio higher than 0.1 include the bilateral IFG, the bilateral precentral gyrus, the bilateral ACC, the bilateral MFG, the bilateral superior temporal gyrus, and the right cingulate gyrus. Additionally, the resting state induced lower alpha in the parietal and occipital lobes with maximum deactivation in the right PCC (Appendix Table 3, Figure 3.4)

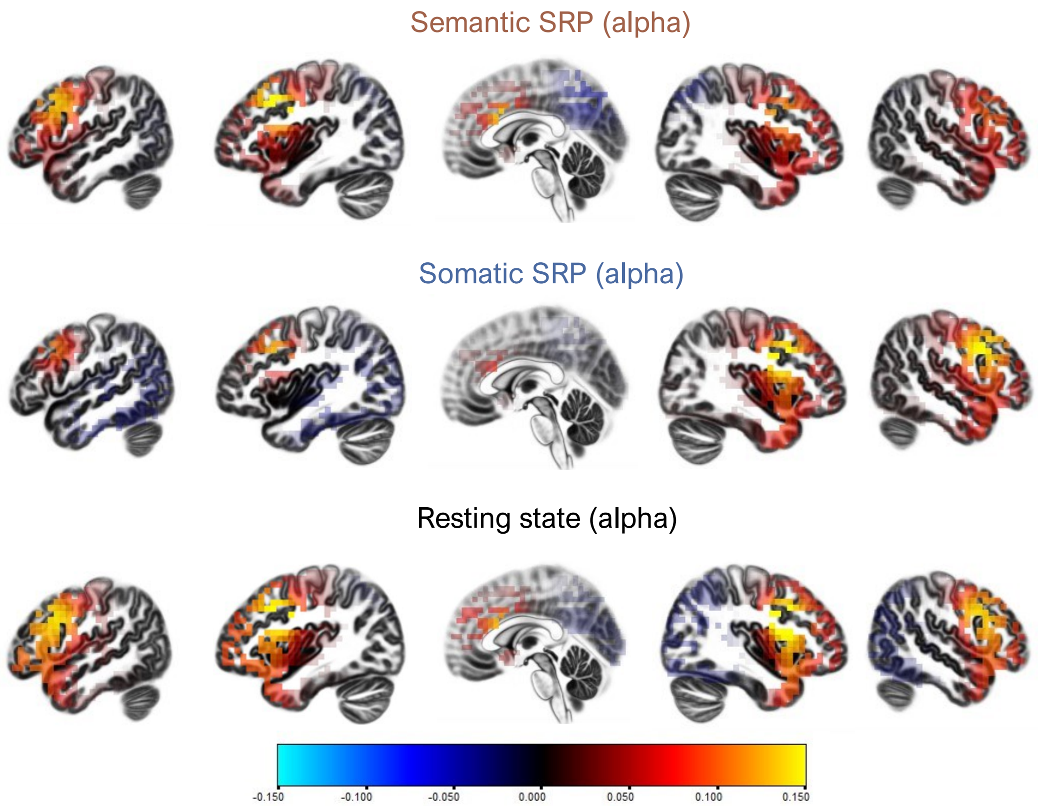


Figure 3.4 Significant eLORETA maps comparing internal attention conditions (SRP and resting state) with external attention in the alpha band. Note. The log of F-ratio thresholds for significance: semantic SRP = 0.017, P = 0.006; somatic SRP = 0.017, P = 0.026; resting state = 0.019, P < 0.001

SRP vs. resting state

Semantic SRP vs. resting state. The exceedance proportion tests comparing semantic SRP and resting state showed significance in the theta but not the alpha band with a two-tailed log of F-threshold = 0.006 (P = 0.008). Semantic SRP induced lower theta in the bilateral insula and a frontal cluster with maximum deactivation in the ACC and MPFC. Semantic SRP also induced higher theta in a posterior cluster with maximum activation in the right supramarginal gyrus and the temporal gyri (Appendix Table 4, Figure 3.5).

Somatic SRP vs. resting state. In comparison, our results showed significant two-tailed contrasts between somatic SRP and resting state with the log of F-threshold = 0.010 (P = 0.002) in the alpha but not theta band. Somatic SRP induced lower alpha activity in the left insula but higher alpha activity in the right insula. Additionally, somatic SRP induced lower activity in the left frontotemporal cortex with maximum deactivation in the IFG and the superior temporal gyrus. Finally, somatic SRP induced higher alpha activity in the right temporal-parietal–occipital (TPO) cortex with maximum activation in the lingual gyrus, the posterior cingulate, the fusiform gyrus, and the cuneus (Appendix Table 4, Figure 3.5)

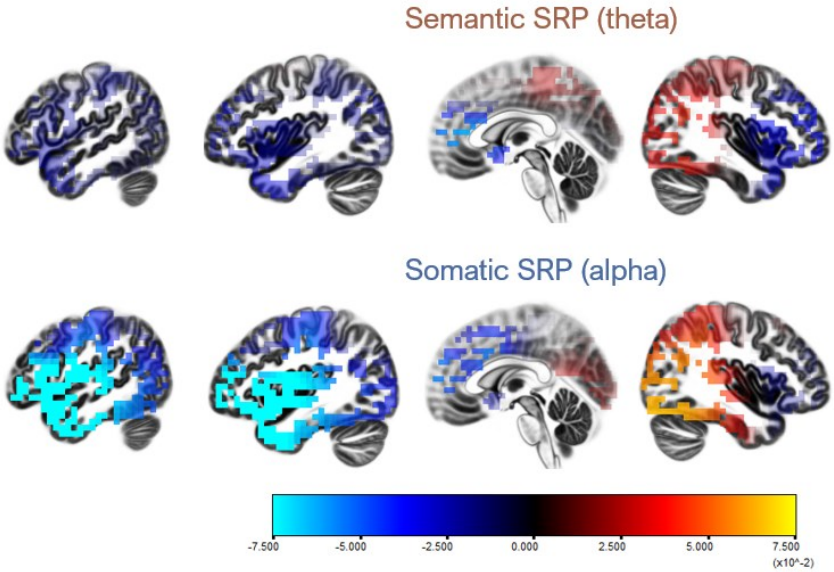


Figure 3.5 Significant eLORETA maps comparing SRP with resting state in the theta and alpha bands. Note: the log of F-ratio thresholds for significance: semantic SRP (theta) = 0.006, P = 0.008; somatic SRP (alpha) = 0.010, P = 0.002

Semantic vs. somatic SRP

The exceedance proportion tests comparing semantic SRP and somatic SRP showed significance in the alpha band with a two-tailed log of F-threshold = 0.007 (P = 0.016). Semantic SRP induced higher alpha in the left cingulate gyrus, the left precentral gyrus, the left insula, the left superior temporal gyrus, the bilateral ACC, the left middle temporal gyrus, the left inferior temporal gyrus, the left IFG, the left postcentral gyrus, the left parahippocampal gyrus, the left MFG, the right frontal pole, the right superior frontal gyrus, the bilateral medial frontal gyrus, the middle occipital gyrus, the left PCC, and the left lingual gyrus. In contrast, somatic SRP induced higher alpha in the right IFG; the bilateral precentral gyrus, the right precuneus, the right insula, the right MFG, the right inferior parietal lobule, the right PCC, the right cuneus, the right postcentral gyrus, the right superior, middle, and inferior temporal gyrus, the right parahippocampal gyrus; and the left paracentral lobule (Appendix Table 5, Figure 3.6). The follow-up regression analysis investigating the potential mediating effect of attentiveness and pleasantness in the EEG results indicated that no cluster or single voxel significantly predicted the difference in ratings between experimental conditions.

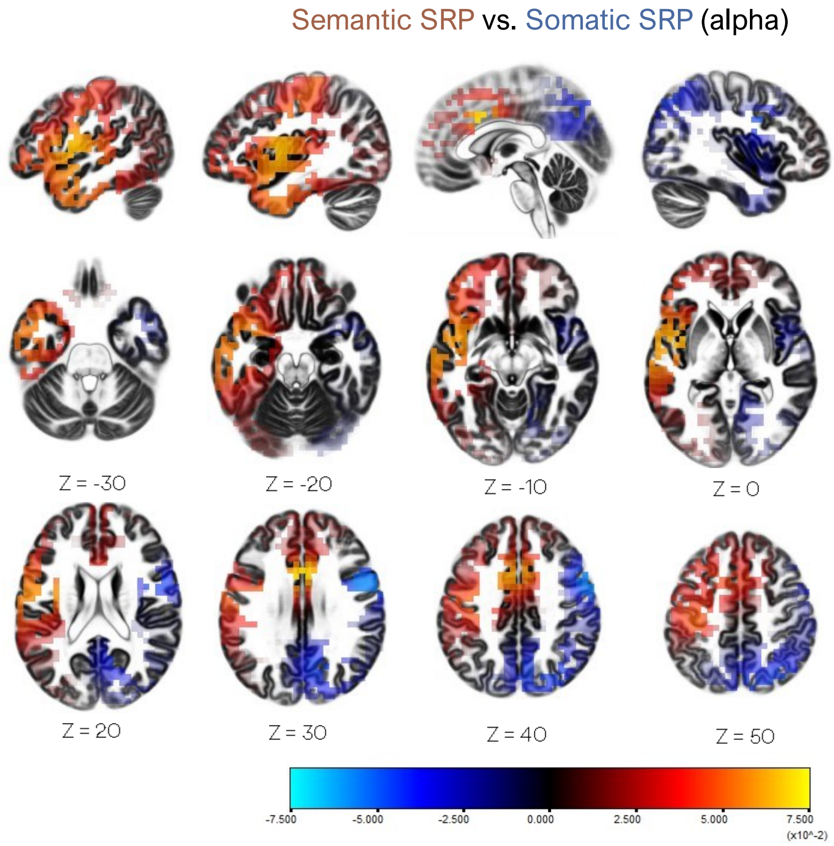


Figure 3.6 Significant eLORETA maps comparing semantic SRP with somatic SRP in the alpha band. Note: the log of F-ratio threshold for significance = 0.007, P = 0.016

3.4.7 Discussion

To our knowledge, this EEG study was the largest to investigate the response to a structured SRP task when it comes to participant sample size and the first to compare the EEG alpha and theta oscillatory correlates of semantic SRP with somatic SRP as well as to both an internal (resting state) and external attention control condition utilizing eLORETA. Our study yielded several findings. First, SRP conditions exhibited differences in source-level spectral power and ITC among parietal electrodes but not in functional connectivity within the DMN ROIs. Second, compared to a simple external attention task (letter counting), conditions that involved internal attention (SRP and resting state) induced increasing alpha activity in the bilateral insula, the MFG (i.e. dorsolateral prefrontal cortex, DLPFC), the VLPFC (i.e. IFG), and the ACC, while decreasing alpha activity in the precuneus (**Error! Reference source not found.**). Third, w ithin the internal attention tasks, when compared with the passive and unstructured resting state, active and structured SRP induced increasing alpha and theta activity in the right TPO cortex but decreasing alpha and theta activity in the left TPO cortex, the bilateral insula, the ACC, the VLPFC, and DLPFC (Figure 3.5). Fourth, within the active and structured SRP conditions, direct comparison between semantic and somatic SRP suggested differential alpha activities in the anterior vs. posterior cortex and the left vs. right hemisphere, including notably the insula and the dorsal ACC (Figure 3.6). Such findings were observed while completing an SRP task that was generally pleasant, associated with improved mood, and sensitive to certain psychophysiological arousal measures. These self-reported findings may suggest that brief sessions of semantic and somatic SRP interspersed with breath-focused meditations might have stress-reduction and mood-enhancing effects, albeit requiring further investigation with control conditions. We discuss each set of findings in turn.

3.4.7.1 Internal vs. External attention

During the SRP task and resting state, participants were asked to focus their attention internally on their character (semantic SRP), bodily sensations (somatic SRP), or spontaneous thoughts (resting state) that may be generated by the DMN and BSC system (Davey et al. 2016; Park and Blanke 2019). In our study, these internal attention task conditions induced increases in alpha activity in the DLPFC, the VLPFC, the ACC, and the anterior insula compared to external attention, which agrees with several fMRI studies on SRP.

Regarding the VLPFC, fMRI studies have suggested that the right VLPFC may play a role in cognitive control during self-face processing as part of somatic SRP (Hu et al. 2016), while the left VLPFC may play a role in internal speech production as part of semantic SRP (Morin and Hamper 2012). Regarding the ACC and the insula, in addition to the insula's role in interoception, several studies found that both the dorsal ACC and the anterior insula are involved in the salience of the self during emotional SRP, such as during negative self-attribution, self-face recognition, and social rejection tasks (Cabanis et al. 2013; Morita et al. 2014; Perini et al. 2018). Our results appear consistent with the meta-analysis of Hu et al. (2016), who suggested that the VLPFC/insula region and the ACC are consistently found in both semantic and somatic SRP studies, suggesting a "core self-representation" that integrates multimodal self-relevant stimuli underlying SRP.

Interestingly, compared to external attention, we also found that internal attention toward the self-induced increased alpha activity in the DLPFC bilaterally (Appendix Table 3). Although the DLPFC is known to play a role in executive control during negatively valenced SRP, such as occurs during rumination and major depression (Renner et al. 2015; Delaveau et al. 2016; Baeken et al. 2017), few studies investigated the DLPFC in the context of internal and emotionally neutral SRP among healthy participants. In our study, we found the involvement of the alpha band in the DLPFC when participants were engaged in SRP, which they rated, on average, to be emotionally neutral to slightly positive. Given the DLPFC's role in executive control and our results, the DLPFC may be involved in attentional control of internal focus toward the self and coupling with the self-relevance of stimuli. In summary, the internal component of SRP-induced alpha and theta activities may be involved in cognitive control, internal speech, interoception, and affective regulation.

Finally, we found that, compared to external attention, internal attention during the resting state also induced higher alpha activity in the previously mentioned brain areas, such as the bilateral VLPFC, bilateral insula, bilateral DLPFC, and the ACC. We know from fMRI evidence that the resting brain overlaps with the self-referential brain and that sub-networks of the DMN may be associated with different aspects of SRP (Gusnard et al. 2001; van Buuren et al. 2010; Wen et al. 2020). Furthermore, evidence suggests that internal attention that is not goal-directed may encompass numerous processes, including both semantic and somatic SRP (Welhaf et al., 2020). Therefore, our findings may support these previous findings that various unprompted forms of SRP may occur during passive, unstructured periods of resting state.

3.4.7.2 SRP vs. Resting State

Despite both usually being associated with an internal focus, SRP tasks differ from the resting state in their increased structure and goal-directedness, contrasting the task-free nature of the resting state. Therefore, our SRP vs. resting state contrasts reflect the active "on-task" component of SRP, such as attending to task-relevant stimuli and inhibiting task-irrelevant stimuli. We found large areas across the right TPO cortex exhibiting higher alpha and theta activities during task-related SRP than resting state. In fMRI studies, activations in the PCC and the right inferior parietal lobule were consistently found to be essential for both semantic and somatic SRP, exhibiting DMN-wide connections with other regions of interest in SRP, such as the MPFC (Davey et al. 2016). Referring to regions outside of the DMN, activities in the primary visual cortex, the posterior parietal cortex, and the fusiform cortex may be interpreted as multisensory integration required during SRP. However, it remains unclear why these processes during SRP were heavily lateralized to the right hemisphere in our study.

In the opposite direction, comparing the resting state with SRP yields the background "at-rest" component that is less involved during active SRP. We found that higher activities in the VLPFC, the bilateral insula, and the ACC were observed during the resting state in both the alpha and theta bands. These findings are consistent with the "core self-representation" mentioned previously and suggest that activities in the VLPFC/insula and ACC may be SRP-specific and cannot be accounted for only by internal attention in general. Again, this finding is consistent with Hu et al. (2016), who found that semantic and somatic SRP share these regions. Our findings thus suggest that such a "core self-representation" may be an endogenous background activity occurring during rest and that such resting-state SRP exceeds that occurring even during structured SRP tasks. An important note is that even though our results indicate that endogenous SRP during rest may be different from goal-oriented SRP, evidence suggests that both at-rest and on-task SRPs share substantial anatomical and functional similarities (Kim, 2012). Interestingly, more recent literature suggested that brain activities during the resting state may be a "foundation" for semantic SRP. For example, Bai et al. (2016) found that high glutamate concentration in the perigenual ACC predicted higher alpha band activity before presentations of semantic SRP stimuli and higher subjective ratings of self-relevance. Additionally, Meyer and Lieberman (2018) demonstrated that BOLD activities in the MPFC/Brodmann Area 10 during the resting state predicted faster response times to semantic SRP stimuli in an SRET. Although our experimental design cannot address the direction of causality between resting state and SRP, our findings may contribute to the three-level processing model of the self (Qin et al. 2020) that on-task SRP may be an extension of at-rest SRP when we direct attention to exogenous self-related stimuli.

3.4.7.3 Semantic vs. Somatic SRP

When comparing semantic vs. somatic SRP, we observed an apparent dissociation between anterior vs. posterior and left vs. right hemisphere response. We found that semantic SRP involved the left frontal brain, while somatic SRP involved the right posterior brain. Differences were also seen in some of the cortical midline structures, specifically the dorsal ACC, PCC, and precuneus.

In the frontal lobe, we found peak alpha activity in the dorsal ACC during semantic SRP compared to somatic SRP. Evidence suggests that dorsal ACC is involved in several self-related processes such as self–other face discrimination (Hu et al. 2016), processing emotional responses in autobiographical memory retrieval (Yang et al. 2012), and salience to self-related stimuli (Murray et al. 2012). Therefore, increases in alpha activity in the dorsal ACC may indicate that semantic SRP is associated with a higher salience and emotional processing than somatic SRP. The difference between semantic and somatic SRP in emotional processing is also supported by participants' lower levels of experienced pleasantness during semantic SRP. In this regard, Yang et al. (2012) found that BOLD activity in the dorsal ACC exhibited a negative association with state-level self-esteem. Our results may imply that alpha activity in the dorsal ACC relates to the potentially greater emotional salience of semantic SRP when compared to somatic SRP in our task.

In the parietal lobe, somatic SRP induced higher alpha activity in the precuneus/PCC region, which is consistently found to be associated with SRP. However, the directionality of our findings is different from that of the existing fMRI literature. For example, Araujo et al. (2015) found that participants undergoing SRETs exhibited higher BOLD responses in responding to their traits (semantic SRP) compared to facts about their body (somatic SRP). In the meta-analytical review conducted by Qin et al. (2020), semantic SRP was associated with higher BOLD responses in the precuneus/PCC region compared to somatic SRP. Although one may argue that such differences may be accounted for by the anticorrelation between the alpha wave and BOLD responses (Pang and Robinson 2018), more studies are needed before making solid conclusions.

In addition to the dissociation between frontal and parietal responses in semantic vs. somatic SRP, we also observed differential responses to semantic vs. somatic SRP in the left vs. right hemispheres, respectively. First, somatic SRP induced higher alpha activity in the right insula. Ample evidence supports the roles of the right insula in somatic SRP, including processing interoceptive signals and body ownership (Craig 2002; Simmons et al. 2013; Salvato et al. 2020). A meta-analysis of fMRI studies of SRP suggested that semantic SRP is located on higher layers of the self (i.e. requiring more integration) compared to somatic SRP and that the right insula serves an integrative role over all domains of SRP (Qin et al. 2020). Moreover, Scalabrini et al. (2021) showed that the right insula exhibits a wider autocorrelation window than the left insula during a face-morphing task. Given the link between autocorrelation and information integration (Honey et al. 2012), these results support that response within the right insula may reflect a more fundamental layer aspect of SRP when compared to the left.

Comparably, the role of the left insula in semantic SRP is less clear. Here, we report a novel finding where semantic SRP induced higher alpha activity in the left insula compared to somatic SRP. As a possible interpretation, such differences might reflect the different levels of sensory integration involved in semantic vs. somatic SRP. The life roles task would appear to require little sensory processing when switching from self-evaluating oneself in the roles of “student” vs. “friend,” for example, implying that BSC may be processed holistically in each life role, if at all. In contrast, differentially attending to one area of one’s outer body (e.g. arms) vs. another (e.g. legs) may require more sensory processing implemented within the right insula.

We also observed higher alpha activity in the left VLPFC/superior temporal cortex during semantic than somatic SRP. Self-related inner speech production may be more salient in semantic SRP than somatic SRP, supporting the findings of a meta-analysis on left VLPFC (Morin and Hamper 2012) and consistent with the proposal that semantic SRP is more linguistic in nature than is somatic SRP (Frewen et al. 2020). The right VLPFC–DLPFC area, on the other hand, exhibited higher alpha activity during somatic SRP. These results contrast with those of Araujo et al. (2015), who found that somatic SRP was associated with higher BOLD signals in the bilateral VLPFC. Notably, given the role of the right VLPFC in attending to self-relevant stimuli and cognitive and emotional inhibition within the frontoparietal attention network, Hu et al. (2016) suggested that the right VLPFC may reflect high demands of cognitive control during SRP. However, our tasks did not explicitly require cognitive inhibition, and participants in our study did not report differential levels of attentiveness during somatic and semantic SRP. Our results, therefore, imply that right VLPFC involvement during somatic SRP may subserve a more general function than specifically cognitive inhibition.

Finally, we reported a novel finding that alpha activity increased in the left vs. right DLPFC, corresponding with semantic vs. somatic SRP. Regarding the observed lateralization in semantic vs. somatic SRP, our findings in the insula, VLPFC, and the DLPFC may suggest that distinct neural processes associated with semantic and somatic SRP exist in the left vs. right hemisphere in addition to the involvement of cortical midline structures, extending the findings of Fingelkurts et al. (2020) for the parietal cortex. The laterality of the results implies a possible fundamental distinction within the brain in processing SRP in semantic vs. somatic domains.

