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The Impact of Stand-Alone And Combined Brief Virtual Reality Induced Focused Mindfulness and TDCS on Attention

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ABSTRACT

Attention is a critical component influencing various cognitive abilities, as well as in the interference of daily distractions with other cognitive functions. Given its crucial role in other executive functions and in clinical populations such as dementia, and ADHD, interventions like transcranial direct current stimulation (tDCS) and mindfulness meditations have been investigated for their potential to improve cognitive performance. However, the outcomes of these non-pharmacological approaches have shown variable efficacy in research findings. This study investigates the effects of brief sessions of virtual reality induced focused mindfulness, single session tDCS, and their combination on attentional enhancement. A randomized controlled trial was conducted, comprising 107 participants distributed across five groups according to their intervention types, which included mindfulness or mind-wandering scenarios, active or sham tDCS, and a control group without any intervention. Participants' attentional performance was assessed using the Sustained Attention Response Task (SART), comparing the effects across groups. The results indicate that there are no significant differences between the five experimental groups in terms of SART performance as a cognitive outcome. However, there is a significant difference in skin conductance levels, with the group that received active tDCS and mindfulness meditation showing lower levels during the intervention compared to the control group (which received the mind wandering scenario and sham tDCS). This suggests that neither a single session of tDCS, a brief mindfulness induction, nor the combined versions of these two interventions have any effect on participants' sustained attention ability. Further research is needed to explore these methods more thoroughly.

Keywords: brief mindfulness induction, mind-wandering, attention, virtual reality, single session tDCS, skin conductance level

The Impact of Stand-Alone and Combined Brief Virtual Reality Induced Focused Mindfulness and tDCS on Attention and Inhibitory Control

1. INTRODUCTION

1.1 What is Mindfulness?

In recent times, the terms 'mindfulness' and 'being mindful' have become commonly used, in the sense of well-being, particularly through the emphasis on the present moment. Mindfulness practices, often underscored by the promise of feeling better 'now and here', include mindfulness-based meditations that many of us have encountered. However, if we have tried one or more of these practices, we may have experienced them in varied ways, each of us having unique perceptions and outcomes. In addition to the increasing exposure in our daily lives, there has been substantial growth in research exploring meditation and its effects (Valluri et al., 2024). However, there is a lack of consensus in the literature regarding its impacts and also definition.

Mindfulness draws its roots from Buddhist meditation practices, providing individuals with the opportunity to live in harmony with themselves and the world by expanding their awareness and enabling us to be more conscious about our lives, ourselves and the vast array of conscious and unconscious possibilities (Kabat-Zinn, 1994). Facilitating this for individuals, mindfulness practices direct awareness to the present moment by noticing internal aspects such as one's own thoughts and feelings, as well as external cues like sounds or smells in the environment, with a non-judgmental attitude (Im et al., 2021).

Despite the significant increase in studies related to mindfulness, the term remains difficult to define clearly, as there is still a lack of consensus regarding the detailed aspects of the underlying concept it refers to (Dam et al., 2017).

Taking into account the interchangeability of the terms ‘mindfulness’ and ‘meditation’, it is imperative to establish measurable and assessable definitions for mindfulness, facilitating its study. In order to construct heterogeneity, Lin et al. (2021) proposed taxonomy that has four different operationalizations of mindfulness: dispositional mindfulness (natural propensity to be mindful), state mindfulness (shifting concentration without judgment), mindfulness skill (gained from long-term mindfulness practice) and mindfulness training (future oriented practices involve intentional contemplative techniques such as meditation). Dispositional mindfulness, a term also used interchangeably with trait mindfulness, refers to an intrinsic quality that exists irrespective of any formal mindfulness training or meditation experience. It is commonly defined as the overall inclination of an individual to exhibit nonjudgmental awareness of their present-moment experiences in their daily life (Karl & Fischer, 2022). This tendency could vary from one individual to another. Notably, regularly incorporating mindfulness practices into one’s life has been identified as a factor contributing to an augmentation in the baseline of this trait (Tomlinson et al., 2018). Trait mindfulness and individual differences could be assessed through self-report questionnaires such as the Mindfulness Attention Awareness Scale (MAAS; Brown & Ryan, 2003), Five Facet Mindfulness Questionnaire (FFMQ; Baer et al., 2008) or Mindfulness Process Questionnaire (Erisman & Roemer, 2012). These questionnaires help reveal distinctions in the frequency of attention to and awareness of present-moment experiences (Deng et al., 2012). On the other hand, state mindfulness pertains to a cognitive state marked by being attuned to the present moment, with the duration varying across instances, focusing on what experiences an individual attends to and how they engage with those experiences (Ruimi et al., 2022). According to proponents, practicing mindfulness or meditation could also enhance one’s state mindfulness, and questionnaires like State-MAAS (Brown & Ryan, 2003) and Toronto Mindfulness Scale (TMS; Lau et al., 2006) are used to quantify such improvements.