3.4.7.4 The pattern of Phase Synchrony between SRP Conditions

Regarding phase synchrony, we observed a pattern in the left-posterior OM where semantic SRP and resting state exhibited higher synchrony than somatic SRP and external attention. This finding may support the definition of the left posterior OM as mediating a form of “reflective agency,” highlighting its function in introspection and autobiographical and semantic memory referring to oneself (Fingelkurts et al., 2020).

In the right-posterior OM, semantic SRP exhibited higher synchrony than all three conditions. This finding deviated from the model proposed by Fingelkurts et al. (2020), where the right-posterior OM was described as the “representational-emotional agency,” highlighting its close relationship with emotional states and the embodied nature of SRP. Therefore, one might have expected that somatic SRP would exhibit higher phase synchrony within the right posterior OM instead of semantic SRP, while this was not found in the current research.

Instead, we observed that the life roles condition theorized to involve semantic SRP was associated with increased synchrony in both left and right posterior OMs, possibly reflecting that the life roles condition engaged both self-related semantic and emotional processing. Compared to the outer body condition (somatic SRP), life roles exhibited significantly lower pleasantness in participants’ self-reports in the current Study 2, which is also different from the non-significant differences seen in Study 1. Therefore, it is possible that participants experienced semantic memory processing as being associated with increased negative self-related emotions compared to somatic SRP. Despite the differences in findings, definitions of OMs, and outcome measures between the current study and Fingelkurts et al. (2020), these findings may further support the separation between semantic and somatic SRP on a neurobiological level, consistent with our source-level findings on EEG alpha power.

Additionally, we observed that the resting state condition exhibited the same level of phase synchrony as life roles in the left posterior OM but not in the right posterior OM. This may reflect some level of unstructured autobiographical and semantic memory processing during the resting state but without the same degree of emotional reactivity that may have been experienced during the life roles condition. Again, the comparisons between the current study and Fingelkurts et al. (2020) should be treated with caution since we used different electrodes to define OMs and different measures of phase synchrony. The main objective of analyzing 10 Hz phase synchrony in the current chapter was to set a baseline in the absence of NIBS for analyses conducted in later chapters that did involve the administration of NIBS.

3.4.7.5 Study Limitations, Future Directions, and Conclusion

Our study is not without limitations. First, we did not include additional self-reported measures out of consideration of the length of study sessions. However, we recommend future SRP studies include questionnaire measures of self-esteem and body self-awareness to be compared with task-related ratings of semantic and somatic SRP. Moreover, our task blocks were 30 seconds long, requiring sustained attention and potential depth of introspection and interoception beyond that facilitated by responding to discrete stimuli as in most prior studies utilizing the SRET, albeit less than that used in other studies that have used lengthy meditations. Future studies should consider the depth of SRP provoked by their tasks as a relevant design feature. Second, our homogenous sample consists of only undergraduate students aged 18–22, while studies have suggested that SRP may vary based on factors such as culture (Knyazev et al. 2012) and age (Moses-Payne et al. 2022). Future studies may investigate both semantic SRP and somatic SRP across different demographic groups. Third, while our EEG study was aimed at discovering some of the electrophysiological correlates of different forms of SRP, causal conclusions regarding the role of various brain regions in SRP would be stronger following the direct manipulation of oscillations in these brain regions, such as might be accomplished by non-invasive brain stimulation (Bao et al. 2021). In the same vein, future EEG studies may use an electrode-driven approach to investigate differences in autocorrelation window (ACW) between the SRP conditions, given the close relationship between ACW and self-specificity (Smith et al. 2022). Fourth, we used eLORETA with only a small number of channels, resulting in low spatial resolution. Given the positive correlation between electrode density and source localization accuracy, future studies may investigate SRP with high-density montages. Fifth, although we decided against analyzing the involvement of high gamma (>50 Hz) due to the small number of prior studies on which to base hypotheses and the impact on multiple comparisons, future studies may nevertheless be interested in investigating the high gamma band's role in SRP, especially given the results of Dastjerdi et al. (2011). Finally, in our study, we investigated the differences between SRP conditions and the resting state but did not address the direct correlation between SRP and the resting state. Given the close relationship between the brain functions involved during the resting state and SRP (Bai et al. 2016; Northoff 2016; Meyer and Lieberman 2018), future studies may directly investigate the correlation between semantic and somatic SRP and resting state.

Despite our study limitations, our study suggests that SRP in the brain may be primarily associated with alpha oscillations, with source localization and phase synchrony suggesting that different elements of SRP (internal attention, somatic, and semantic) may be associated with distinct spatial patterns in the insula, the frontal cortex, the parietal cortex, and the cingulate cortices.

Chapter 4

4 The effects of MPFC transcranial direct current stimulation (tDCS) on alpha-EEG during SRP

4.1 Introduction

Behavioural and neuroimaging studies have contributed to our understanding of self-referential processing (SRP), referring to the human brain's response to self-related stimuli. Since Willian James' (1980) distinction between the "me" and "I" aspects of the self, two broad categories of SRP have been recognized: a semantic form of SRP that processes verbal-conceptual autobiographical stimuli (e.g., one's name), and a somatic form of SRP that processes nonverbal-bodily stimuli, such as interoceptive and proprioceptive signals. As described in the previous chapters, neuroimaging and non-invasive brain stimulation (NIBS) studies have sought to understand the brain bases of SRP and whether these can be modulated to alter self-experience.

4.1.1 Neuroimaging studies of SRP

A meta-analysis summarized brain regions that underlie both semantic and somatic SRP (e.g., the insula) and areas that correspond to one type of SRP more than the other (Qin et al., 2020). For example, semantic SRP activates the medial prefrontal cortex (MPFC) more so than somatic SRP, while somatic SRP elicits activities in the right insula more so than semantic SRP (Qin et al., 2020). Based on findings from the functional magnetic resonance imaging (fMRI) literature, Qin et al. (2020) also proposed a three-level model of SRP that considers semantic SRP as an extension of somatic SRP. The three-level model proposes that semantic SRP emerges from the integration of somatic signals with non-bodily stimuli, involving regions of the default mode network (DMN), including the MPFC for self-specific processing, the anterior cingulate cortex (ACC) for emotional processing, and the posterior cingulate cortex (PCC) for general cognitive processing.

Compared with fMRI studies, few studies have used electroencephalography (EEG) to investigate the neural oscillations underlying SRP, especially those that compared semantic and somatic SRP under the same experimental design. However, a recent EEG source analysis indicated that semantic and somatic SRP elicited alpha activity in the left and right frontal cortex, respectively, when compared to focusing on external, non-self-referential stimuli (Bao & Frewen, 2022). Further, when compared to a state where participants focused on external stimuli, semantic SRP, which involved asking participants to self-evaluate how they feel about themselves in reference to specific life roles (e.g., “How do I feel about myself as a friend?”), induced increased alpha activity in the frontal cortex, with the peak of the difference in the left inferior frontal gyrus (IFG). Similarly, somatic SRP, which involved asking participants to attend to how they feel in reference to specific body parts (e.g., “How do my hands feel?”) also induced increased alpha activity in the frontal cortex, but the peak of the difference was in the right IFG. Further, when EEG sources of semantic and somatic SRP were compared directly, semantic SRP was associated with alpha activity most prominently in anterior regions and the left hemisphere, with the peak of difference in the ACC and left insula. In contrast, somatic SRP was associated with alpha activity most prominently in posterior regions and the right hemisphere, with the peak of the difference in the right IFG and the right precuneus. These results suggest a significant role of alpha oscillations within various brain regions in differentiating 1) internally focused SRP from externally focused non-SRP and 2) semantic SRP from somatic SRP.

4.1.2 Non-invasive brain stimulation studies of SRP

Researchers have also sought to modulate SRP by targeting SRP-related NIBS. Our recent systematic review summarized NIBS studies that used transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) to modulate neural activities underlying SRP with both positive and null results (Bao et al., 2021). Taken together with more recent studies, findings related to NIBS targeting the MPFC have been particularly interesting, including four TMS studies that reported significantly reduced self-criticism (i.e., negatively valenced semantic SRP) in active NIBS compared to sham (Kwan et al., 2007; Barrios et al., 2008; Luber et al., 2012; De Pisapia et al., 2019), albeit that one TMS study produced null results (Lou et al., 2010). Comparably, several studies failed to find significant effects of tDCS over the MPFC on self-other discrimination (Schäfer & Frings, 2019), self-referential encoding of adjectives (Mainz et al., 2020), and self-referential memory recall (Burden et al., 2021). To our knowledge, only Yin et al. (2021) yielded positive findings, showing that cathodal tDCS over the ventromedial prefrontal cortex (VMPFC) attenuated self-referential working memory processing.

The fact that the majority of prior studies have failed to show the effects of MPFC-tDCS on SRP is surprising for several reasons. First, tDCS studies that targeted other frontal cortex regions reported successful modulation of behavioural outcomes of SRP. For example, stimulation over the dorsolateral prefrontal cortex (DLPFC) was found to reduce SRP in three studies (De Raedt et al., 2017; Dedoncker et al., 2019; Allaert et al., 2021). Second, other studies demonstrated that MPFC-tDCS modulated brain processes that are arguably closely related to SRP, such as emotional valence processing (Abend et al., 2019) and mind-wandering (Bertossi et al., 2017). Third, a study of the effects of tDCS on resting state showed small increases in broadband spectral power, albeit non-significantly (Ghafoor et al., 2021).

Further, it may be premature to conclude that MPFC-tDCS cannot modulate SRP due to a number of methodological considerations. Firstly and most fundamentally, past MPFC-tDCS studies primarily focused on semantic SRP without investigating the impact of tDCS on somatic SRP. Here, past meta-analyses of neuroimaging studies of SRP suggested that semantic and somatic SRP may be organized hierarchically, where semantic SRP consists of brain areas involved in somatic sensory processing plus unique processes in the frontal cortex (Qin et al., 2020; Frewen et al., 2020). Accordingly, it may be that MPFC-tDCS has more demonstrative effects on somatic than semantic SRP, including on brain regions involved in SRP outside of but functionally connected with the MPFC, such as regions of the DMN. Consistent with this, tDCS studies targeting other DMN regions, such as the left and right IPL, have found success in modulating somatic SRP (Payne & Tsakiris, 2017; Hari et al., 2023). Without investigating semantic and somatic SRP together, potential results of NIBS on somatic SRP may be overlooked, while outcomes for semantic SRP may be confounded by the effects of NIBS on underlying processes involved in somatic SRP. Secondly, while the previous studies evidencing null results for the effects of MPFC-tDCS on semantic SRP reported subjective and behavioural outcomes, none conducted electrophysiological measurements such as EEG of alpha oscillations. Presumably, the primary effects of NIBS will be mediated neurophysiologically, which may or may not further result in secondary, downstream effects on participants' subjective states or behaviour during or in response to SRP. Particularly insofar as SRP is a complex process including memory, affect, and attention, both semantically and somatically, SRP is likely to engage various neural networks, including the brain's DMN, salience, limbic, executive and attention networks (Frewen et al. 2020), each of which may or may not be directly modulated by NIBS. Therefore, one explanation for the null results in MPFC-tDCS studies may be that performance in cognitive-behavioural tasks is insufficiently sensitive to detect the effects of MPFC-tDCS on SRP, given the complexity of SRP and the potential that, while certain brain regions may be affected, the engagement of other neural networks may play a compensatory effect. Third, electrode sizes and montages used in past MPFC-tDCS studies on SRP may not have been optimized. Based on modelling research of tDCS current density, smaller electrode sizes result in more focal stimulations, and for electrodes that are less than 8 cm apart, maximum current density exists between the two electrodes (Faria et al., 2011). Therefore, the optimal montage for stimulation strength targeting the MPFC may be by using a pair of small electrodes placed near each other over the MPFC. Meanwhile, relatively large electrodes (35 cm2) have been used in several past SRP studies, and their electrode placements seemingly would not maximize the current density under the MPFC (e.g., FPz + F3 for Schäfer & Frings, 2019; Fpz + Oz for Mainz et al., 2020; Fz + right upper arm for Burden et al., 2021). In fact, the only MPFC-tDCS study with positive findings (Yin et al., 2021) used smaller electrodes (9 cm2) with previously optimized stimulation montages that maximized the focality over the VMPFC. Overall, the lack of optimized strength and focality in MPFC-tDCS studies might account for the generally negative findings for the effects of MPFC-tDCS on SRP.

4.1.3 NIBS and functional connectivity

Additionally, while existing research demonstrated that tDCS can alter functional connectivity of the stimulated region with regions outside of the range of stimulation (Chan & Han, 2020; Adams et al., 2022), to our knowledge, the effects of tDCS on functional connectivity is currently unexplored in the context of SRP. Prior research has established that SRP may be a result of the complex integration of multiple functional neural networks rather than merely the result of localized brain activity (Frewen et al., 2020). For example, Davey et al. (2016) conducted dynamic causal modelling on functional MRI data of semantic SRP and found that semantic SRP was driven by PCC activity that is moderated by the activity in the MPFC and the left IPL; their model also revealed that the MPFC exhibited negative endogenous influences on the PCC. Moreover, a follow-up study conducted by the same group showed that the left IPL can also inhibit PCC activity during SRP (Delahoy et al., 2023). Additionally, Knyazev et al. (2020) found that self-other discrimination was associated with increased connectivity between the DMN (represented by the MPFC, the PCC, and the bilateral IPL) and the left DLPFC and decreased connectivity between the task-positive network and DMN regions such as the precuneus. Finally, regarding somatic SRP, Park and Blanke (2019) reviewed prior research and proposed exteroceptive and interoceptive systems that involve connections between the insula, the temporoparietal junction (TPJ), the premotor cortex and the IPL in the right hemisphere. Clearly, multiple brain regions and neural networks may be involved in mediating the complex psychosomatic experience of having and being a self.

Given the current understanding of SRP as a result of complex neural networks and prior findings that prefrontal tDCS can modulate DMN functional connectivity during resting state (Chan et al., 2021), it seems that the effects of NIBS on SRP may thus be driven – at least in part – by altering functional connectivity between brain regions. This may include regions of interest (ROIs) within the DMN widely known to be involved in semantic SRP, including the MPFC, the PCC/precuneus, the ACC, and the bilateral IPL, as well as other regions more often associated with somatic SRP including response within the bilateral insula (Frewen et al., 2020).

4.1.4 The current study

Currently, the efficacy and neural mechanisms underlying the effects of MPFC-tDCS on SRP remain largely unknown due to a reliance on the use of semantic but not somatic SRP tasks, the measurement of self-report and behavioural outcomes but not a direct measurement of electrophysiological responses within the brain, and the possible selection of sub-optimal montages. A deeper understanding of the neural mechanisms of change induced by MPFC-tDCS during SRP may thus contribute to better outcome measures and SRP task designs that are consistent with its impact on neurophysiology, which may have further implications on basic and clinical NIBS research.

Therefore, we designed an MPFC-tDCS paradigm that aimed to investigate the effect of MPFC-tDCS not only on subjective self-report outcomes but also on EEG outcomes in response to semantic and somatic SRP with a focus on the measurement of alpha oscillations and their functional connectivity. We implemented the same experimental design used by Bao and Frewen (2022) with adaptations to incorporate tDCS over International 10-20 positions AF3 and AF4 during the SRP task to maximize focality to the MPFC. We anticipated changes in alpha power near the stimulation site, together with possible additional changes in functional connectivity between the MPFC and other regions involved in SRP within and outside of the DMN after real but not sham tDCS.

4.2 Method

4.2.1 Participants

We conducted a Power analysis (using G*Power 3.1) and found that to achieve conventional power = .8 for sensitivity to a minimum effect size of f = .2 at a critical p-value of .05, with two groups and two measurements, we required a sample size of 52. Thus, 52 participants enrolled in an introductory psychology course at Western University were invited to participate in this research for partial course credit.

Within our sample, 47 (90%) participants were between 18 and 22 years old, and 42 (81%) were females. The reported ethnicity of participants was as follows: 17 White (33%), 13 Chinese (25%), 10 South Asian (19%), and 12 “Other” (24%). In addition to being undergraduate students, 37 participants reported working part-time (71%), 8 working full-time (15%), and 7 currently not working (14%).

4.2.2 Procedures and materials

We implemented a within-subject design to test the effect of MPFC-tDCS compared to sham stimulation during two testing sessions. In other words, all participants underwent two experimental sessions (one real and one sham) that were held at least 24 hours apart. For the between-subject factor, participants were randomly assigned to either receive the real tDCS session before (n=25, stim-1st) or after the sham session (n=27, stim-2nd).

The experimental SRP task was identical to the one used in Chapter 3. The task was divided into three runs. Real or sham tDCS was conducted during the second run and straddled by two 7.5-minute periods of mindful breathing. The experimental procedure for the current study is depicted in Figure 4.1. Participants also completed the same self-report scales described in Chapter 3, including the Modified Differential Emotions Scale (mDES; Fredrickson et al. 2003) and the 10-item Buddhist Affective States Scale (BASS; Zhu et al. 2019).

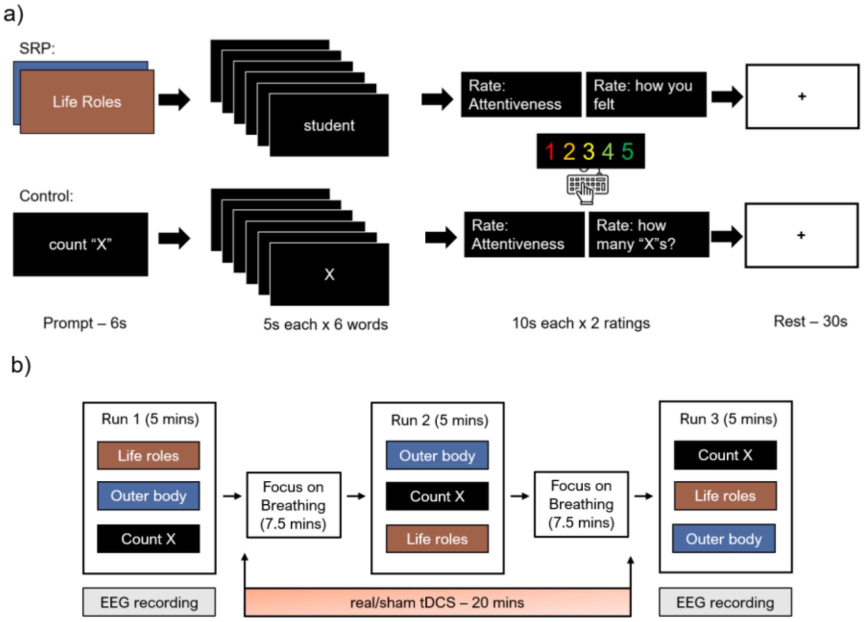


Figure 4.1 Graphical illustration of the SRP task and the tDCS experimental design. Note: (a) example of the life roles and the letter counting conditions of the SRP task and (b) the overall structure of the SRP task used in the tDCS experiment. The order of conditions within runs was randomized rather than fixed.

4.2.3 tDCS parameters

Transcranial direct current stimulation (real tDCS or sham) began immediately after the first run of the SRP task, coinciding with the starting of a breath-focused session, and lasted 20 minutes for each experimental session. Brain stimulation was delivered using neuroConn DC-Stimulator-Plus (neuroConn, Ilmenau, Germany) at 2 mA with 3 X 3 mm rubber pads coated with approximately 1 mm of Ten20TM conductive paste (Weaver & Co., Aurora, CO). Electrodes were positioned at the AF4 and AF3 locations according to the international 10-20 system to maximize electrode coverage of the bilateral MPFC. Which electrode was in the position of the anode versus cathode was randomized every session due to their nearly identical effects on electric current density, as noted in simulations conducted using SimNIBS software version 4.0.0 (Thielscher et al., 2015; Figure 4.2).

During real stimulation, current strength ramped up to 2 mA from 0-15 seconds and ramped down during the last 15 seconds of the 20-min stimulation, while for sham stimulation, current ramped up during the initial 15 seconds but ramped down for the next 15 seconds, followed by continuous impedance checks for the remainder of the 20-minute period (requiring only a 110 μA pulse to occur for 15 ms every 550 ms).

Double-blindness was implemented using the STUDY mode of the DC-Stimulator-Plus. Blinding effectiveness was assessed at the end of every session via self-report questions rated on an 11-point scale: “1) How much do you feel like you received a real/true intervention rather than a fake/sham one?” 2) “How much do you feel like you were aware of what was happening during the intervention?” 3) “How much do you feel like you were in control over what was happening during the intervention?”

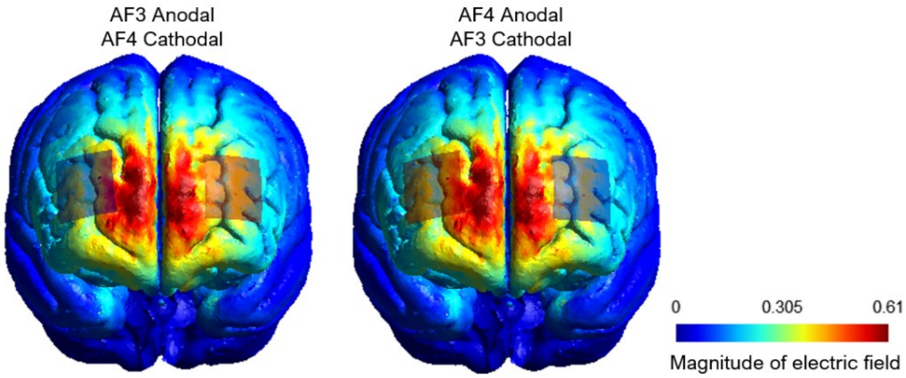


Figure 4.2 Simulation of the current density of the AF3 AF4 stimulation montage with SimNIBS (Thielscher et al., 2015) using 3x3 cm electrodes with 1mm of conductive paste.

4.2.4 EEG data acquisition and preprocessing

We collected participants' eyes-closed EEG data in response to run 1 of the SRP task as the pre-stimulation baseline and during run 3 as the post-stimulation outcome (Figure 1b). EEG data was collected using the 19-channel Nexus-32 system at 512 Hz with the Biotrace+ software.

EEG data was subsequently preprocessed using custom EEGLAB (Delorme & Makeig, 2004) code in the MATLAB environment with the following steps that explicitly replicate those used in Chapter 2: 1) bandpass filtering between 1 and 50 Hz; 2) re-referencing to common average; 3) continuous data and channel rejection using clean_rawdata() with its default settings; 4) interpolation of rejected channels with pop_interp(); 5) independent component analysis (ICA) using the 'picard' method followed by IClabel that only accepts components estimated to be in the "brain" category with at least 70% probability. Then, we calculated the mean spectral power of the alpha band (8-12 Hz) using the EEGLAB function spectopo(), which outputs spectral power for each channel on a logarithmic scale on a trial-to-trial basis to optimize sensitivity for statistical analysis (Smulders et al., 2018). We also measured participants' inter-trial coherence (ITC) as phase synchrony with steps identical to those used in Chapter 2.

4.2.5 Statistical analysis

We used the R package “rstatix” for statistical analyses of 1) participants’ log-transformed mean alpha spectra power and phase synchrony, 2) blinding effectiveness, 3) their self-reported ratings of attentiveness and pleasantness during the SRP task, and 4) their mood ratings. For alpha band power, we first imputed outliers outside of 1.5 times the interquartile range. Then, we conducted mixed analyses of variance (ANOVA) with post hoc tests on the difference between pre-and post-stimulation (post minus pre-stimulation) for each channel with two within-subject factors (1) SRP task condition (4 levels): life roles, outer body, resting state, count X; and 2) Stimulation condition (2 levels: real and sham), and one between-subject factor, Group (2 levels: whether stimulation was conducted during 1st or 2nd session, annotated Stim-1st and Stim-2nd). For ratings of attentiveness and pleasantness from the SRP task, we conducted two repeated measures ANOVAs with three within-subject variables: 1) SRP task condition, 2) Stimulation condition, and 3) Run (3 levels: Run 1, Run 2, and Run 3). For ratings of blinding effectiveness, we conducted pairwise t-tests comparing the ratings between real vs. sham stimulation sessions. For mood ratings, we conducted mixed ANOVAs with two within-subject factors, including 1) Stimulation condition (2 levels: real and sham), 2) Order (2 levels: pre- and post-session), and one between-subject variable, Group (2 levels: stim-1st and stim-2nd). Considering the number of mDES and BASS items, only results with $p \leq 0.01$ were considered significant for mood rating analysis, while the p-threshold was 0.05 for other analyses. For all analyses, multiple comparisons were corrected using the false-discovery rate (FDR) method for each dependent variable. Participants’ data was only retained for analysis when they had no missing data.

Comparably, referring to EEG analysis, only task conditions that showed significance at the scalp level were then followed up with post hoc source and functional connectivity analyses. We conducted source analysis using the LORETA-KEY software package (www.uzh.ch/keyinst/loreta, Pascual-Marqui et al. 1999), also replicating the previous methods of Bao and Frewen (2022). This involved first computing the cross-spectra for cleaned EEG data tapered using the Hann window function for the alpha band only and then generating 5 x 5 x 5 mm eLORETA maps for each participant’s data using the cross-spectra files and the transformation matrix for the 19-channel electrode montage. For statistical analysis of source data, we used the ‘statistics’ program from the LORETA-KEY software, selecting the option to normalize the eLORETA maps subject-wise, correcting for global sources of variability. We then performed two-tailed paired Wilcoxon signed-ranked tests using the Statistical non-parametric Mapping (SnPM) methodology with 5000 randomizations. Results of the exceedance proportions tests indicating clusters with FDR-corrected $p \leq 0.05$ were considered statistically significant and reported herein. When multiple thresholds were significant for multiple conditions, we chose the highest common significant threshold to maximize specificity.

To group the eLORETA results into clusters, we first exported the t-value and MNI-coordinates of all voxels above the significant threshold from LORETA and converted t-values to effect size r by dividing the t-value by the square root of the number of observations (Pallant, 2020). Then, we used MATLAB’s Statistics and Machine Learning Toolbox (The MathWorks Inc., 2022) for cluster analyses. We determined the optimal number of clusters by evaluating the gap statistics using MATLAB’s evalclusters() function by varying the evaluated cluster from 1 to 52, representing the total number of Brodmann areas noted by eLORETA automated labelling. Then, we conducted agglomerative hierarchical clustering with ward linkage implemented with the MATLAB function clusterdata() by setting “maxclust” to the optimal number of clusters for each condition.

Finally, we also conducted functional connectivity analysis on the SRP conditions that showed statistical significance in scalp alpha power using the LORETA-KEY software package using the identical procedure used in Study 2, Chapter 2. The coordinates of ROIs are listed in Appendix Table 2. Again, the ROIs are all voxels within a 15 mm radius of the seed. Then, the linear lagged connectivity for the alpha band was calculated for each eLORETA file with the Hann window function selected as the mean-corrected discrete Fourier transform taper. Third, the connectivity matrix files were entered into the “statistics” program from the LORETA-KEY package for Wilcoxon signed-rank tests using SnPM with 5000 randomizations. Significant t-thresholds with $p \leq 0.05$ were then entered into the ‘connectivity viewer’ to visualize the significant connectivity results after FDR correction.

4.3 Results

4.3.1 Ratings of mood states and blinding effectiveness

The mood ratings of two participants were removed due to incomplete data (one from each group). Herein, we report all significant results with FDR-corrected $p \leq 0.01$. ANOVA showed main effects of Order for serene ($F(1,48) = 21.7$, p.adj < 0.001), stressed ($F(1,48) = 14.5$, p.adj = 0.003) and confusion ($F(1,48) = 16.0$, p.adj = 0.002). Also, there was a significant interaction of Group by Stimulation condition for awe ($F(1,48) = 18.9$, p.adj < 0.001). Post-hoc analyses of the main effect of Order showed that participants felt less stressed ($\Delta M = -8.1$, $t(50) = 3.84$, p.adj < 0.001), less confusion ($\Delta M = -5.6$, $t(50) = 4.05$, p.adj < 0.001), and more serene ($\Delta M = 9.9$, $t(50) = 4.71$, p.adj < 0.001) after the experiment. Post-hoc analysis of the Group by Stimulation condition interaction showed that participants reported more awe ($\Delta M = 15.7$, $t(24) = 4.00$, p.adj = 0.001) during the real stimulation sessions compared to sham sessions regardless of Order, but only when they were in the group where real stimulation was administered in the first session (stim-1st).

Regarding blinding effectiveness, ratings obtained following real stimulation sessions (M=62%) showed a slightly higher but non-significant ($p = 0.087$) confidence rating in comparison with the sham stimulation sessions (M=49%). Ratings in real stimulation vs. sham sessions neither differed regarding the other two blindness questions, indicating that our blinding procedure was effective (Table 4.1 Results of blinding effectiveness).

Table 4.1 Results of blinding effectiveness

Item	group1	M1(SD)	group2	M2(SD)	t	df	p	p.adj	sig
Real	real	62(30)	sham	49(28)	2.252	48	0.029	0.087	ns
Aware	real	63(24)	sham	62(27)	0.583	48	0.563	0.844	ns
Control	real	57(26)	sham	57(24)	-0.063	48	0.950	0.950	ns

Note. Real = “At the current moment, how much do you experience or feel like you… received a real/true intervention rather than a fake/sham one?”; Aware = “… were aware of what was happening during the intervention?”; Control = “…were in control over what was happening during the intervention?”. ns = not significant.

4.3.2 Ratings of pleasantness and attentiveness during the SRP task

While ratings of pleasantness exhibited a normal distribution, ratings of attentiveness were negatively skewed, indicating that most participants rated high attentiveness throughout the SRP task. Still, we decided to proceed with mixed ANOVA for both variables, given the robustness of ANOVA against violations of normality, but used the non-parametric Wilcox signed-rank tests in post-hoc pairwise comparisons.

Regarding pleasantness ratings, we found no significant differences in SRP task conditions or runs. Comparably, a mixed ANOVA on attentiveness indicated a significant main effect of task condition, $F(2,90) = 16.77$, $p < 0.001$, and run, $F(2,90) = 6.28$, $p = 0.004$, but no interaction between condition and run. All subsequent multiple pairwise comparisons were corrected using the FDR method. Post-hoc pairwise Wilcox tests for the main effect of task condition on attentiveness indicated that consistent with prior results reported in Bao and Frewen (2022), participants reported significantly higher attentiveness during letter counting ($M = 4.23$, $SD = 0.94$) compared to paying attention to their life roles, $M = 3.86$, $SD = 0.96$, $t(51) = 174.0$, $p < 0.001$, or outer body ($M=3.93$, $SD = 0.94$), $t(51) = 203.5$, $p < 0.001$, while participants' reported that their attentiveness did not differ between the life roles and outer body conditions, $t(51) = 354.5$, $p = 0.23$. Post-hoc matched-pairs Wilcox signed-rank tests for the main effect of run on attentiveness indicated that participants paid significantly greater attention during run 1 ($M = 4.14$, $SD = 0.84$) compared to run 3 ($M = 3.91$, $SD = 1.02$), $z(51) = 903.0$, $p = 0.01$. Meanwhile, participants' self-reported attention during run 2 ($M = 3.96$, $SD = 0.98$) did not significantly differ from their attention ratings during run 1, $z(51) = 665.5$, $p = 0.10$, or run 3, $z(51) = 520.5$, $p = 0.40$.

4.3.3 Scalp-level EEG results

Spectral Power

Herein, we only report significant main effects or interactions that involve stimulation conditions in text, with the full results detailed in Appendix Table 6 to Appendix Table 8. After imputing only a single outlier to the 75th quantile + 1.5 * inter quantile range, mixed ANOVA showed significant three-way interactions between group, SRP task condition, and stimulation condition for 6 of the 19 electrodes (Fz, F4, T3, T4, T6, and O1; see Appendix Table 6). Post-hoc two-way ANOVA showed FDR-corrected significant interaction effects between SRP task condition and stimulation condition only for the group that received real stimulation during the second session for the following 3 of those electrodes: Fz, T4, and O1 (Appendix Table 7, Figure 4.3). Finally, follow-up t-tests revealed that real stimulation lowered alpha power among those who received stimulation during the second session compared to sham stimulation during the outer body and the external attention condition only at 2 of those 3 electrodes: Fz and O1 (Appendix Table 8, Figure 4.3). Comparably, no significant results were found for the life roles or resting state conditions. Finally, direct comparisons of the significant change in alpha power between the outer body and external attention conditions did not yield any significant results.

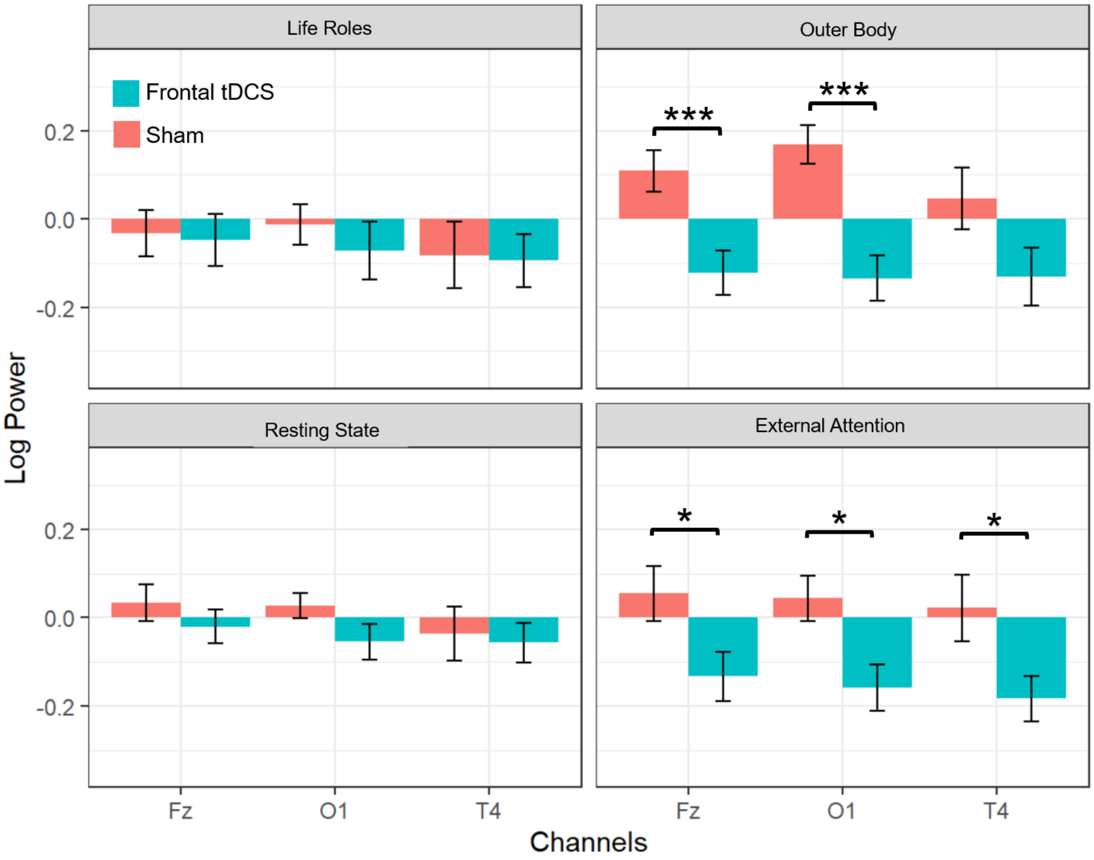


Figure 4.3 Graphical illustration of significant results on scalp-level EEG for frontal tDCS for the group where participants received real stimulation after the sham session (stim-2nd). *: $p<0.05$; **:$p<0.01$; ***:$p<0.001$.

Phase Synchrony

ANOVA of the six ITC variables showed a significant main effect of stimulation condition on the ITC between the frontal and left-posterior OM, F(1,50) = 8.10, p.adj = 0.042. Post hoc analysis showed that tDCS increased the ITC between the frontal and left-posterior OM compared to sham, t(52) = 2.84, p.adj = 0.006, Cohen's d = 0.40.

4.3.4 Source-level EEG results

Since only the outer body and external attention conditions showed a statistically significant reduction of alpha power on the scalp level, we reserved the conduct of eLORETA source localization and further statistical analyses on data segments corresponding to those two conditions. The exceedance proportion test comparing real vs.

sham stimulation showed the highest common two-tailed significant t-threshold = 1.730, with corresponding p = 0.035 for the outer body and with p = 0.038 for external attention (Figure 4.4). The cluster analyses revealed 8 clusters for the outer body condition and 17 for the external attention condition. The results of hierarchical clustering analyses are summarized in Table 4.2. Compared to sham, tDCS resulted in reduced alpha in the outer body condition in 8 clusters whose centroids were the bilateral premotor cortex, the primary somatosensory cortex, the bilateral superior frontal cortex, the mid and posterior cingulate cortex, the left orbitofrontal cortex, the left temporal pole, the left prefrontal cortex, and the left superior and inferior parietal lobule. For the external attention condition, tDCS reduced alpha power in 17 clusters compared to sham, whose centroids were the bilateral frontal eye field, the bilateral supplementary motor area, the premotor cortex, the primary somatosensory cortex, the left premotor cortex, the bilateral superior parietal lobule, the bilateral parahippocampal gyrus, the mid and posterior cingulate cortex, the left orbitofrontal cortex, the right inferior parietal lobule, and the right superior temporal gyrus.

Regarding functional connectivity, the exceedance proportion test comparing real vs. sham stimulation showed a significant reduction of linear lagged connectivity between the ventral PCC and the left IPL during the outer body condition (two-tailed threshold = 2.90, p = 0.03). No significant results were seen for the external attention condition.

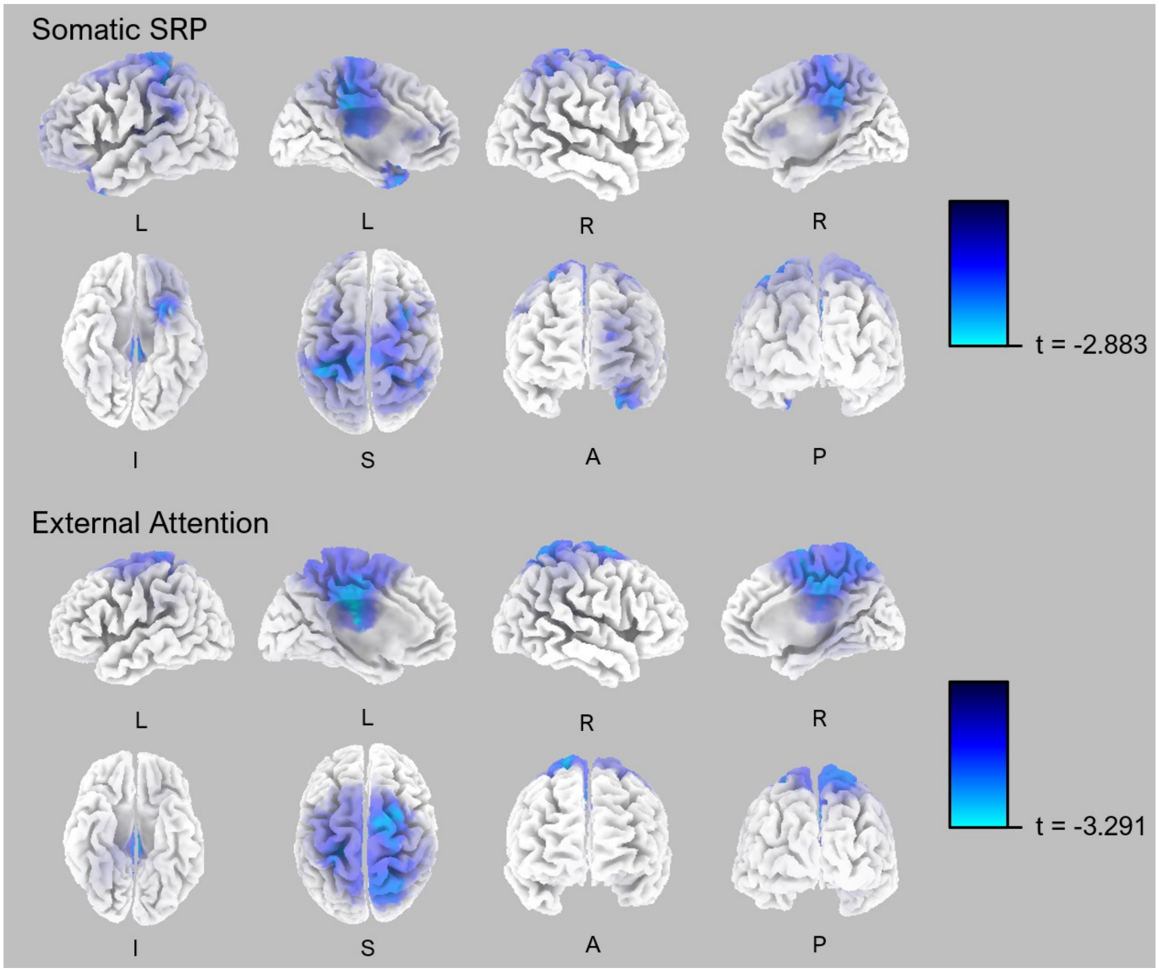


Figure 4.4 Visualization of source-level results from the eLORETA exceedance proportion tests. Abbreviations: L = left, R = right, I = inferior, S = superior, A = anterior, P = posterior. For somatic SRP (outer body), the significant t-threshold = 1.730, p = 0.038; for external attention (counting "X"), the significant t-threshold = 1.730, p = 0.035. Since no significant increase of alpha power was observed, the colour bars only indicate the negative t-values shown in blue.

Table 4.2 Results of hierarchical clustering of significant voxels from eLORETA exceedance proportion tests

Structure labels	Cluster Size	Effect size r	Brodmann Areas	X	Y	Z
Outer Body						
R frontal eye field, R premotor cortex	127	-0.277	6, 24, 9, 4, 8, 3, 32	30	0	55
L frontal eye field, R premotor cortex	136	-0.277	6, 4, 8, 3	-30	0	60
L/R primary somatosensory cortex, posterior cingulate cortex	290	-0.308	31, 6, 3, 5, 7, 24, 23, 32	0	-15	50
L orbitofrontal cortex, L temporal pole	170	-0.285	38, 47, 13, 28, 20, 34, 36, 11, 45, 25, 10	-30	20	-20
L prefrontal cortex	144	-0.258	10, 9, 24, 32, 33, 11	-15	50	10
R primary somatosensory cortex	309	-0.284	5, 31, 7, 3, 2, 4, 40, 6, 1	25	-45	55
L primary somatosensory cortex	330	-0.293	40, 3, 2, 4, 5, 6, 7, 31, 19, 18	-15	-50	55
L superior and inferior parietal lobule	314	-0.286	3, 1, 40, 2, 4, 13, 6, 22, 41, 7, 42, 21	-45	-35	40
External Attention						
L primary somatosensory cortex	165	-0.272	4, 3, 40, 6, 2, 1	-45	-30	45
L primary somatosensory cortex	86	-0.347	3, 4, 2, 40, 5, 6, 1, 7	-25	-40	60
L/R primary somatosensory cortex	110	-0.381	31, 6, 5, 7, 4, 3	5	-35	60
L superior parietal lobule	106	-0.321	5, 3, 7, 4, 31	-10	-55	55
L frontal eye field	75	-0.361	6, 24	-15	-10	65
R frontal eye field	91	-0.333	6, 4	30	-5	60
L premotor cortex	98	-0.307	6, 4	-35	-5	50
L parahippocampal gyrus	25	-0.262	13, 30, 29, 27	-25	-35	10
R parahippocampal gyrus	146	-0.266	27, 28, 30, 35, 19, 37, 36, 29, 20, 18, 34, 31	25	-40	-10
L/R posterior cingulate cortex	112	-0.293	23, 31, 7, 30, 29	0	-50	30
R superior temporal gyrus	56	-0.265	13, 41, 39, 22, 37	40	-40	15
R inferior parietal lobule	159	-0.276	5, 40, 7, 2, 13, 3, 39	50	-45	45
R primary somatosensory cortex	155	-0.319	5, 7, 4, 3, 2, 40, 6, 1	35	-30	55
L/R mid cingulate cortex	168	-0.389	23, 31, 24, 6, 7, 5	0	-20	45
L/R supplementary motor area	145	-0.333	6, 24, 32, 8	0	5	55
L orbitofrontal cortex	25	-0.247	47, 13, 45, 11	-25	25	-10
R superior parietal lobule	147	-0.333	7, 5, 40	15	-60	55
Note. XYZ-values represent coordinates of the centroid of the cluster in MNI space						

4.4 Discussion

The objective of this study was to evaluate the subjective and neuroelectrophysiological (EEG) effects of MPFC-tDCS on both semantic and somatic SRP, compared to a resting state and external attention control conditions. We explored the effects of MPFC-tDCS on self-report measures, including ratings of pleasantness, attentiveness, and mood. Further, we explored changes in source-level EEG spectral power and functional connectivity as a post hoc analysis only for those experimental conditions that showed significant scalp-level changes in alpha activity. To our knowledge, this is the first MPFC-tDCS study on SRP to include not only self-report outcomes but also measurements of EEG.

Our results align with prior literature showing that MPFC-tDCS may be insufficient to produce alterations in self-reported affective experience in response to semantic or somatic SRP. However, MPFC-tDCS resulted in significant reductions in alpha-EEG during somatic SRP and a non-SRP (external attention) task primarily in PCC, somatosensory cortex, premotor cortex, and parietal lobule when compared to sham stimulation, and reduced functional connectivity between the ventral PCC and left IPL. Comparably, no differences were seen for EEG outcomes during semantic SRP or resting state. The current study provides insight into the question of what aspects of SRP may be modulated by MPFC-tDCS.

4.4.1 MPFC-tDCS did not affect self-report outcomes of SRP

Participants reported increased positive emotion (feeling serene) and decreased negative emotions (feeling scared, stressed, and confused) over the course of the experimental sessions, regardless of stimulation condition (real MPFC-tDCS vs. sham stimulation) or whether it was the first or second experimental session. This pattern of mood changes is consistent with a previous study that also found participants felt more positive affect (awe, joy, gratitude, serenity, insight, and oneness) and less negative affect (sadness, confusion, embarrassment, stress) after completing the same combined semantic and somatic SRP task used herein without NIBS (Bao & Frewen, 2022). As such, the current findings suggest that tDCS did not augment the significant mood changes that will often occur simply as a result of semantic and somatic SRP alone.

As such, the current results are consistent with several prior investigations that failed to show positive results for MPFC-tDCS on self-report and behavioural outcomes of SRP, at least as regards semantic SRP. Indeed, while Yin et al. (2021) found cathodal VMPFC-tDCS attenuated self-referential memory, three other studies failed to find an effect of MPFC-tDCS on similar tasks (Burden et al., 2021; Mainz et al., 2020; Schäfer & Frings, 2019). Moreover, our findings suggest that MPFC-tDCS may also be insufficient to modulate the subjective outcomes of somatic SRP, at least in terms of participants' experience of pleasantness, attentiveness, and mood.

4.4.2 MPFC-tDCS reduced alpha-EEG during somatic SRP and external attention

In stark contrast, our EEG data showed that MPFC-tDCS significantly reduced alpha band power, specifically during the somatic SRP and external attention conditions across multiple brain regions. An explanation of the effect of MPFC-tDCS requires an understanding of the mechanism of action of tDCS. Previous evidence has established that low-dosage tDCS, such as that used in the current study (<5-6 mA), induces indirect neural spiking by modulating membrane potentials and potentially alters spike timing and plasticity (Kronberg et al., 2017). Because tDCS does not directly induce spiking, changes in neural firing rates may be results of stochastic and rhythm resonance, so the effect of tDCS interacts with the state of the neural network during the stimulation period (Bikson et al., 2013; Liu et al., 2018). In our experiment, although we did not measure EEG during the stimulation, we assume that the DMN and other brain regions involved in SRP will be active throughout the duration of the stimulation due to its being conducted during body-focused meditation practices and over the course of the second run of the SRP task.

Suppose our assumption that participants will predominantly occupy a DMN-like state throughout the experiment is reasonable. In that case, our findings of the reduction of alpha activity as a result of MPFC-tDCS may be understood in the context of the dynamics of resting-state alpha activity within the DMN. For example, an independent component analysis (ICA) of resting-state alpha activity within the DMN found two alpha components with significant overlap in the PCC, where one component included the PCC, precuneus, and bilateral IPL, and another component included the PCC and the MPFC (Bowman et al., 2017). Importantly, Bowman et al. also found that the PCC-precuneus-IPL component was the only component that was positively correlated with the BOLD signal within the DMN, whereas the PCC-MPFC was negatively correlated with the DMN BOLD signals. Given our findings, it is possible that MPFC-tDCS resulted in stochastic resonance that then increased the spiking of MPFC and PCC activity during the stimulation through network communication in the PCC-MPFC component. Further, as an aftereffect, alpha power may have been reduced through its connection with the IPL through the PCC-precuneus-IPL component, which was observed in both somatic SRP and external attention conditions in the current study. Such an explanation coincides with the known general inhibitory function of the MPFC on other brain regions. Therefore, our results regarding alpha reduction in the bilateral IPL as a result of MPFC-tDCS may extend the findings from BOLD studies of the DMN to emphasize the role of alpha oscillation in the modulatory effects of the MPFC. Next, we will discuss the specific effects of MPFC-tDCS on somatic SRP and external attention conditions.

4.4.2.1 Somatic SRP

Our prior EEG study using the same task found that somatic SRP involved alpha activity when comparing SRP conditions with both external attention and resting state that appear to differ from those affected by MPFC-tDCS in the current study (Bao & Frewen, 2022). For example, considering the contrast between somatic SRP and external attention examined by Bao and Frewen (2022), somatic SRP was maximally associated with increased alpha in the right frontotemporal cortex, including the right insula and the right IFG. Meanwhile, for the most part, MPFC-tDCS in the current study did not modulate alpha activity in right frontotemporal regions (Figure 3). Given that the contrast between somatic SRP and external attention in our previous study represented the internal attention component of somatic SRP, our current findings may suggest that this aspect of somatic SRP was relatively unaffected by MPFC-tDCS. Moreover, considering the contrast between somatic SRP and the resting state in the prior research of Bao and Frewen (2022), somatic SRP was found to be associated with decreased alpha in the left frontotemporal cortex and a slight increase of alpha in the right temporoparietal cortex, indicating hemispheric lateralization in the on-task component of somatic SRP. Meanwhile, the current study failed to observe a lateralized effect of MPFC-tDCS during somatic SRP because alpha was reduced in both hemispheres within the parietal cortex. Thus, it may be premature to suggest that MPFC-tDCS directly altered the task-specific aspects of somatic SRP in the current study compared to external attention and resting state controls, especially given the overlap between on-task and at-rest SRP (Kim, 2012).

In contrast, when considering the contrast between semantic and somatic SRP in the study by Bao and Frewen (2022), somatic SRP was associated with increased alpha in the right premotor cortex and the right superior parietal cortex, which partially overlaps with the effect of MPFC-tDCS in the current study. These comparable findings suggest a potential effect of MPFC-tDCS on modulating brain regions involved in SRP of internal somatic signals as compared with SRP at a psychological level, such as evaluating oneself in reference to various life roles.

A possible additional explanation of our findings on the effect of MPFC-tDCS on somatic SRP entails attentional inhibition that may be required during somatic SRP. Research has shown the role of alpha in the top-down processing of attention by inhibiting task-irrelevant signals and facilitating task-specific signals (Foxe & Synder, 2011; Van Diepen et al., 2019). This interpretation coincides with our finding that the effect of MPFC-tDCS reduced alpha power outside of the areas needed for the internal attention component of somatic SRP. Specifically, we found that MPFC-tDCS reduced alpha connectivity between the left IPL and the ventral PCC, in addition to observing the reduction of alpha activity in the left IPL during somatic SRP while not during the external attention task. The association between MPFC-ventral PCC connectivity and attentional control (Leech et al., 2011; Leech & Sharp, 2014) may further suggest an alteration of attentional inhibition of task-irrelevant signals during somatic SRP as a result of MPFC-tDCS. However, it must still be treated with caution, given recent evidence that alpha increasing did not cause a suppression of distraction (Antonov et al., 2020).

4.4.2.2 External Attention

In addition to the modulatory effect of MPFC-tDCS on somatic SRP, we also observed reduced alpha activity during the external attention task performance. Regarding the contrast between external attention and internal attention, Bao and Frewen (2022) found that external attention was associated with reduced alpha in the bilateral frontotemporal cortex, with the maximum distinction in the bilateral inferior frontal gyrus. Comparably, in the current study, MPFC-tDCS mostly reduced alpha in the parietal cortex during external attention and appeared not to have selectively impacted regions that distinguish internally vs. externally focused attention, as our previous EEG study documented.

This may be consistent with our observation that participants showed near-perfect accuracy in the external attention task and consistently reported generally neutral to pleasant affect throughout different task conditions. Thus, while our task required participants to toggle between internally and externally repeatedly focused attention, we suspect that participants were likely easily able to do so.

Switching between SRP, such as during the resting state and an external attention task, is thought to be partially mediated by activities within the DMN and dorsal attention network (DAN) that may correlate to alpha activities. For example, a large resting state connectivity study between the DMN and DAN found higher peak alpha frequency was correlated with the anti-correlation between the DMN and DAN, and that participants with intrinsically higher alpha peak frequency showed higher within-DMN and DAN connectivity (Tripathi & Somers, 2023). Further, within the DMN, alpha activity was found to positively correlate with the suppression of attention to the external environment and internal distracting sensory processing (Foxe & Synder, 2011; Payne & Sekuler, 2014). Such findings are important because, in our experiment, MPFC-tDCS appears to have reduced alpha activity across the dorsal and parietal regions of the DAN (Figure 3). Therefore, during the external attention task, it is possible that MPFC-tDCS attenuated the “switching” between DMN and DAN, albeit the interpretation is complicated by a lack of significant differences between rated levels of attentiveness between real and sham stimulation sessions. The use of time-sensitive measurements of attention, such as reaction time or event-related potential, could be used in future studies to disambiguate the effect of MPFC-tDCS on EEG alpha, attentional switching, and the relationship between DMN and DAN activity.

4.4.3 MPFC-tDCS failed to reduce alpha-EEG during semantic SRP or resting state

While MPFC-tDCS significantly reduced alpha-EEG in various brain regions during both somatic SRP and external attention, no changes in alpha-EEG were seen during semantic SRP or resting state. This pattern of results implies an unexpected distinction between the high receptivity of alpha-EEG during somatic SRP and external attention tasks to MPFC-tDCS, on the one hand, and the low receptivity of alpha-EEG during semantic SRP and resting state to MPFC-tDCS, on the other. Here, during both somatic and external attention conditions, participants were instructed to attend to concrete stimuli, such as the sensations on their arms or the number of times they heard a particular letter. On the other hand, during the semantic SRP condition, participants self-evaluated themselves in reference to abstract concepts such as “friend” and “student”, while during the resting state, participants simply allowed their minds to wander. With these distinctions in mind, it may be that MPFC-tDCS was more effective in reducing alpha activity associated with processing concrete stimuli, whether they are self-referential in nature or not, in comparison with SRP at an abstract or conceptual level. Future research will be required to test this hypothesis directly, perhaps utilizing a task that requires responding to both concrete and abstract self-referential and non-self-referential stimuli.

4.4.4 DMN nodes and phase synchrony affected by MPFC-tDCS

We observed that MPFC-tDCS reduced the functional connectivity between the left IPL and the PCC, and MPFC-tDCS increased the phase synchrony between the left-posterior and the frontal OMs. Since the changes in phase synchrony were not specific to task conditions, our findings may reflect the general effects of MPFC-tDCS on the DMN but are not specific to SRP. Again, mapping of alpha correlations with ICs during the resting state found four ICs within the DMN and one MPFC-precuneus-IPL IC showed positive correlations with alpha activity (Bowman et al., 2017). Since both ICs are positively correlated with alpha activity, our findings may suggest that MPFC-tDCS may strengthen the intrinsic connectivity in alpha synchrony at rest between the frontal and left posterior regions of the DMN.

Regarding the effects of tDCS on DMN functional connectivity, a surprising but important finding was that we did not observe any direct effects of MPFC-tDCS on the MPFC at the source level but rather only on other brain regions. Such results may imply that the results of MPFC-tDCS are exhibited primarily across network-wide communications rather than localized effects at the stimulation site. Considering the IC, including both the MPFC and PCC that showed a negative correlation with alpha activity in Bowman et al. (2017), MPFC-tDCS may have produced changes in the PCC via this MPFC-PCC component during somatic SRP, which may explain the reduction of functional connectivity. Overall, the functional organization of ICs within the DMN described in Bowman et al. (2017) may help explain the reduction of functional connectivity and increase of phase synchrony between the frontal and left-posterior Oms observed in the current research, given the negative and positive correlations between the component and alpha activity. When considered together, our findings may suggest that the MPFC-PCC component may be specifically susceptible to modulation during somatic SRP, while the MPFC-precuneus-IPL IC may reflect more general changes as a result of MPFC-tDCS.

Nevertheless, the lack of direct changes in aftereffects on alpha source power in the MPFC in our study contrasts with findings from studies that stimulated the occipitoparietal cortex and found significant changes in alpha and BOLD signals as the aftereffect directly underneath the area of stimulation (Vosskuhl et al., 2016; Clancy et al., 2022). Such differences in aftereffects may be explained by the endogenous organization of functional connectivity within the DMN during SRP. Through dynamic causal modelling during semantic SRP, Davey et al. (2016) found that MPFC exhibited both endogenous and modulatory effects in the negative direction, seemingly congruent with our finding that MPFC-tDCS reduced brain oscillatory activity in the ventral PCC.

Therefore, future MPFC-tDCS studies on SRP may need to carefully consider the long-range effects of MPFC-tDCS as a result of network-wide connectivity in addition to the local effects at the area of stimulation when choosing stimulation montages.

Finally, our findings highlight the left IPL as a region that may be susceptible to the modulatory effects of MPFC-tDCS, particularly when examining outcomes during somatic SRP. Other studies have also successfully modulated SRP as a result of altering activity within the left IPL. For example, a prior single-pulse TMS study also found that stimulation over the PZ location decreased cerebral blood flow in the left IPL during semantic SRP (Lou et al., 2004). Further, Hari et al. (2023) directly targeted the left IPL with tDCS and observed that cathodal tDCS reduced participants' self-bias towards auditory signals.

A recent dynamic causal modelling study may help elucidate the role of left IPL, albeit in the context of semantic SRP (Delahoy et al., 2022). In Delahoy et al.'s study, participants were asked to engage in either direct self-appraisal (e.g., "Would you describe yourself with this word?") or reflected self-appraisal (e.g., "Would others describe you with this word?"). The researchers found that the left IPL exhibited negative modulatory effects toward the PCC only during reflected self-appraisal. Here, our results continue to highlight a possible role for the left IPL in not only the semantic but also somatic aspects of SRP that is modifiable by MPFC-tDCS.

4.4.5 MPFC-tDCS affected alpha-EEG during somatic SRP and external attention tasks during the second experimental session, but not during the first experimental session

It is important to point out that the effects of MPFC-tDCS on EEG alpha during somatic SRP and external attention were only apparent when real stimulation was applied at the second session; in other words, no differences were seen between MPFC-tDCS vs. sham stimulation when applied at the first session, implying a session order effect. Such results were surprising insofar as the two testing sessions used identical testing procedures.

The finding of an order effect may be important insofar as most prior studies of MPFC-tDCS have only utilized a single experimental session and a between-subjects design

(Bao et al., 2022). As a result, future studies should consider the use of multiple testing sessions to evaluate the effects of MPFC-tDCS on SRP. Further, while unexpected, one interpretation of the order effect seen in the current research is that participants may be more sensitive to MPFC-tDCS in the second session after already having been familiarized with the experimental procedures during the first session. In other words, while the general novelty of the experimental procedures may provide a less receptive state for MPFC-tDCS modulation of SRP, the practice and familiarity gained at the first session may facilitate a greater receptivity to MPFC-tDCS augmentation at the next session. These considerations may bear on the design of future multi-session investigations of the outcomes of MPFC-tDCS on SRP.

4.4.6 Study limitations

Our study has several limitations. First, our small, young, and culturally diverse sample from a university student population limits the generalizability of our findings. Importantly, cultural heterogeneity may influence semantic SRP, given that multiple studies found the mediating effect of Western vs. Eastern culture on alpha oscillation and semantic SRP (Kraus et al., 2021; Knyazev et al., 2021; Salvador et al., 2022). Regarding our experimental procedure, we also did not control for the impact of eyes open vs. eyes closed states; participants were always tested in the latter state, and thus, our results may not generalize to states in which participants' eyes are open. Further, we did not account for the effect of room illumination on alpha activity in our procedure, which may have a considerable impact on parietal alpha EEG during attention tasks (Min et al., 2013). These environmental variables may have mediating or confounding effects in the context of MPFC-tDCS of SRP and should be better accounted for in future studies.

Regarding the brain stimulation montage, since we randomized the anode/cathode placement between AF7 and AF8, we could not conclude whether the changes in EEG were results of increase of decrease of neural excitability in the MPFC. A past study showed that the direction of electric current flow can be important for a stimulation montage specific for M1 (Rawji et al., 2018). Meanwhile, another study pointed out that the impact of current direction is heavily influenced by individual variability, choices of stimulation montages, and the polarity stimulation (Naros et al., 2016; Evans et al., 2022). Therefore, future tDCS studies should carefully consider the impact of current flow and its related factors to further our understanding of the mechanisms of action of tDCS on neurobiological and behavioural outcomes.

Regarding our statistical analysis, we were only able to investigate simple effects on a source level instead of interaction effects. In the same vein, we focused our analysis on the alpha oscillation based on the strong support for its role in SRP to limit multiple comparisons, but SRP is not limited to the alpha band. For example, in our prior investigation of the EEG correlates using the same experimental task, we also found the involvement of the theta band when comparing semantic SRP with resting states (Bao et al., 2022). Additionally, other studies also found involvement of the gamma band during various SRP tasks (Mu & Han, 2010; Berkovich-Ohana et al., 2012). Therefore, future studies are recommended to examine multiple EEG bands to investigate the impact of MPFC-tDCS on SRP comprehensively with a larger sample.

4.4.7 Conclusion

Despite these limitations, to our knowledge, this study is the first to investigate the impact of MPFC-tDCS on both semantic and somatic SRP and to include measurements of EEG. We found that during an eyes-closed SRP task, whereas no results were seen for semantic SRP, MPFC-tDCS reduced alpha activity in the frontal eye fields, the sensorimotor regions, and posterior-parietal regions during somatic SRP and external attention, with further reductions of functional connectivity between the left IPL and the ventral PCC unique to somatic SRP. Moreover, these effects of MPFC-tDCS were present only when real stimulation was applied at the second session after receiving sham stimulation during the first session, while not in the reverse order. Such results imply that the effect of NIBS on SRP may be subtle and complex, dependent on past experience, and varying by the psychological and physical dimensions of the sense of self being assessed. Our study highlighted the importance of measuring neurophysiological signals in future investigations of NIBS' effects on SRP and the importance of including somatic SRP as well as external attention controls in experimental designs.

Chapter 5

5 The Effects of MPFC and IPL 10-Hz transcranial alternating current stimulation (tACS) on alpha-EEG during SRP

5.1 Introduction

In Chapter 2, I reviewed NIBS studies that sought to modulate SRP systematically and summarized the regions of interest of past semantic and somatic SRP-NIBS studies. Then, in Chapter 3, I presented an EEG study on SRP that found the strong involvement of the alpha oscillation during SRP. Therefore, in Chapter 4, I analyzed the changes of alpha oscillation as a result of MPFC-tDCS, which, while insufficient to modulate self-reports in response to SRP, itself consistent with the null results reported in several previous tDCS studies, was sufficient to modulate alpha EEG in several brain regions of interest to SRP.

Considering the results of the previous chapters together, it seems that the alpha oscillation is not only involved in differentiating domains of SRP but also susceptible to the impact of tDCS applied over the MPFC. These findings further support the significant role of alpha in SRP and suggest that future NIBS studies may focus on the alpha oscillation to modulate neural correlates of SRP.

However, tDCS does not modulate brain activity in a frequency-specific manner, and so in order to further explore the role of alpha during SRP, we continue our investigation in the current chapter using transcranial alternating current stimulation (tACS). Currently, tACS still remains unexplored in SRP despite its potential to stimulate the brain in a frequency-specific manner, with the same merits as tDCS in its accessibility, cost-effectiveness, and portability.

In brief, tACS delivers currents by alternating the anode and cathode at a user-defined frequency. Compared to tDCS, tACS delivers frequency-specific current at nearly twice the amplitude (Ghafoor et al., 2021). In this view, tACS may be a more effective tool for modulating the alpha frequency associated with SRP than tDCS. Similar to tDCS, tACS does not directly induce action potential, but it changes the timing of neural firing by altering neuronal membrane potentials (Vöröslakos et al., 2018).

Although the exact mechanisms of tACS on neural activity have not been understood, the current understanding suggests entrainment as the online mechanism and neural plasticity as the offline mechanism. Entrainment facilitates alignments of phase angles to the stimulating frequency for the duration of the stimulation (Elyamany et al., 2021). For offline effects, tACS may cause neuroplasticity changes via neural spike timing with excitatory or inhibitory effects based on the difference between the stimulating frequency and the brain's intrinsic dominant frequency (Vossen et al., 2015).

In the previous chapter, we also found that tDCS did not modulate alpha during SRP near the area of stimulation but rather at distant regions in the brain, perhaps through communication within and across neural networks. Meanwhile, we could not generalize such distant effects of brain stimulation from only one stimulation site. We also know from other tES studies that the effect of tES varies based on stimulation location, but such differential effects have not been explored in the context of SRP.

Therefore, in the current study, we seek to use tACS not only over the same regions stimulated in the tDCS study but also over another important region of the DMN, specifically over the bilateral IPL, in order to investigate the differential effects based on stimulation montage.

The current study

As described in Chapter 3, a resting state EEG-fMRI study found several BOLD ICA components to be significantly correlated with alpha activity within the DMN at rest (Bowman et al., 2017). Specifically, two components involving the MPFC showed significant correlations with alpha: an MPFC-PCC component and an MPFC-insula component. The MPFC-PCC component showed a negative correlation with alpha power, while the MPFC-insula component showed a positive correlation with alpha power. Given the close relationship between the DMN and SRP, and that we found a strong involvement of alpha in the SRP task described in Chapter 2, and the results of the

MPFC-tDCS study in Chapter 3, we expected that alpha-tACS over the MPFC could invoke network-wide changes in either direction during the SRP task, depending on the experimental condition (e.g., semantic vs. somatic) and the experimental session (i.e., first vs. second).

In addition to alpha-tACS over the MPFC, we explored the effects of alpha-tACS on the bilateral IPL in the current chapter, given that the previous MPFC-tDCS study showed changes in alpha power in the bilateral IPL and changes in functional connectivity between the left IPL and the PCC. Additionally, the significance of bilateral IPL has been shown in the functional organization of alpha oscillation within the DMN. In the previously cited alpha EEG-fMRI study, Bowman et al. (2017) also found a PCC-ACC-precuneus-IPL component that exhibited a positive correlation with alpha, overlapping with the MPFC-PCC component. Therefore, both MPFC and IPL alpha-tACS may influence DMN activity through the PCC hub and potentially modulate SRP throughout the process.

Another reason to target the IPL in the context of SRP is the mixed results of past NIBS studies that targeted IPL. From our systematic review, in the semantic SRP domain, two studies investigated the effect of TMS on the left and right IPL using similar experimental paradigms and found different results on reaction time and task performance accuracy (Lou et al., 2010; Luber et al., 2012). Then, twelve NIBS studies targeted the left and right IPL in the somatic SRP domain with four null findings and eight positive findings under different experiment paradigms, including self-other discrimination and rubber hand illusion (Figure 2.5, Figure 2.6).

Importantly, regardless of stimulation montage, no past study, to our knowledge, has targeted the alpha oscillation with tACS. From this perspective, the mixed results from NIBS studies in SRP might be potentially due to the lack of frequency specificity from past studies, which may be resolved by stimulating at the alpha frequency that has been found to be highly relevant to SRP in our investigations. Indeed, studies have already demonstrated the efficacy of 10 Hz alpha-tACS on modulating local alpha power at the resting state by targeting both the prefrontal and the parietal cortex (Ghafoor et al., 2021; Clancy et al., 2022).

Therefore, I describe two experiments in the current study where we applied 10 Hz tACS over the MPFC in Study 1 and the bilateral IPL in Study 2. We chose 10Hz as the stimulated frequency, given that the average peak alpha frequency is usually around 10Hz for a young adult sample (Haegen et al., 2014; Grandy et al., 2013). Although studies advise that tACS may be most effective when targeting the participants' peak frequency, also known as the individual alpha frequency (IAF), for maximum modulatory effects, we decided to use the same frequency across both studies. This decision was made to ensure comparability between the two studies because the IAF measured from the parietal sites is likely to be higher than that from the frontal site. For example, De Koninck et al. (2021) measured different mean IAF between their frontal (M = 9.48 Hz) and parietal (M = 9.63 Hz) sites.

Since we stimulated the brain at 10 Hz, we will report all EEG parameter outcomes (power, coherence, and synchrony) at 10 Hz for the current study. Through EEG source localization, we also aim to explore the potential impact of tACS on the spatial distribution of 10 Hz alpha during SRP. We hypothesized that 10Hz-tACS over the MPFC and bilateral IPL will modulate 10 Hz power and functional connectivity within the DMN and related ROIs when we compare pre-stimulation with post-stimulation EEG under our SRP paradigm. In addition to spectral power analysis of 10 Hz alpha, we also continue to explore the changes in its coherence and phase synchronization as a result of tACS during the SRP task, given that tACS has shown efficacy in modulating coherence and phase synchronization both locally and within functional brain networks (Negahbani et al., 2019; Huang et al., 2021; Orendáčová & Kvašňák, 2021). Finally, given the results of our prior MPFC-tDCS study, we were aware that our results might be moderated by session order.

5.2 Methods

5.2.1 Participants

Undergraduates enrolled in psychology courses at Western University participated for partial course credit. Forty-seven participants who enrolled in study 1 received tACS over the MPFC, while forty-nine participants who enrolled in study 2 received tACS over the bilateral IPL. All recruitment procedures were identical, and the studies were conducted simultaneously. However, participants were not fully randomized to these groups and, as a result, while differences may be directly comparable as a result of stimulation montages, we have refrained from doing so here and only report the two sets of results separately.

Within our sample, 97% of participants were between 18 and 22 years old, and 66% were female. The reported ethnicity of participants was as follows: White (41%), Chinese (16%), South Asian (16%), multiple (7%), Arab (4%), Black (3%), other (3%). Within our sample, 72% of participants indicated being Canadian citizens born in Canada, 17% were Canadian citizens born outside of Canada, 4% were first-generation permanent residents of Canada, and 7% were international students.

5.2.2 Study procedures and materials

We aimed to test the effect of alpha (10Hz) tACS compared to sham stimulation for frontal (MPFC) stimulation in study 1 and parietal (IPL) stimulation in study 2. Study 1 and 2 followed the same experimental procedure except for the stimulation location. The experimental procedures were identical to the tDCS protocol described in Chapter 3, except that the current study used 10Hz-tACS.

As was conducted in the previously reported MPFC-tDCS study, all participants underwent two experimental sessions (real and sham) that were held at least 24 hours apart. The order of real vs. sham stimulation was counterbalanced for both stimulation sites. In study 1 (frontal stimulation), 23 participants received real stimulation at session 1, and 24 participants received real stimulation at session 2. In study 2 (parietal stimulation), 24 participants received real stimulation at session 1, and 25 participants received stimulation at session 2.

5.2.3 tACS parameters

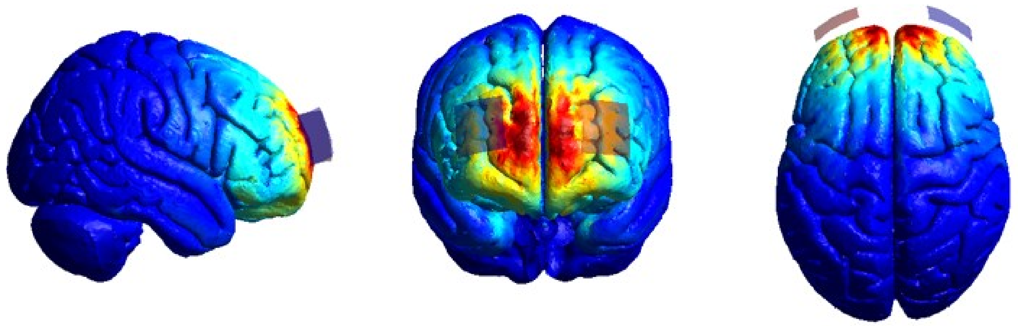
For study 1, electrodes were positioned at international 10-20 system positions AF4 and AF3 as had been conducted in the MPFC-tDCS study. For study 2, electrodes were positioned at CP3 and CP4. Positioning over AF4 and AF3 again maximized stimulation to the MPFC, while positioning over CP3 and CP4 maximized stimulation to the bilateral IPL, respectively, based on computer modelling (SimNIBS software version 4.0.0; Thielscher et al., 2015; see Figure 5.1). The electrodes in the position of the anode versus cathode were randomized every session due to their nearly identical effects on electric current density, as noted in Figure 5.1.

Brain stimulation (real or sham) again began immediately after the first run of the SRP task and over the course of the second run of the task, which was in turn preceded and followed by breathing-focused sessions of about 7 minutes; thus, the alpha tACS lasted a total of 20 minutes for each experimental session. For both studies, 2mA-tACS at 10 Hz was delivered using the same equipment used in the MPFC-tDCS study, specifically, the neuroConn DC-Stimulator-Plus (neuroConn, Ilmenau, Germany). Again, we elected to use 3 X 3 mm rubber pads coated with approximately 1 mm of Ten20TM conductive paste (Weaver & Co., Aurora, CO). We used the same stimulating frequency for frontal and parietal sites to ensure the comparability between the two stimulations.

During real stimulation, tACS was delivered for 20 minutes with 15 seconds for ramp-up and ramp-down. For sham stimulation, the current ramped up during the initial 15 seconds but ramped down for the next 15 seconds, followed by continuous impedance checks for the remainder of the 20-minute period (requiring only a 110 μA pulse to occur for 15 ms every 550 ms).

Double-blindness was again implemented using the STUDY mode of the DC-Stimulator-Plus, while blinding effectiveness in the participants was assessed at the end of every session via self-report questions. Such procedures were identical to those used in our MPFC-tDCS study.

a) Study 1: Frontal stimulation (AF3, AF4)



b) Study 2: Parietal stimulation (CP3, CP4)

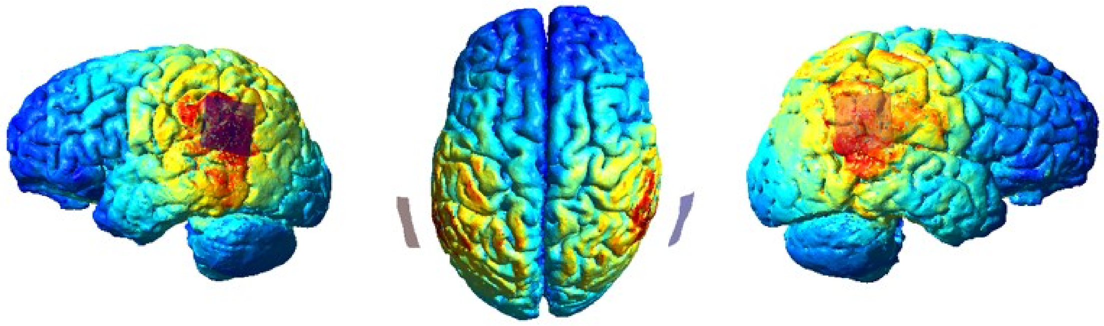


Figure 5.1 Simulation of the current density of the tACS montage with SimNIBS (Thielscher et al., 2015) using 3x3 cm electrodes with 1mm of conductive paste. The anode and cathode of each montage are randomized between the two electrode locations for each experimental session. a) Simulation of frontal tACS; b) Simulation of parietal tACS.

5.2.4 Data preprocessing and analysis

All preprocessing and statistical analyses followed the exact same steps as described in Chapter 3 for both Study 1 and Study 2. The only exception is the EEG outcome variable reported in the current chapter, which was specifically 10Hz instead of the full alpha band (8-12 Hz) as had been used in the prior investigation. This decision facilitated an enhanced precision in the outcome variable given that this was the stimulated frequency and so thought to be the most appropriate outcome measure in the current circumstances.

5.3 Study 1 results (Frontal tACS)

5.3.1 Ratings of mood states

The mood ratings of one participant from the stim-1st group were removed due to incomplete data. Herein, we report all significant results with FDR-corrected $p \leq 0.01$. After FDR-correction, ANOVA showed main effects of Order for serene ($F(1,44) = 21.5$, p.adj < 0.001), scared ($F(1,44) = 23.1$, p.adj < 0.001), inspired ($F(1,44) = 14.1$, p.adj = 0.001), oneness ($F(1,44) = 12.1$, p.adj = 0.007), and insight ($F(1,44) = 15.6$, p.adj = 0.002). Also, there were significant interactions of Group-by-Stimulation conditions for awe ($F(1,44) = 15.0$, p.adj = 0.002), interested ($F(1,44) = 28.2$, p.adj < 0.001), compassion ($F(1,44) = 18.1$, p.adj = 0.001), and observant ($F(1,44) = 18.1$, p.adj = 0.001).

Post-hoc analyses of the main effect of Order showed that participants felt less scared ($\Delta M = -7.0$, $t(46) = 4.80$, p.adj < 0.001), more serene ($\Delta M = 7.3$, $t(46) = 4.63$, p.adj < 0.001), more insight ($\Delta M = 4.6$, $t(46) = 4.00$, p.adj < 0.001), more inspired ($\Delta M = 5.5$, $t(46) = 3.80$, p.adj = 0.001), and more oneness ($\Delta M = 4.1$, $t(46) = 3.51$, p.adj = 0.001) after the experiment. Post-hoc analysis of the Group-by-Stimulation condition interaction showed that participants who received real stimulation first (stim-1st) reported more awe ($\Delta M = 9.6$, $t(23) = 2.20$, p.adj = 0.039), more compassion ($\Delta M = 6.7$, $t(23) = 2.40$, p.adj = 0.029), more interest ($\Delta M = 19.0$, $t(23) = 4.41$, p.adj = 0.002), and more observant ($\Delta M = 10.7$, $t(23) = 3.00$, p.adj = 0.011) in real stimulation sessions compared to sham stimulation sessions. However, participants who received real stimulation second (stim-2nd) reported less awe ($\Delta M = -9.8$, $t(23) = 4.03$, p.adj = 0.002), less compassion ($\Delta M = -7.6$, $t(23) = 2.86$, p.adj = 0.012), less interest ($\Delta M = -10.2$, $t(23) = 2.99$, p.adj = 0.011), and less observant ($\Delta M = -8.0$, $t(23) = 3.18$, p.adj = 0.011) in real stimulation sessions compared to sham stimulation sessions.

5.3.2 Ratings of pleasantness and attentiveness during the SRP task and Blinding Effectiveness

While ratings of pleasantness exhibited a normal distribution, ratings of attentiveness were negatively skewed, indicating that the majority of participants rated high attentiveness throughout the SRP task. Still, we decided to proceed with mixed ANOVA for both variables, given the robustness of ANOVA against normality violations. We used the non-parametric Wilcox signed-rank tests in post-hoc pairwise comparisons. All subsequent pairwise multiple comparisons were corrected with the false discovery rate (FDR) method. Regarding pleasantness ratings, we did not find any significant differences in SRP task conditions or runs. A mixed ANOVA on attentiveness indicated a significant main effect of task condition, F(2,69) = 29.73, padj < 0.001, and run, F(2,88) = 10.30, p = 0.001, but no interaction between condition and run. Post-hoc pairwise Wilcox tests for the main effect of task condition on attentiveness indicated that consistent with prior results reported in Bao and Frewen (2023), participants reported significantly higher attentiveness during letter counting (M = 4.42) compared to paying attention to their life roles, M = 4.03, t(46) = 69.0, p.adj < 0.001, or outer body M=4.19, t(46) = 119.0, p.adj < 0.001. Participants also reported that their attentiveness significantly differed between the life roles and outer body conditions, t(46) = 53.5, p.adj < 0.001. Post-hoc matched-pairs Wilcox signed-rank tests for the main effect of run on attentiveness indicated that compared to run 1, participants paid significantly less attention during run 2 (M = 4.20, z(46) = 575.0, p.adj = 0.02) and run 3 (M = 4.08, z(46) = 713.0, p.adj < 0.001. Meanwhile, participants' self-reported attention during run 2 did not significantly differ from run 3 (p.adj = 0.07).

The results of blinding effectiveness are summarized in Table 1. When asked to guess whether they received real stimulation, participants reported significantly higher confidence ratings in real stimulation sessions compared to sham sessions. Ratings of self-awareness and subjective sense of control did not show significant differences between real and sham sessions.

Table 5.1 Results of blinding effectiveness in both studies

Item	M_{stim}(SE)	M_{sham}(SE)	t	df	p	p.adj	p.adj.sig
Frontal tACS							
Real	61(4)	40(4)	3.31	45	0.002	0.006	**
Aware	63(3)	60(3)	0.83	45	0.412	0.412	ns
Control	52(3)	60(3)	-2.18	45	0.034	0.051	ns
Parietal tACS							
Real	57(4)	43(4)	2.26	48	0.029	0.087	ns
Aware	58(3)	55(4)	1.02	48	0.315	0.315	ns
Control	54(3)	58(4)	-1.41	48	0.166	0.249	ns

Note. Real = At the current moment, how much do you experience or feel like you received a real/true intervention rather than a fake/sham one; Aware = At the current moment, how much do you experience or feel like you were aware of what was happening during the intervention; Control = At the current moment, how much do you experience or feel like you were in control over what was happening during the intervention. ns = not significant. M = mean; SE = standard error of the mean. **: p <0.01.

5.3.3 EEG results

Herein, we only report significant main effects or interactions that involve stimulation conditions in text, with the full results detailed in Appendix Table 9 and Appendix Table 10. Mixed ANOVA showed significant two-way interactions between group and stimulation condition for 6 of the 19 electrodes (Fz, Cz, T5, PZ, T4, and O1; see Appendix Table 9) on the change value of 10 Hz spectral power between post-and pre-tACS measures.

Post-hoc t-tests revealed that, for the group that received stimulation first (stim-1st), real stimulation *increased* 10 Hz alpha power compared to sham stimulation at CZ, PZ, and O1 (Figure 5.2, Appendix Table 10). For the group that received stimulation second (stim-2nd), real stimulation *lowered* 10 Hz alpha power compared to sham stimulation for all six significant electrodes (Figure 5.2, Appendix Table 10).

Nevertheless, follow-up eLORETA analysis revealed neither significant source-level differences in spectral power nor linear lagged connectivity between real and sham MPFC-tACS. Additionally, mixed ANOVA of ITC did not show any significant effect of frontal stimulation within or between OMs. Thus, results were limited to findings at the electrode level; subsequent post-hoc analyses found only non-significant outcomes.

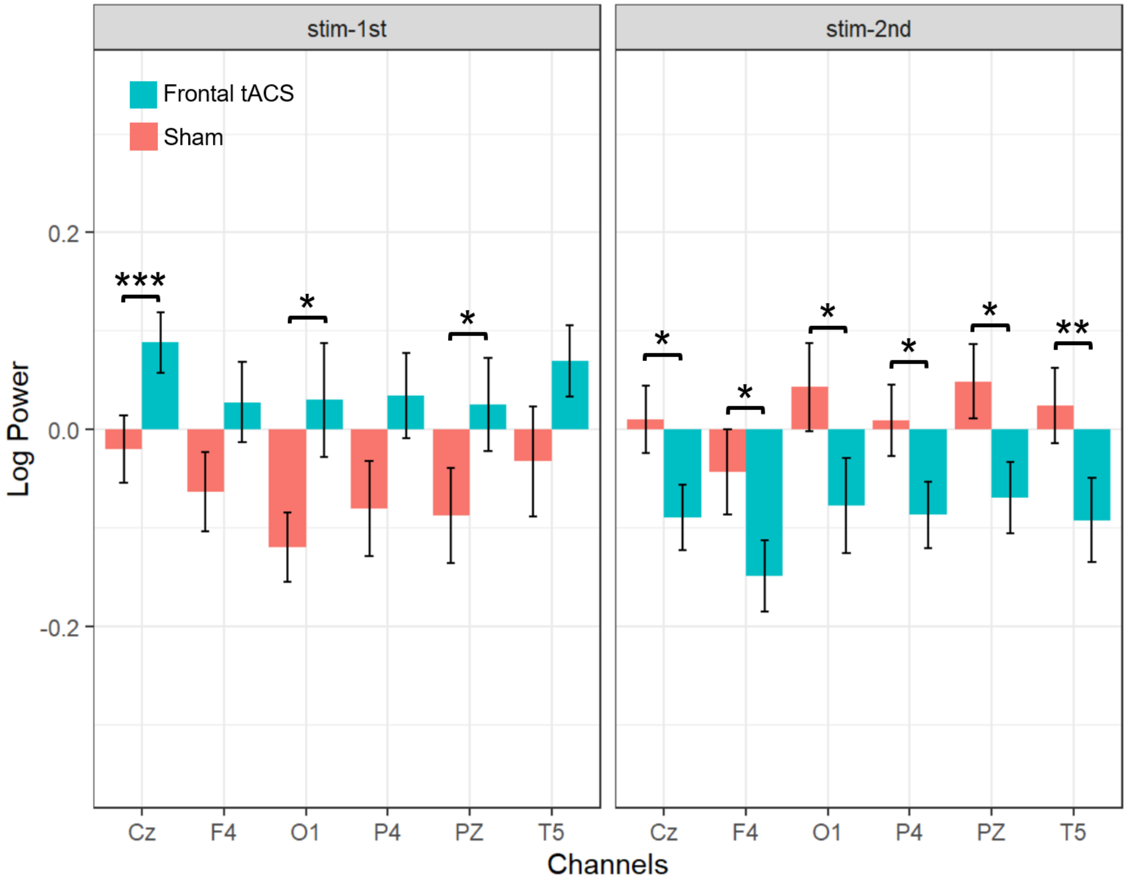


Figure 5.2 Graphical illustration of statistical results on scalp-level EEG for frontal tACS. *: p<0.05; **:p<0.01; ***:p<0.001.

5.4 Study 2 results (Parietal tACS)

5.4.1 Ratings of mood states

After FDR-correction, ANOVA showed main effects of Order for awe (F(1,47) = 21.0, p.adj < 0.001), scared (F(1,47) = 26.2, p.adj < 0.001), serene (F(1,47) = 14.4, p.adj = 0.003), fatigued (F(1,47) = 20.5, p.adj < 0.001), and insight (F(1,47) = 12.0, p.adj = 0.007). Then, ANOVA showed a significant Group by Stimulation Condition interaction for interested (F(1,47) = 26.2, p.adj < 0.001). Finally, there was a significant three-way interaction of Order*Group*Stimulation conditions for stressed (F(1,47) = 18.6, p.adj = 0.001).

Post-hoc analyses of the main effect of Order showed that participants felt less scared (ΔM = -6.0, t(49) = 4.51, p.adj < 0.001), more *awe* (ΔM = 6.4, t(49) = 4.62, p.adj < 0.001), more *serene* (ΔM = 6.8, t(49) = 3.80, p.adj = 0.001), more *insight* (ΔM = 4.6, t(49) = 3.44, p.adj = 0.001), and more *fatigued* (ΔM = 10.0, t(49) = 4.54, p.adj < 0.001) after the experiment. Post-hoc analysis of the Group*Stimulation Condition interaction for *interested* showed that compared to sham stimulation sessions, participants in real stimulation sessions felt more interested (ΔM = 10.8, t(24) = 4.01, p.adj = 0.001) when they received real stimulation in the first session, and they felt less interested (ΔM = -14.6, t(24) = 3.54, p.adj = 0.002) when the received real stimulation in the second session. Post hoc analysis of the three-way interaction for *stressed* did not yield any significant simple effects of Order or Stimulation Condition.

5.4.2 Ratings of pleasantness and attentiveness during the SRP task and blinding effectiveness

The ANOVA of pleasantness and attentiveness during the SRP task did not reveal any significant effects of the included factors. The results of blinding effectiveness are summarized in Table 1. When asked to guess whether they received real stimulation, participants reported a slightly higher but non-significant (p.adj = 0.084) difference in confidence ratings in real stimulation sessions (M=57/100) compared to sham sessions (M=42/100). Ratings of self-awareness and subjective sense of control did not differ between real and sham sessions.

5.4.3 EEG results

Similarly, only significant results involving stimulation conditions are reported in the following section. Mixed ANOVA showed significant two-way interactions between group and Stimulation Condition for 8 of the 19 electrodes (F3, FZ, C4, T4, P3, P4, and T6; see Appendix Table 11) on the post-pre change value of 10 Hz spectral power.

Post-hoc t-tests revealed that, for the group that received stimulation first (stim-1st), real stimulation *increased* 10 Hz alpha power compared to sham stimulation at C4, P3, and T6 (Figure 5.3; Appendix Table 12). No significant scalp-level spectral power differences were observed for the group who received stimulation second (stim-2nd).

Given the large degrees of difference in sham responses between the two groups, we conducted a follow-up mixed ANOVA analysis to explore the effect of tACS for the first and second sessions separately. This exploratory analysis included the between-subject factor of stimulation condition (stim, sham) and the within-subject variable of task condition (life roles, outer body, resting state, external attention). To clarify, the main mixed ANOVA considered stimulation condition as a within-subject factor, comparing participants' responses to tACS and sham between two sessions (Appendix Table 11). In contrast, the follow-up ANOVA for the first session only considered stimulation condition as a between-subject factor, comparing the responses of participants who received tACS with participants who received sham. Results for session 1 indicated significant interactions between stimulation and task condition for 7 out of the 19 electrodes (Appendix Table 13). Comparably, the ANOVA of session 2 did not yield any significant results. Then, follow-up post hoc analyses revealed parietal tACS *reduced* scalp-level power at Fz, F4, Cz, and P4 for life roles, outer body, and resting state (Figure 5.5, Appendix Table 14).

Next, we conducted post hoc independent t-tests using LORETA for the three significant task conditions and found that parietal tACS significantly *reduced* 10Hz power in a cluster in the left precentral gyrus, with the peak voxel at X=-50, Y=-10, Z=35 ($t = -3.51$, $p = 0.008$; Figure 5.6).

Analysis of phase synchrony showed a main effect of Stimulation Condition on ITC within the left-posterior OM, and the ITC between frontal and left-posterior OMs (Figure 5.3; Appendix Table 12). Post-hoc analysis indicated that real stimulation increased 10Hz ITC within the left-posterior OM ($\Delta M = 0.05$, $t(49) = 4.20$, $p.adj < 0.001$, Cohen's $d = 0.60$), and between the frontal and left-posterior OMs ($\Delta M = 0.05$, $t(49) = 3.22$, $p.adj = 0.002$, Cohen's $d = 0.46$).

Further, at the source level, follow-up eLORETA analysis for the stim-1st group revealed significant source-level differences in spectral power between real and sham tACS (Figure 5.4). The exceedance proportion test comparing real vs. sham stimulation showed the highest common two-tailed significant t-threshold = 3.514 ($p = 0.024$). A total of 2 voxels in the PCC met that threshold, showing a significant *increase* of 10 Hz in real stimulation sessions compared to sham (Voxel #1: X=5, Y=-60, Z=15, t=3.66; Voxel #2: X=5, Y=-65, Z=15, t=3.60, Figure 5.4). However, follow-up linear lagged functional connectivity analysis between the ROIs did not reveal significant changes in coherence between real and sham tACS.

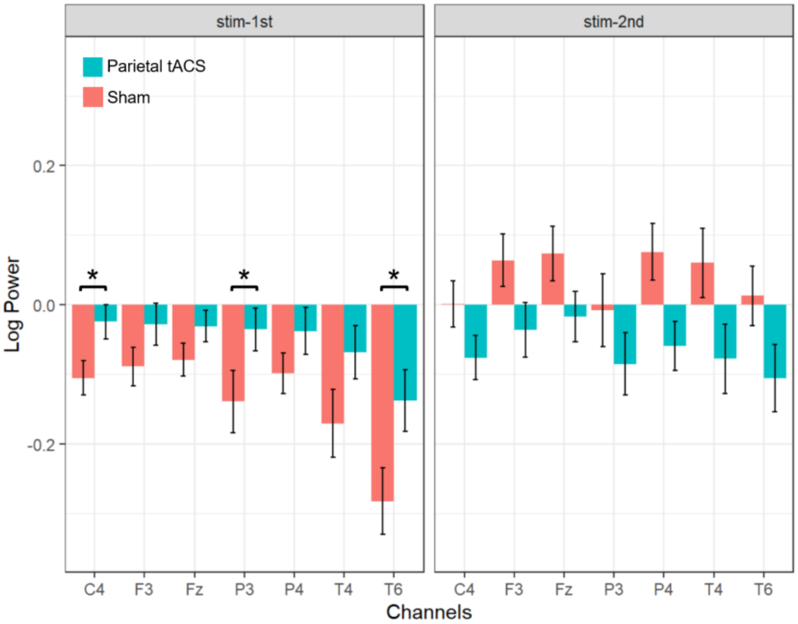


Figure 5.3 Graphical illustration of statistical results on scalp-level EEG for parietal tACS. *: $p<0.05$. Participants who received stimulation first (stim-1st) exhibited lower alpha after the sham session for channels F3, Fz, C4, T4, P4, and T6.

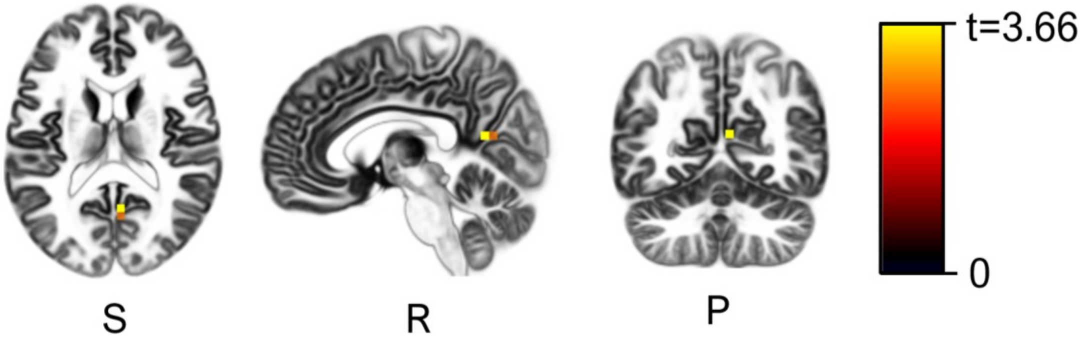


Figure 5.4 Visualization of source-level results from the eLORETA exceedance proportion tests for parietal tACS. The contrast shown here was only for participants who received real stimulation first (Stim-1st) and indicated the within-subject effect between

their tACS (session 1) and sham (session 2), regardless of task condition. Red indicates an increase of alpha power in tACS compared to sham. Abbreviations: R = right, S = superior, P = posterior. The significant t-threshold = 3.51, p = 0.024.

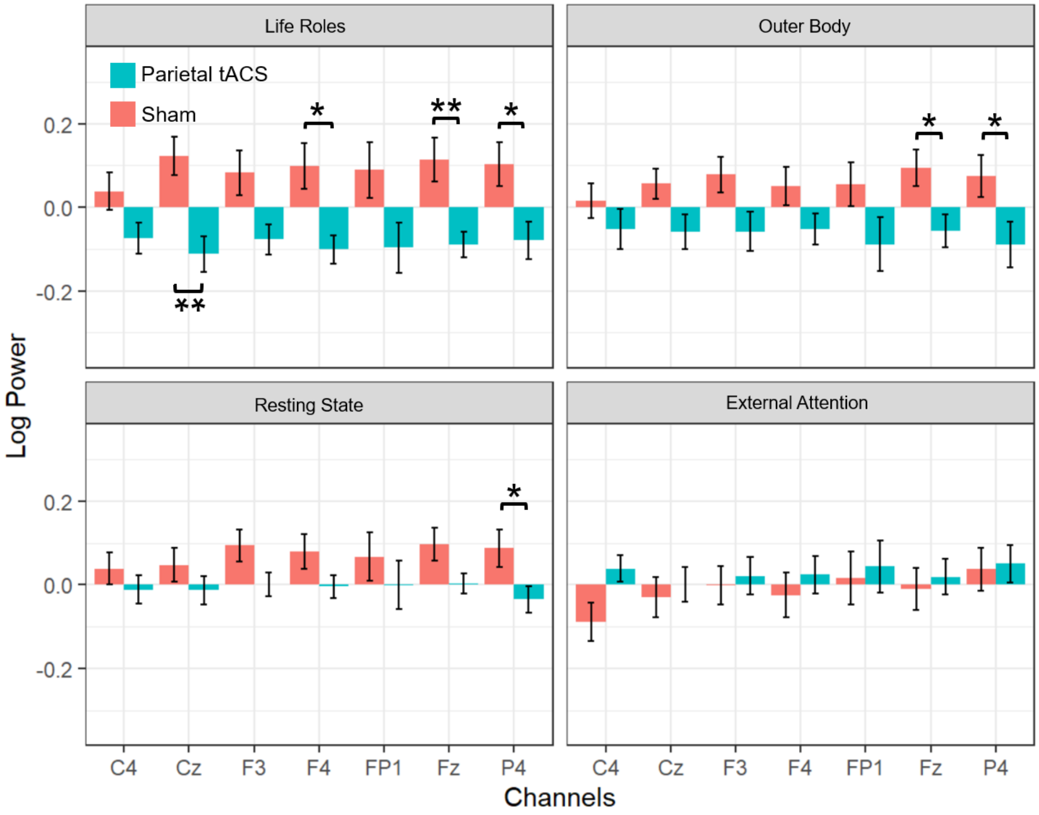


Figure 5.5 Graphical illustration of statistical results on scalp-level EEG for session 1 of parietal tACS. *: p<0.05; **:p<0.01.

Figure 5.6 Visualization of source-level results from the eLORETA exceedance proportion tests for parietal tACS only for session 1, blue indicates a reduction of alpha

spectral power in life roles condition. The contrast shown here indicated differences between participants who received tACS and participants who received sham at session 1. Abbreviations: R = right, S = superior, P = posterior. The significant t-threshold = -3.46, p = 0.008.

5.5 Discussion

The current study is the first to use tACS as a potential neuromodulatory tool for influencing the self-report and EEG correlates associated with SRP. The current chapter is different from the previous chapter regarding its use of 10Hz-tACS in comparison to tDCS and the inclusion not only of a montage focused on MPFC stimulation as used in Study 1, but also of parietal stimulation sites over the left and right IPL in Study 2.

The self-report data showed that the experimental sessions generally produced more positive emotions and even reduced some negative emotions, albeit they may only reflect more baseline level differences between sessions as there were no significant effects of tACS vs. sham. Comparably, our findings continued to indicate that although NIBS produced changes in alpha-EEG parameters, our self-report measures were relatively unaffected by tACS in either location.

Comparably, the EEG data again showed interesting scalp and source-level results that 10Hz-tACS produced significant changes in alpha parameters. Specifically, 1) frontal tACS *increased* alpha power on the scalp for participants who received tACS first but *decreased* alpha power for participants who received tACS second (Figure 5.2); 2) parietal tACS *increased* alpha power on both the scalp and source level for participants who received tACS first, but had *no* effects on participants who received tACS second (Figure 5.3, Figure 5.4); 3) considering only the first session, participants received parietal tACS exhibited significantly *decreased* source level alpha for semantic SRP, compared to participants who received sham. Finally, 4) parietal but not frontal tACS affected phase synchrony within the left-posterior OM and between the frontal and left-posterior OMs. Note that findings 1), 2) and 4) were results of within-subject comparisons and finding 3) was from a between-subject comparison. These specific findings are discussed in the following sections, and comparisons between the findings of the tDCS study are made.

5.5.1 The role of session order in alpha-tACS during SRP

We observed that the effects of alpha-tACS were largely dependent on group, indicating that the order of real vs. sham stimulation sessions played a significant role regarding participants’ receptivity to both frontal and parietal tACS (Figure 5.2, Figure 5.3). For frontal alpha-tACS, we observed that participants receiving real stimulation first exhibited an *increase* of alpha in the midline scalp areas (e.g., Cz and Pz). Meanwhile, participants who received real stimulation second exhibited a *decrease* of alpha power across frontal, central, and temporal regions (Figure 5.2). An altogether different set of results was seen in response to parietal alpha-tACS, where participants’ baseline responses to sham stimulation changed based on group assignment (Figure 5.3). These findings indicate that participants’ receptivity and baseline alpha response to the SRP task potentially change from session to session, suggesting considerable within-subject variability between testing sessions. For example, in Study 2, we found that parietal alpha-tACS reduced alpha associated with semantic SRP on the source level when only considering the first session, but such an effect was no longer significant for the second session.

A common finding between the two studies is that participants who received stimulation first tended to show an increase of alpha, whereas participants who received stimulation second tended to show a decrease of alpha; this finding tended to occur across multiple locations on the scalp. Therefore, we suspect that the novelty of the experimental procedures may have played a significant role in moderating the effects of alpha-tACS. Our findings also point to the significance of the first session, during which participants were seemingly more receptive to tACS when they had not previously been exposed to the experimental procedure. Such findings appear opposite to the findings for MPFC-tDCS, where positive findings were specific to the second session.

5.5.2 Frontal tDCS and parietal tACS produced source-level alpha but not frontal tACS

Comparing frontal stimulations

Despite the use of the same montage, we observed similarities and differences between the effects of frontal tDCS vs. frontal tACS. Regarding similarity, both frontal tDCS and frontal tACS reduced alpha oscillations on the scalp when participants received stimulation after sham (stim-2nd group). Meanwhile, while the effects of frontal tDCS were specific to the conditions with so-called more “concrete” stimuli (i.e., the somatic SRP and external attention conditions), the effect of frontal tACS did not vary based on task conditions. However, whereas both frontal tDCS and frontal tACS produced changes on the scalp level, frontal tACS did not produce significant post hoc changes in eLORETA source analyses. These results make interpretation difficult but suggest that the effects of frontal tACS may have been non-specific or not modulated alpha sources in a consistent manner.

Comparing frontal vs. parietal stimulation

We also observed that both frontal tDCS, frontal tACS, and parietal alpha-tACS tended to produce results in the parietal areas, which means that frontal stimulations tended to create distant effects, while parietal stimulation tended to create local effects. The distant effect of MPFC-tACS was consistent with the results of our investigation in Chapter 4, where MPFC-tDCS also produced effects on the scalp away from the area of stimulation.

Thus, while frontal tACS did not seem to produce significant aftereffects near the areas of stimulation but altered alpha power at distant regions, the effects of parietal tACS were more focal, also primarily affecting channels over the parietal cortex near the areas of stimulation (Figure 5.3). The findings regarding the localized effect of parietal alpha stimulation are consistent with other studies that targeted the parietal and occipital lobe with tACS under different experiment setups (Clancy et al., 2022; Mokhtarinejad et al., 2024). Meanwhile, since we did not conduct a parietal tDCS study, we cannot conclude that the differences between the results of frontal tDCS and parietal tACS are due to stimulation sites only. Future SRP studies should continue to consider the effects of tES regarding its differential local vs. network-wide impacts by implementing different stimulation methods (tDCS vs. tACS) and montages.

Comparing frontal tACS vs. parietal tACS

In addition to the network-wide modulatory effects that might account for such differences, the alpha frequency that dominates the parietal brain may also account for the localized effects of parietal but not frontal tACS. Based on the entrainment mechanism of online tACS, assuming that participants' DMN was active during the stimulation period, our results may be considered in the context of the dominant frequencies of the resting human brain. Mapping of the resting human brain showed that the dominant frequency in the MPFC is *not* within the alpha (8-12Hz) range but is rather between 20-30 Hz, with marked individual differences (Capilla et al., 2022). Importantly, the researchers found that all generators of the alpha frequency were instead located in the parietal and occipital brain, with the PCC considered as the primary alpha generator during the resting state. Therefore, the alpha power in the MPFC might be intrinsically low due to its distance from the alpha generators in the brain. A comparison study of frontal vs. parietal alpha and theta stimulation supported this notion (De Koninck et al., 2021). In their study, the resting EEG responses of frontal (F3, F4) and parietal stimulation (PO7, PO8) of individualized alpha the theta tACS protocols were directly compared. Their findings showed that parietal alpha-tACS induced more change in the targeted frequency than parietal theta-tACS and that only parietal alpha-tACS but not frontal alpha-tACS induced significant alpha change compared to sham, which is consistent with the source-level findings in the current study. Therefore, it is possible that frontal alpha-tACS was not adequately entraining the MPFC into an alpha frequency insofar as alpha oscillations do not dominate within the MPFC. This may also help explain why tACS was able to modulate alpha frequency when applied near the parietal alpha generators in the parietal tACS study.

5.5.3 Parietal tACS modulated source alpha power at the first session

We observed interesting alpha responses to parietal tACS, where the within-subject analysis of participants who received stimulation before sham (stim-1st) showed increased alpha in the PCC regardless of task condition, but the between-subject effect of the first session showed decreased alpha in the left precentral gyrus for semantic SRP only. In other words, participants' first real stimulation session resulted in significant changes in alpha, albeit the direction of change differed based on the control group. This result is in stark contrast with the findings of the tDCS study, where the effect of stimulation was seen only at session 2, when the stimulation session followed the sham session (stim-2nd).

Moreover, for parietal stimulation, the changes in alpha power between the two groups reflected differences in the sham response baseline. Importantly, participants in the stim-1st group completed their sham session at session 2, whereas participants in the stim-2nd group completed their sham session at session 1. The changes in sham responses may have partly reflected the impact of participants' familiarity with the task and experimental setup. However, our current experiment was not designed to compare the magnitude of influence between within-subject session differences and between-subject individual differences. Therefore, future studies should continue to implement mixed designs such as ABAB or AABB to evaluate the changes in alpha between sessions and participants.

Nevertheless, the areas modulated by parietal tACS are highly relevant in general SRP (PCC) and semantic SRP (left IFG). FMRI studies have established the PCC as the hub area for the DMN and SRP, and alpha oscillation within the PCC has also been found to have both positive and negative correlations with other regions of the DMN (Davey et al., 2016; Bowman et al., 2017). Then, the left IFG is associated with both speech production and autobiographical memory retrieval (Morin & Hamper, 2012; Itabashi et al., 2016), which are highly relevant in semantic SRP. Therefore, our preliminary findings suggest that bilateral IPL stimulation may have modulated both general SRP and semantic SRP-specific processes. Future studies may continue exploring the impact of alpha-tACS over the bilateral IPL on SRP.

5.5.4 Parietal tACS modulated phase synchrony but not functional connectivity

We also observed that bilateral IPL stimulation increased the alpha phase synchrony measured by ITC within the left-posterior OM and the phase synchrony between the left-posterior and the frontal OM, regardless of the SRP task condition. The increases in phase synchrony between the left-posterior and the frontal OMs are consistent with the findings of MPFC-tDCS.

We previously interpreted the increase of synchrony between the frontal and the left-posterior OMs as a result of a resting state MPFC-precuneus-IPL component found to be positively correlated with alpha. The current finding may also reflect the same mechanism but via a different stimulation site and modality. Additionally, although we did not observe changes in functional connectivity as a result of tACS over the bilateral IPL, we found increases in phase synchrony within the left-posterior OM regardless of task condition.

While Fingelkurts et al. (2020) theorized the involvement of the left-posterior OM in semantic SRP, our findings indicated that phase synchrony changes as a result of tACS over the bilateral IPL may reflect changes in more general processes such as attention, rather than those specific to semantic SRP, insofar as the effect was present not only during semantic SRP but all task conditions. Still, our interpretation in the context of Fingelkurts et al. (2020) should be treated with caution since there are non-trivial differences between the current study and those utilized by Fingelkurts et al. (2020), including the sample, definition of OMs, and phase synchrony metrics. Therefore, future studies should continue to investigate the specificity of the effect of alpha-tACS on phase synchrony in response to SRP.

5.5.5 Limitations and conclusions

A primary limitation of the current tACS studies is using a uniform stimulating frequency across participants (10Hz) instead of stimulating at participants' IAF. Research has found that the stimulating frequency in tACS tends to compete with the dominant frequency in the brain, and the effect of tACS depends on the mismatch between the stimulation frequency and the brain's dominant frequency in a non-linear fashion (Krause et al., 2022). Therefore, not stimulating at the frequencies near the dominant frequency may produce null or opposite effects based on the degree of mismatch. We did not implement IAF protocols for our participants to ensure the comparability between the frontal and parietal stimulation sites, but future tACS studies that seek to maximize or induce a unidirectional influence over the stimulation area should carefully consider the dominant frequency for the area of stimulation.

Another limitation was the issue of blinding effectiveness, particularly in the frontal tACS study, where participants generally rated 40% confidence that the stimulation was real after sham sessions but 60% for stimulation sessions. It is relevant to point out that, while a statistically significant difference was identified, confidence ratings remained qualitatively “low” near a coin toss in both cases. Notably, our study used a sensitive measurement for assessing blinding effectiveness, including an 11-point scale instead of the typical “yes” or “no” binary response. Although it may be unlikely that this 20% difference in confidence ratings heavily influenced participants’ neuro-electrophysiological responses, we suspect that the difference was due to the proximity of the tACS electrode to the eye, potentially contributing to phosphene during the stimulation. Therefore, future studies should carefully choose the stimulation montage to maximize blinding in tACS experiments.

Despite the limitations, the current study produced a collection of positive findings. We found that bilateral IPL alpha-tACS successfully modulated alpha source level spectral power regardless of task condition, but only when participants received real stimulation before sham stimulation. Then, bilateral IPL alpha-tACS increased phase synchrony within the left posterior OM and between the frontal and the left posterior OMs, regardless of stimulation order or task condition. When considering only the first session, bilateral IPL alpha-tACS reduced alpha activity in the left IFG during semantic SRP only. In comparison, although frontal alpha-tACS altered scalp-level alpha spectral power, it did not produce significant differences at the source level.

We conclude that alpha-tACS over the bilateral IPL may influence alpha activity during SRP both near and distant to the stimulated area. Further, its influence may be moderated by the order in which real and sham stimulation sessions take place.

Chapter 6

6 General Discussion

With the development of neuroimaging evidence for the neural correlates of SRP, investigating the effects of NIBS on SRP is a natural next step to further our causal understanding of the brain bases of our sense of self and its semantic (verbal, psychological) and somatic (non-verbal, physical) sub-domains (V-SRP and NV-SRP, respectively). To return to the broad framework described in the General Introduction reported in Chapter 1, the current dissertation may be considered an attempt to progress research by connecting second wave measurement approaches with third wave modulation approaches using EEG neuroimaging and tES methods, respectively.

In Chapter 2, I conducted a systematic review summarizing the relevant NIBS literature on SRP, categorizing its study into V-SRP (semantic) and NV-SRP (somatic) sub-domains based on the use of different experimental tasks. Chapter 2 identified the gaps of knowledge in NIBS-SRP research, mainly including the lack of uniform task designs, the lack of studies investigating both semantic and somatic SRP, and the scarcity of neurobiological measurements as outcomes of NIBS on SRP.

In Chapter 3, I conducted two experiments to test a new SRP paradigm that measures semantic and somatic SRP that could be used in subsequent NIBS research. The first study reported in the chapter was conducted online and provided an initial validation of the SRP task through analysis of self-report data, while the second study reported in the chapter used the new SRP paradigm to measure the EEG correlates of SRP. Both sets of findings supported the semantic vs. somatic distinction of SRP, while the second study highlighted the significance of alpha oscillations in both SRP domains when compared to internal and external attention control conditions. Such findings, conducted in the absence of administration of any form of NIBS, thus set foundational knowledge for the subsequent investigation of the effects of NIBS that were conducted in subsequent experiments.

Here, in the next two chapters (4 and 5), we tested the effects of tDCS and tACS on participants' response to the SRP task. The tES experiments generally showed successful modulation of alpha parameters but with a few caveats.

In the next sections, I discuss the findings of the past chapters in the context of the entire series of experiments and the relevant literature. Then, I discuss the broader implications of this dissertation's results and future directions for NIBS-SRP research.

6.1 Summary of findings

In Chapter 2, the systematic review summarized the methodology and findings of 38 studies that investigated the effects of NIBS on measures of SRP with different experimental tasks, broadly including self-referential encoding tasks, self-other discrimination tasks, rubber hand illusion tasks, and heartbeat detection tasks. In terms of outcome measures, studies investigated the changes in performance accuracy, reaction time, subjective reports of embodiment, motor-evoked potential, amd fMRI BOLD measures.

We observed that studies using TMS have found more consistent change in SRP measures in general, whereas tDCS studies found mixed results that vary based on electrode placement, experimental design, and the control conditions. Additionally, no study used tACS as a modulatory tool for SRP.

It is not surprising that TMS has been more successful in modulating SRP, given there are relevant differences between tDCS and TMS in strength and mechanism, as reviewed in the General Introduction (Chapter 1). To review again, considering strength, the peak electric field value for 1-2 mA tDCS is about 1V/m, whereas the peak electric field value for TMS can reach 100V/m (Lefaucheur & Wendling, 2019). Such differences reflect the different mechanisms of action of the two stimulation methods, with TMS having the power to directly induce action potentials whereas tES indirectly introduces polarization on the effect of underlying neuronal structures.

Evidently, the effect of tES on SRP bears more complexity due to its potential interaction with the brain states during the stimulation period, the network activity underlying the areas of stimulation, and the brain's effort for homeostatic balance during and after the stimulation period (Fertonani & Miniussi, 2017). Therefore, one of the main gaps identified in the NIBS-SRP literature from the systematic review was the lack of understanding of the mixed results of tDCS studies. Moreover, few studies measured neurobiological changes as results of tES, further restricting establishing a more fundamental understanding of the impact of tES on SRP.

Another key problem with existing SRP studies was that they were separated by SRP sub-domains, with experimental tasks exclusively focused on either semantic or somatic SRP but not both. This makes comparison of results difficult, and fails to account for recent developments in SRP neuroimaging that suggested the nested nature of semantic and somatic SRP (Qin et al., 2020; Frewen et al., 2020).

With these limitations in mind, Chapter 2 first aimed to address these gaps by introducing a new SRP task designed to measure both semantic and somatic SRP whilst controlling for internal (resting state) and external attention. In a large online self-report study, we found that participants generally respond pleasantly to all conditions with similar levels of attentiveness between internal attention conditions (life roles, outer body, inner body and resting state), but higher levels of attentiveness for the external attention condition. Moreover, participants ratings of pleasantness and attentiveness in the life roles and outer body condition moderately correlated with some of the relevant mental health measures, providing evidence for the external validity of these two conditions over the inner body condition.

Based on these findings, we retained the life roles and outer body conditions of the SRP task to carry over to the second study reported in Chapter 3, where participants' EEG correlates during the SRP task were also measured. The most prominent result of this study was that the alpha oscillation (8-12Hz) differentiated all task conditions in various brain regions. Then, there was a strong indication of hemispheric lateralization when the structured SRP conditions were compared to resting state, and when semantic SRP was directly compared with somatic SRP (Figure 3.5, Figure 3.6). Moreover, in our analysis of phase synchrony associated with SRP, we found an interesting pattern in the left posterior OM where semantic SRP exhibited similar levels of phase synchrony to resting state, and somatic SRP exhibited similar levels of phase synchrony to external attention (Figure 3.3). Meanwhile, in the right posterior OM, semantic SRP exhibited higher levels of phase synchrony compared to the rest of the conditions.

With the EEG correlates of all SRP conditions measured in Chapter 3, we reported the results of tDCS and two tACS experiments targeting the frontal and parietal lobes in subsequent chapters. Firstly, consistent with previous findings, we did not observe changes in self-report measures of pleasantness, attentiveness, and mood ratings as results of tES. Then, the alpha EEG outcomes of tES experiments are summarized in **Error! Not a valid bookmark self-reference.**. All tES studies produced significant aftereffects in scalp-level EEG. However, only the mPFC-tDCS and the parietal tACS study produced source-level changes in alpha power. In contrast, only the tDCS study produced changes in functional connectivity between SRP ROIs. Further, only the tDCS and the parietal tACS study produced changes in phase synchrony, but such changes may only reflect the general effects of tES instead of effects specific to SRP. Finally, results often interacted with the order of administration of tES vs. a sham (placebo) NIBS session. The results from the tES experiments in Chapters 4 and 5 furthered the current understanding of tES on SRP.

Table 6.1 Summary of results from tES studies in Chapters 3 and 4.

		Frontal tDCS	**Frontal 10Hz-tACS**	**Parietal 10Hz-tACS**
Spectral power	Scalp-level	tDCS reduced scalp alpha power somatic SRP and external attention, only for stim-2nd	tACS reduced scalp alpha for stim-1st group, and increased alpha for stim-2nd group, regardless of task condition	tACS increased scalp alpha for stim-1st group. Also, tACS reduced scalp alpha for semantic, somatic SRP and resting state when only the first session was considered
Spectral power	Source-level	tDCS reduced source alpha for somatic SRP and external attention	No significant result	tACS increased source alpha for stim-1st group regardless of task condition, and reduced source alpha for semantic SRP when only the first session was considered
Connectivity	Scalp-level	tDCS increased the phase synchrony between frontal and left-posterior OMs, regardless of task or group	No significant result	tACS increase phase synchrony 1) between frontal and left posterior OMs, and 2) within the left posterior OM, regardless of task or group
Connectivity	Source-level	tDCS reduced linear lagged connectivity between the left IPL and the ventral PCC for somatic SRP	No significant result	No significant result
Note. Semantic SRP has been referred to as V-SRP, and somatic SRP has been referred to as NV-SRP.				

6.1 Implications and future directions

Modulating SRP with NIBS methods has received increasing interest among researchers in recent years, perhaps due to recent advancements in consciousness science and the increasing need for effective and cost-efficient mental healthcare. Among the 38 reviewed NIBS SRP studies in Chapter 2, 28 were conducted within the last ten years, and 10 were conducted within the last three years.

Philosopher Daniel Dennett defined the sense of self as “the centre of narrative gravity” (1992), highlighting both the intangibility of the self and its significance as a focal point around which other brain processes such as sensorimotor, attention and memory may revolve. Therefore, modulating SRP with NIBS may have implications in multiple fields of study, highlighting the significance of a comprehensive understanding of all SRP domains and the importance of establishing scientifically valid experimental tasks and effective NIBS protocols.

In Chapter 3, we addressed some of these gaps in NIBS SRP research through the design of new SRP task and explored participants' response to the task with self-reports and EEG data. Theoretically, our findings in Chapter 3 suggest the crucial role of alpha oscillations during SRP and support the distinction between a kind of "thinking self" (semantic SRP) and a "feeling self" (somatic SRP). While alpha oscillations in the brain have been associated with a wide range of cognitive processes, our experiment highlighted the attentional aspects of alpha during SRP, especially given alpha's role in distinguishing internal vs. external attention (Magosso et al., 2021).

Additionally, the distinction between the EEG correlates of semantic and somatic SRP suggested further divisions of the function of alpha beyond distinguishing internal vs. external attention. Specifically, the pattern of hemispheric lateralization observed in Chapter 3 coincided with Fingelkurts et al. (2020) that also supported functional separations between semantic and somatic SRP on an electrophysiological basis as a response to different meditation practices.

Considering the results of our three tES experiments together, we observed several factors that influenced the effects of tES on alpha EEG. For example, stimulation modality and location produced differential effects, suggesting the importance of carefully considering the match between the brain states during stimulation and the stimulation montage. Then, it is crucial to consider the direction of neuromodulation within the brain network underlying SRP tasks, exemplified by the different modulatory effects of MPFC and the bilateral IPL within the DMN that were discussed in Chapters 4 and 5 and previous dynamic causal modelling studies (Davey et al., 2016; Delahoy et al., 2022). Finally, both of those prior dynamic causal modelling studies only investigated the DMN dynamics during semantic SRP with fMRI. Therefore, our results expanded the current understanding of the modulatory effects of DMN nodes to include somatic SRP, resting state, external attention, and alpha EEG.

We also observed the surprisingly strong moderating effect of the order of stimulation sessions on the effects of tES, which presents new questions and challenges for future tES studies on SRP. The systematic review presented in Chapter 2 summarized 24 studies that used a within-subject design, 13 studies that used a between-subject design, and only one study that used a mixed (between- and within-subjects) design. Therefore, our findings using a mixed design highlighted potential concerns for past NIBS studies that only implemented within-subject or between-subject analyses.

Broadly speaking, individual differences in tES receptivity have been documented previously (Krause & Kadosh, 2014; Pellegrini et al., 2018). For example, in terms of the magnitude of influence, one recent study of 6Hz-tACS suggested that 54-65% of the effect of tACS can be accounted for by individual differences in electric field and peak frequency (Zanto et al., 2021). In the recent four years, researchers have found both stable and variable individual differences may affect tES receptivity, including morphology, genetic features, hormone, and substance use, level of engagement, baseline brain activity, and task difficulty (Vergallito et al., 2022). Therefore, future tES studies on SRP should carefully consider these between-subject variables to improve the efficacy of tES protocols.

Meanwhile, our study also highlighted the potential influence of within-subject variables across two testing sessions. We therefore suggest that future studies of the effects of NIBS on SRP implement multi-session protocols, such as using AABB or ABAB designs to investigate how changes occur as an effect of different experimental sessions within and across participants exposed to a different ordering of those sessions; it is possible that response to subsequent sessions of NIBS will be influenced by prior exposures.

Furthermore, although the findings of this dissertation illustrated the strong effects of alpha spectral power, phase synchrony, functional connectivity, and tES receptivity during SRP, alpha EEG is not the only neural oscillation that is likely relevant in processing self-related stimuli. For example, early evidence suggested the involvement of gamma in processing self-traits and autobiographical memory (Mu & Han, 2010; Choi et al., 2017). Then, the theta, beta and gamma bands have been associated with self-hand

and face processing in recent studies (Alzueta et al., 2020; Ueda et al., 2022; Kotlewska et al., 2023). Moreover, our own results reported in Study 2 of Chapter 3 also found that theta differentiated semantic SRP with resting state. Therefore, we encourage future studies to explore the effects of NIBS targeting different frequencies to unveil the neuro-electrophysiology of SRP more fully.

To conclude, we hope that the current dissertation has contributed some modest level of insight into the alpha-EEG correlates accompanying our senses of self in the semantic (verbal, psychological) and somatic (non-verbal, physical) modalities, and their susceptibility to neuromodulation by tDCS and tACS over the midline frontal and bilateral inferior parietal cortex. It is hoped that further neuroscience research along these lines can ultimately be applied to the design of effective treatments for people suffering from mental health problems associated with negative thoughts about themselves and distressing and unpleasant bodily feelings.

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Appendices

Appendix Table 1: Studies excluded from the systematic review

Study excluded because task did not involve SRP	Study excluded because only included spontaneous SRP condition (e.g., resting state)
Bellis et al., 2017	Axelrod et al., 2015
David et al., 2009	Kajimura, et al., 2016
Guise et al., 2007	Alon, et al., 2011
Hu et al., 2017	Baeken et al., 2017
Liepelt et al., 2016	Kajimura & Nomura, 2015
Martin et al., 2017	van der Werf et al., 2010
Mondino et al., 2016	Coulborn et al., 2020
Pisoni et al., 2018	McCallion et al., 2020
Preston & Newport, 2008	
Schuwerk et al., 2014	
Zhang et al., 2019	
Giardina et al., 2012	
Salerno et al., 2012	
Civai et al., 2015	
Jung et al., 2020	
Salehinejad et al., 2020	
Ljubisavljevic et al., 2022	
Zhang et al., 2022	
Sun et al., 2023	
Bellard et al., 2023	

Appendix Table 2 Coordinates of the regions of interest used in functional connectivity analyses of the DMN, extracted from Frewen et al. (2020)

Region of Interest	X (MNI)	Y (MNI)	Z (MNI)
Ventral PCC	0	-60	20
Precuneus	0	-60	40
Right IPL	50	-60	30
Left IPL	-50	-60	30
Right Anterior Insula	40	20	0
Left Anterior Insula	-40	20	0
Perigenual ACC	0	40	0
Dorsal Middle ACC	0	20	20
Ventral Medial PFC	0	40	-20
Middle Medial PFC	0	60	0
Dorsal Medial PFC – 1	0	60	20
Dorsal Medial PFC – 2	0	40	40

Appendix Table 3 Results of exceedance proportion tests from LORETA: internal attention vs. external attention

hemisphere	Structure	Brodmann area	Peak Voxel Value (Log of F-ratio)	X_MNI	Y_MNI	Z_MNI
Semantic SRP vs. External attention (log of F-threshold = 0.017, p=0.006)						
Alpha band (8-12 Hz)						
left	Inferior Frontal Gyrus	9, 44, 45, 47	0.17401	-35	5	30
left	Precentral Gyrus	4, 6, 43	0.15234	-35	0	30
left	Cingulate Gyrus	24, 31, 32	0.15207	-10	15	30
left	Insula	13	0.15031	-35	5	20
left	Anterior Cingulate	25, 33	0.14445	-5	10	25
right	Anterior Cingulate	24, 33	0.14108	5	15	25
right	Inferior Frontal Gyrus	9, 44, 45	0.13457	35	5	30
left	Middle Frontal Gyrus	8, 10, 11, 46	0.1299	-30	15	45
right	Insula	13	0.12499	35	5	20
right	Cingulate Gyrus	32	0.11631	5	20	30
right	Precentral Gyrus	4, 6, 43	0.10858	40	0	30
right	Middle Frontal Gyrus	8, 10, 11, 46	0.09926	50	20	25
right	Extra-Nuclear	47	0.08897	35	20	0
right	Superior Temporal Gyrus	22, 38	0.07456	40	15	-20
right	Middle Temporal Gyrus	21	0.06247	40	10	-40
left	Superior Temporal Gyrus	22, 38	0.05696	-50	10	0
left	Postcentral Gyrus	1, 2, 3, 5	0.0557	-55	-15	45
right	Parahippocampal Gyrus	35, 34, 35	0.0551	30	5	-20
right	Uncus	28, 36	0.05202	30	5	-25
right	Inferior Temporal Gyrus	20, 37	0.04673	40	0	-45
left	Transverse Temporal Gyrus	41, 42	0.0457	-60	-10	15
right	Medial Frontal Gyrus	25	0.04501	10	30	-15
left	Parahippocampal Gyrus	34	0.04427	-30	5	-20
left	Middle Temporal Gyrus	21	0.04177	-40	10	-40
left	Uncus	28, 36	0.0408	-30	5	-25
right	Transverse Temporal Gyrus	41, 42	0.04019	60	-10	15
right	Postcentral Gyrus	1, 2, 3	0.03768	55	-15	50
left	Inferior Temporal Gyrus	20	0.03168	-40	0	-45
right	Precuneus	7, 19, 31	-0.0599	5	-65	40
left	Precuneus	7, 19	-0.0592	-5	-70	50
right	Inferior Parietal Lobule	39, 40	-0.0472	35	-65	40
right	Paracentral Lobule	5	-0.0444	5	-45	50
right	Posterior Cingulate	23, 29, 30	-0.0433	5	-50	25
right	Cuneus	17, 18	-0.0398	5	-80	25
left	Inferior Parietal Lobule	39, 40	-0.0389	-35	-55	60
left	Cuneus	17, 18	-0.0372	-5	-80	25
left	Posterior Cingulate	23, 29, 30	-0.0334	-5	-45	25
left	Middle Occipital Gyrus	37	-0.021	-55	-75	0
Somatic SRP vs. External attention (log of F-threshold = 0.017, p=0.026)						
Alpha band (8-12 Hz)						
right	Inferior Frontal Gyrus	9, 44, 45	0.17008	40	5	30
right	Insula	13, 47	0.15891	35	5	20
right	Precentral Gyrus	4, 6, 43	0.15377	40	0	30
left	Middle Frontal Gyrus	8, 9, 10, 46	0.13865	-35	15	35

right	Middle Frontal Gyrus	8, 10, 11, 46	0.12883	50	20	25
left	Precentral Gyrus	4, 6	0.10268	-35	0	30
left	Anterior Cingulate	24, 25, 32, 33	0.1011	-10	20	25
left	Insula	13	0.09974	-35	5	20
right	Superior Temporal Gyrus	22, 38	0.09658	40	10	-15
right	Middle Temporal Gyrus	21	0.08632	45	10	-35
left	Inferior Frontal Gyrus	44, 45, 47	0.08545	-50	10	25
right	Anterior Cingulate	24, 32, 33	0.08086	5	15	25
right	Parahippocampal Gyrus	27, 34, 35	0.07685	30	5	-20
right	Uncus	28, 36	0.07389	30	5	-25
right	Inferior Temporal Gyrus	20, 37	0.0729	40	0	-45
right	Postcentral Gyrus	1, 2, 3, 40	0.07025	65	-10	25
right	Transverse Temporal Gyrus	41, 42	0.06589	60	-10	15
right	Medial Frontal Gyrus	25	0.04263	15	15	-20
left	Subcallosal Gyrus	11	0.02389	-10	25	-10
right	Fusiform Gyrus	19	0.02286	30	-75	-20
right	Lingual Gyrus	18	0.0222	25	-75	-15
right	Posterior Cingulate	30	0.01884	25	-65	5
left	Inferior Temporal Gyrus	19, 20, 37	-0.0473	-60	-30	-25
left	Middle Temporal Gyrus	21, 39	-0.046	-65	-30	-20
left	Parahippocampal Gyrus	27, 28, 34, 35, 36	-0.0449	-40	-30	-25
left	Superior Temporal Gyrus	22, 38, 41, 42	-0.0432	-45	-20	-10
left	Supramarginal Gyrus	40	-0.0389	-60	-55	20
left	Middle Occipital Gyrus	18	-0.038	-45	-80	-15
left	Posterior Cingulate	30	-0.0344	-25	-70	5
left	Superior Parietal Lobule	7	-0.0343	-25	-55	65
left	Precuneus	31	-0.0336	-25	-75	15
left	Postcentral Gyrus	1, 2, 3, 5, 43	-0.0335	-25	-50	65
left	Cuneus	17, 23	-0.0301	-20	-75	10
right	Precuneus	7	-0.0258	5	-50	55
right	Paracentral Lobule	5	-0.0251	5	-45	55
right	Cingulate Gyrus	31	-0.0222	5	-50	40
Resting state vs. External attention (log of F-threshold = 0.019, p<0.001)						
Alpha band (8-12 Hz)						
right	Inferior Frontal Gyrus	9, 44, 45	0.1875	35	5	30
right	Insula	13	0.18731	35	5	20
left	Inferior Frontal Gyrus	9, 44, 45, 47	0.16768	-35	5	30
right	Precentral Gyrus	4, 6, 43	0.157	40	0	30
left	Insula	13	0.15484	-35	5	20
left	Precentral Gyrus	4, 6, 43	0.14736	-35	0	30
right	Anterior Cingulate	24, 25, 33	0.14337	5	15	25
left	Middle Frontal Gyrus	8, 10, 11, 46	0.13796	-45	20	25
left	Anterior Cingulate	24, 25, 32, 33	0.13319	-10	20	25
right	Middle Frontal Gyrus	8, 10, 11, 46	0.12858	50	20	25
right	Extra-Nuclear	47	0.12366	35	20	0
right	Cingulate Gyrus	32	0.11911	10	20	30
right	Superior Temporal Gyrus	22, 38, 39, 41	0.10898	40	15	-20
left	Superior Temporal Gyrus	22, 38	0.10284	-45	20	-15
right	Middle Temporal Gyrus	21	0.0896	40	10	-40
left	Middle Temporal Gyrus	21, 37	0.0815	-50	10	-30

right	Parahippocampal Gyrus	27, 35, 27, 34, 35	0.07941	30	5	-20
right	Uncus	28, 36	0.07357	30	5	-25
left	Postcentral Gyrus	1, 2, 3, 5, 40	0.07291	-65	-10	25
left	Transverse Temporal Gyrus	41, 42	0.06823	-60	-10	15
left	Parahippocampal Gyrus	34	0.06209	-30	5	-20
left	Uncus	28, 36	0.05806	-30	5	-25
right	Inferior Temporal Gyrus	20	0.05718	40	0	-45
left	Inferior Temporal Gyrus	20	0.05637	-50	0	-40
right	Posterior Cingulate	29, 30, 31	-0.0501	20	-60	10
right	Lingual Gyrus	19	-0.0486	20	-65	0
right	Cuneus	17, 18, 23	-0.048	20	-70	15
right	Fusiform Gyrus	37	-0.0445	35	-55	-15
right	Inferior Parietal Lobule	40	-0.0438	40	-60	40
right	Postcentral Gyrus	1, 2, 3, 5	0.04366	55	-15	50
right	Precuneus	7	-0.0435	20	-65	30
right	Transverse Temporal Gyrus	42	0.03523	60	-10	15
left	Superior Parietal Lobule	7	-0.0347	-25	-65	45
left	Cingulate Gyrus	31	-0.0326	-5	-60	30
left	Precuneus	19	-0.0324	-25	-80	40
left	Posterior Cingulate	23, 29, 30	-0.028	-5	-60	15
left	Angular Gyrus	39	-0.0269	-30	-65	35
left	Lingual Gyrus	18	-0.0269	-5	-70	-5
left	Cuneus	17	-0.0249	-5	-80	10

Appendix Table 4 Results of exceedance proportion tests from LORETA: SRP vs. resting state

hemisphere	Structure	Brodmann area	Peak Voxel Value (Log of F-ratio)	X_MNI	Y_MNI	Z_MNI
Semantic SRP vs. Resting state (log of F-threshold = 0.006, p=0.008)						
Theta band (4-8 Hz)						
right	Anterior Cingulate	24, 25, 32, 33	-0.063408	5	35	5
left	Anterior Cingulate	24, 25, 32, 33	-0.060141	-5	35	5
right	Medial Frontal Gyrus	9, 10, 11	-0.059391	5	50	5
left	Medial Frontal Gyrus	9, 10, 11	-0.056387	-5	50	5
right	Insula	13	-0.045671	30	20	15
right	Supramarginal Gyrus	40	0.0439969	60	-55	35
right	Superior Temporal Gyrus	22, 38, 39, 41, 42	0.042747	55	-60	30
right	Inferior Temporal Gyrus	20, 37	0.0425668	50	-55	-10
right	Middle Occipital Gyrus	19	0.0421349	50	-60	-10
right	Middle Temporal Gyrus	21	0.0418275	60	-50	-5
right	Inferior Frontal Gyrus	44, 45, 46, 47	-0.040761	35	35	15
left	Inferior Frontal Gyrus	47	-0.039511	-15	20	-15
left	Subcallosal Gyrus	13, 34	-0.039445	-15	15	-15
right	Cuneus	7, 17, 18, 23	0.0390462	25	-70	15
right	Posterior Cingulate	30	0.0389897	25	-70	10
right	Precuneus	31	0.0385047	25	-75	15
left	Superior Temporal Gyrus	22, 38	-0.037652	-25	10	-40
left	Posterior Cingulate	29, 30, 31	-0.036941	-20	-65	15
left	Uncus	20, 28, 36	-0.036884	-25	0	-45
left	Cuneus	17, 18, 23	-0.035834	-20	-70	15
right	Precentral Gyrus	4, 6, 43	0.0352704	25	-30	65
left	Middle Temporal Gyrus	21, 37	-0.035263	-40	10	-40
right	Postcentral Gyrus	1, 2, 3	0.0351479	25	-35	65
left	Sub-Gyral	39	-0.034363	-30	-60	25
right	Subcallosal Gyrus	34	-0.033638	10	5	-15
right	Paracentral Lobule	5	0.0336322	15	-35	55
left	Middle Frontal Gyrus	8, 46	-0.032951	-40	50	20
right	Fusiform Gyrus	36	0.0318661	50	-40	-30
left	Insula	45	-0.031077	-30	25	5
left	Middle Occipital Gyrus	19	-0.031018	-30	-80	20
left	Parahippocampal Gyrus	27, 35	-0.030904	-20	-10	-30
left	Paracentral Lobule	4, 5, 6	0.0289411	-5	-35	55
left	Precentral Gyrus	43, 44	-0.02821	-45	5	10
left	Postcentral Gyrus	1, 2, 3, 40	-0.028149	-60	-30	45
right	Uncus	28	-0.025907	25	5	-25
left	Precuneus	7	0.0249342	-5	-35	45
right	Middle Frontal Gyrus	8	-0.021755	40	30	45
left	Transverse Temporal Gyrus	41, 42	-0.018886	-60	-10	15
right	Parahippocampal Gyrus	27, 35	0.0160138	25	-35	-5
Somatic SRP vs. Resting state (log of F-threshold = 0.010, p=0.002)						
Alpha band (8-12 Hz)						
left	Superior Temporal Gyrus	22, 38, 39, 41	-0.100767	-55	10	0
left	Inferior Frontal Gyrus	9, 45, 46, 47	-0.099676	-50	20	-10
left	Insula	13	-0.097617	-45	10	-5

left	Precentral Gyrus	4, 6, 43, 44	-0.096151	-60	15	10
left	Middle Temporal Gyrus	21	-0.095998	-55	10	-25
left	Middle Frontal Gyrus	10, 11	-0.090752	-45	45	-15
left	Transverse Temporal Gyrus	42	-0.085254	-60	-10	10
left	Inferior Temporal Gyrus	20, 37	-0.084756	-50	0	-35
left	Postcentral Gyrus	1, 2, 3, 40	-0.078036	-65	-20	15
left	Parahippocampal Gyrus	27, 30, 34, 35, 36	-0.071578	-30	5	-20
left	Uncus	28	-0.070151	-30	5	-25
right	Lingual Gyrus	18, 19	0.0695406	25	-65	-5
right	Posterior Cingulate	29, 30, 31	0.0678927	25	-65	5
right	Cingulate Gyrus	24, 32	-0.066061	10	15	30
right	Fusiform Gyrus	36, 37	0.0637793	40	-60	-20
left	Anterior Cingulate	32, 33	-0.062926	-15	45	-5
right	Cuneus	17, 23	0.0627314	20	-80	5
right	Anterior Cingulate	25, 33	-0.061483	5	10	25
right	Inferior Temporal Gyrus	20	0.0589725	50	-55	-20
right	Middle Temporal Gyrus	21, 22, 39	0.0586978	40	-60	15
right	Medial Frontal Gyrus	6, 9, 10	-0.057701	5	65	20
right	Supramarginal Gyrus	40	0.0545872	60	-55	35
right	Superior Temporal Gyrus	38, 41, 42	0.0540914	70	-30	5
left	Middle Occipital Gyrus	18, 19	-0.053589	-50	-60	-10
right	Insula	13, 47	0.0526277	40	-45	20
right	Parahippocampal Gyrus	27, 28, 34, 35	0.0496901	25	-35	-5
left	Cingulate Gyrus	23, 24, 31	-0.048467	-5	10	30
left	Medial Frontal Gyrus	25	-0.047865	-10	30	-15
right	Superior Frontal Gyrus	8, 11	-0.042734	5	65	-10
right	Inferior Parietal Lobule	7	0.0419569	45	-70	45
right	Postcentral Gyrus	1, 2, 3, 5, 43	0.0418057	40	-40	60
left	Superior Frontal Gyrus	8	-0.041341	-15	50	45
right	Precentral Gyrus	4, 44	0.0330974	35	-30	55
right	Inferior Frontal Gyrus	45, 46	-0.026753	35	25	5
left	Cuneus	17	-0.024701	-20	-85	5
left	Paracentral Lobule	5	-0.020222	-15	-35	50
left	Posterior Cingulate	29	0.0182371	-5	-55	10
left	Precuneus	7	0.0142306	-5	-65	30

Appendix Table 5 Results of exceedance proportion tests from LORETA: semantic SRP vs. somatic SRP

hemisphere	Structure	Brodmann area	Peak Voxel Value (log of F-ratio)	X_MNI	Y_MNI	Z_MNI
Semantic SRP vs. Somatic SRP (log of F-threshold = 0.007, p = 0.016)						
Alpha band (8-12 Hz)						
left	Cingulate Gyrus	23, 24, 31, 32	0.06931	-5	10	30
right	Cingulate Gyrus	24, 32	0.06811	5	15	30
left	Precentral Gyrus	4, 6, 43, 44	0.0658	-45	0	5
left	Insula	13	0.0654	-45	-5	10
left	Superior Temporal Gyrus	22, 38, 39, 41	0.06496	-50	-5	5
left	Anterior Cingulate	33	0.06092	-5	10	25
left	Middle Temporal Gyrus	21	0.06067	-60	-5	-5
right	Anterior Cingulate	33	0.05983	5	10	25
left	Inferior Temporal Gyrus	20, 37	0.05552	-55	-5	-40
left	Inferior Frontal Gyrus	9, 45, 46, 47	0.05496	-55	15	5
left	Postcentral Gyrus	1, 2, 3, 40	0.05474	-65	-20	15
left	Parahippocampal Gyrus	27, 34, 35	0.05376	-30	5	-20
left	Middle Frontal Gyrus	8, 10, 11	0.04501	-20	20	45
right	frontal pole	10	0.0335	5	65	15
right	Superior Frontal Gyrus	11	0.03043	5	60	-20
left	Medial Frontal Gyrus	25	0.02892	-15	10	-20
left	Middle Occipital Gyrus	18	0.02333	-40	-80	-15
left	Posterior Cingulate	29, 30	0.02075	-25	-70	5
left	Lingual Gyrus	17	0.01885	-20	-85	0
right	Medial Frontal Gyrus	25	0.01155	10	30	-15
right	Inferior Frontal Gyrus	9, 44, 45, 47	-0.0594	55	5	35
right	Precentral Gyrus	4, 6, 43	-0.0589	60	5	35
right	Precuneus	7, 19, 31	-0.0451	10	-70	35
right	Insula	13	-0.0421	40	0	20
right	Middle Frontal Gyrus	8, 46	-0.0418	50	10	45
right	Inferior Parietal Lobule	39, 40	-0.0416	35	-65	40
right	Posterior Cingulate	23, 29, 30	-0.0387	5	-60	20
left	Precuneus	7, 19	-0.0358	-5	-70	40
right	Cuneus	17, 18	-0.0353	15	-80	25
right	Postcentral Gyrus	1, 2, 3, 5	-0.0342	65	-10	25
right	Superior Temporal Gyrus	22, 38	-0.0279	40	5	-15
right	Middle Temporal Gyrus	21, 37	-0.0277	45	5	-35
right	Inferior Temporal Gyrus	20	-0.0266	50	0	-40
right	Parahippocampal Gyrus	27, 34, 35	-0.0218	30	5	-20
left	Paracentral Lobule	5	-0.0167	-5	-50	65

Appendix Table 6 Results of ANOVA of scalp-level power for frontal tDCS

Channel	Effect	DFn	DFd	F	p	ges	p.adj	p.adj.signif
Fz	Group:TaskCond:StimCond	3	150	4.506	0.005	0.011	0.035	*
F4	Group:TaskCond:StimCond	3	150	4.215	0.007	0.013	0.049	*
T3	Group:TaskCond:StimCond	3	150	4.743	0.003	0.01	0.021	*
T4	Group:TaskCond:StimCond	3	150	4.395	0.005	0.006	0.035	*
O1	Group:TaskCond:StimCond	3	150	4.133	0.008	0.012	0.046	*

Appendix Table 7 Significant post hoc analyses by group of scalp-level power for frontal tDCS

Channel	Group	Effect	DFn	DFd	F	p	ges	p.adj	p.adj sig
Fz	stim-2nd	TaskCond:StimCond	3	78	4.19	0.008	0.021	0.048	*
T4	stim-2nd	TaskCond:StimCond	3	78	4.712	0.004	0.01	0.024	*
O1	stim-2nd	TaskCond:StimCond	3	78	3.767	0.014	0.023	0.038	*

Appendix Table 8 Simple effects of post hoc analysis by task condition of scalp-level power for frontal tDCS

Task Condition	Channel	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
Life Roles	Fz	sham	stim	27	27	0.365	26	0.718	0.718	ns
Outer Body	Fz	sham	stim	27	27	2.541	26	0.017	0.034	*
Resting State	Fz	sham	stim	27	27	0.723	26	0.476	0.635	ns
External attention	Fz	sham	stim	27	27	2.544	26	0.017	0.034	*
Life Roles	T4	sham	stim	27	27	-0.358	26	0.723	0.723	ns
Outer Body	T4	sham	stim	27	27	0.443	26	0.661	0.723	ns
Resting State	T4	sham	stim	27	27	-0.448	26	0.658	0.723	ns
External attention	T4	sham	stim	27	27	1.542	26	0.135	0.54	ns
Life Roles	O1	sham	stim	27	27	0.899	26	0.377	0.377	ns
Outer Body	O1	sham	stim	27	27	3.555	26	0.001	0.004	**
Resting State	O1	sham	stim	27	27	1.41	26	0.17	0.227	ns
External attention	O1	sham	stim	27	27	2.245	26	0.034	0.068	ns

Appendix Table 9 Results of ANOVA of scalp-level power for frontal tACS

Channel	Effect	DFn	DFd	F	ges	p	p.adj	p.adj.signif
F4	Group:StimCond	1	44	8.743	0.042	0.005	0.035	*
Cz	Group:StimCond	1	44	16.077	0.062	0	0.002	**
T5	Group:StimCond	1	44	10.738	0.044	0.002	0.014	*
PZ	Group:StimCond	1	44	9.94	0.049	0.003	0.021	*
P4	Group:StimCond	1	44	8.081	0.043	0.007	0.049	*
O1	Group:StimCond	1	44	12.53	0.057	0.001	0.007	**

Appendix Table 10 Results of post hoc analyses of scalp-level power for frontal tACS

Group	Channel	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
stim-1st	F4	sham	stim	23	23	-1.777	22	0.09	0.09	
stim-2nd	F4	sham	stim	23	23	2.485	22	0.021	0.042	*
stim-1st	Cz	sham	stim	23	23	-3.888	22	0.001	0.002	***
stim-2nd	Cz	sham	stim	23	23	2.279	22	0.033	0.033	*
stim-1st	T5	sham	stim	23	23	-1.87	22	0.075	0.075	
stim-2nd	T5	sham	stim	23	23	3.044	22	0.006	0.012	**
stim-1st	PZ	sham	stim	23	23	-2.366	22	0.027	0.045	*
stim-2nd	PZ	sham	stim	23	23	2.124	22	0.045	0.045	*
stim-1st	P4	sham	stim	23	23	-1.839	22	0.08	0.08	
stim-2nd	P4	sham	stim	23	23	2.395	22	0.025	0.05	*
stim-1st	O1	sham	stim	23	23	-2.406	22	0.025	0.025	*
stim-2nd	O1	sham	stim	23	23	2.725	22	0.012	0.024	*

Appendix Table 11 Results of ANOVA of scalp-level power for parietal tACS

Channel	Effect	DFn	DFd	F	p	ges	p.adj	p.adj.signif
F3	Group:StimCond	1	47	7.112	0.01	0.036	0.035	*
Fz	Group:StimCond	1	47	6.662	0.013	0.03	0.046	*
C4	Group:StimCond	1	47	9.36	0.004	0.04	0.014	*
T4	Group:StimCond	1	47	7.732	0.008	0.05	0.028	*
P3	Group:StimCond	1	47	8.353	0.006	0.031	0.042	*
P4	Group:StimCond	1	47	7.994	0.007	0.049	0.024	*
T6	Group:StimCond	1	47	8.961	0.004	0.06	0.014	*

Appendix Table 12 Results of post hoc analyses of scalp-level power for parietal tACS

Group	Channel	group1	group2	n1	n2	statistic	df	p	p.adj	p.adj.signif
stim-1st	F3	sham	stim	24	24	-1.585	23	0.127	0.127	
stim-2nd	F3	sham	stim	25	25	2.165	24	0.041	0.082	
stim-1st	Fz	sham	stim	24	24	-1.633	23	0.116	0.116	
stim-2nd	Fz	sham	stim	25	25	2.04	24	0.052	0.104	
stim-1st	C4	sham	stim	24	24	-2.64	23	0.015	0.030	*
stim-2nd	C4	sham	stim	25	25	1.877	24	0.073	0.073	
stim-1st	T4	sham	stim	24	24	-2.058	23	0.051	0.06	
stim-2nd	T4	sham	stim	25	25	1.973	24	0.06	0.06	
stim-1st	P3	sham	stim	24	24	-2.792	23	0.01	0.02	*
stim-2nd	P3	sham	stim	25	25	1.545	24	0.135	0.135	
stim-1st	P4	sham	stim	24	24	-1.728	23	0.097	0.097	
stim-2nd	P4	sham	stim	25	25	2.296	24	0.031	0.062	
stim-1st	T6	sham	stim	24	24	-2.603	23	0.016	0.032	*
stim-2nd	T6	sham	stim	25	25	1.754	24	0.092	0.092	

Appendix Table 13 Results of follow-up exploratory ANOVA of parietal tACS for session 1 only

Channel	Effect	DFn	DFd	F	ges	p	p.adj	p.adj.signif
FP1	StimCond:TaskCond	3.00	141.00	4.122	0.008	0.019	0.024	*
F3	StimCond:TaskCond	3.00	141.00	3.635	0.014	0.028	0.042	*
Fz	StimCond:TaskCond	3.00	141.00	5.639	0.001	0.044	0.003	**
F4	StimCond:TaskCond	3.00	141.00	6.193	0.001	0.042	0.002	**
Cz	StimCond:TaskCond	3.00	141.00	6.100	0.001	0.053	0.002	**
C4	StimCond:TaskCond	3.00	141.00	5.263	0.002	0.050	0.006	**

Appendix Table 14 Post hoc analysis of follow-up exploratory ANOVA of parietal tACS for session 1 only

TaskCond	Channel	group1	group2	n1	n2	p	p.adj	p.adj.signif
LifeR	FP1	sham	stim	25	24	0.047	0.178	
Outer	FP1	sham	stim	25	24	0.089	0.178	
rest	FP1	sham	stim	25	24	0.412	0.549	
XIntr	FP1	sham	stim	25	24	0.751	0.751	
LifeR	F3	sham	stim	25	24	0.019	0.069	
Outer	F3	sham	stim	25	24	0.035	0.069	
rest	F3	sham	stim	25	24	0.059	0.079	
XIntr	F3	sham	stim	25	24	0.724	0.724	
LifeR	Fz	sham	stim	25	24	0.002	0.007	**
Outer	Fz	sham	stim	25	24	0.014	0.028	*
rest	Fz	sham	stim	25	24	0.048	0.064	
XIntr	Fz	sham	stim	25	24	0.652	0.652	
LifeR	F4	sham	stim	25	24	0.004	0.015	*
Outer	F4	sham	stim	25	24	0.088	0.141	
rest	F4	sham	stim	25	24	0.106	0.141	
XIntr	F4	sham	stim	25	24	0.486	0.486	
LifeR	Cz	sham	stim	25	24	0.000	0.002	**
Outer	Cz	sham	stim	25	24	0.043	0.086	
rest	Cz	sham	stim	25	24	0.263	0.351	
XIntr	Cz	sham	stim	25	24	0.637	0.637	
LifeR	C4	sham	stim	25	24	0.063	0.126	
Outer	C4	sham	stim	25	24	0.287	0.335	
rest	C4	sham	stim	25	24	0.335	0.335	
XIntr	C4	sham	stim	25	24	0.029	0.118	
LifeR	P4	sham	stim	25	24	0.011	0.042	*
Outer	P4	sham	stim	25	24	0.030	0.042	*
rest	P4	sham	stim	25	24	0.031	0.042	*
XIntr	P4	sham	stim	25	24	0.842	0.842	

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