Mindfulness training is a form of mental training that serves various purposes, such as improving attention and overall well-being. It may encompass structured interventions, including the eight-week Mindfulness-Based Stress Reduction (MBSR; Kabat-Zinn, 2013) and Mindfulness-Based Cognitive Therapy (MBCT; Segal et al., 2013), along with meditation practices. Numerous studies have been conducted to investigate the effectiveness of Mindfulness-Based Interventions (MBI) in both clinical and healthy populations, assessing the reliability of their impact. Research efforts aim to revise programs based on empirical evidence, examining not only their efficacy but also their applicability to various issues. For instance, in the review of Vibe et al. (2012), demonstrated a moderate and consistent impact of Mindfulness-Based Stress Reduction (MBSR) on various mental health conditions. Additionally, the intervention exhibited potential in the realm of personal development and was associated with an enhancement in quality of life (Vibe et al., 2012).

While there is substantial evidence supporting the effectiveness of structured mindfulness-based interventions, the impact of brief mindfulness induction remains inconclusive in the literature. The review by Jimenez (2020) showed that brief mindfulness induction has both negative and positive effects in terms of positive affect, anxiety, dysfunctional attitudes, rumination, intrusive thoughts and more. Therefore, it is important to consider these varying outcomes in the context of our study. Due to this gap in the literature, this study will employ a brief mindfulness induction as an intervention method.

1.1.1 Mindfulness and Cognitive Functions

Mindfulness training has been extensively emphasized in the literature for its significant impact on cognitive abilities, including executive functions, memory and attention (Chiesa et al., 2010). Executive functions refer to a set of mental processes that enable cognitive control in line with personal goals, typically involving inhibitory control, conflict monitoring, planning, reasoning, problem-solving, decision-making, and cognitive flexibility (Im et al., 2021).

Given that executive functions comprise numerous components, studying them as a singular entity presents challenges. Studies suggest that the integration of three fundamental mental processes, which cannot be conceptualized independently, may form executive functions, namely, working memory, attention shifting, and inhibitory control (Millett et al., 2021). Studies based on mindfulness training programs lasting up to eight weeks have found varying results regarding the effects of mindfulness on executive functions (Cásedas et al., 2020; Whitfield et al., 2022; Zhou et al., 2020). Controversial findings have also emerged concerning the subgroups of executive functions.

In the context of memory, both science and Buddhist philosophy acknowledge it as the retention of past experiences, underscoring the importance of understanding one's history in shaping cognitive frameworks and fostering personal development (Levi & Rosenstreich, 2019). Though memory is a complex topic with different systems and models, we can simplify the discussion by delineating it into three primary categories: short-term memory, working memory and long-term memory. Short-term memory and long-term memory can be differentiated based on their storage capacity and duration (Cowan, 2008). As implied by its name, short-term memory is considered as a dynamic system that temporarily holds a limited amount of information. On the other hand, long-term memory encompasses procedural skills, non-factual and factual knowledge such as facts, meanings, and concepts, also enables the exploration of past experiences, akin to a journey through time (Levi & Rosenstreich, 2019). Alongside definitions such as working memory being alternatively characterized as short-term memory applied to cognitive tasks, a multi-faceted system for handling information in short-term memory, and utilization of attention to manage short-term memory (Cowan, 2008), it is evident that correlational studies have faced challenges in consistently differentiating these concepts (Aben et al., 2012).

Levi and Rosenstreich's review (2019) has indicated that mindfulness practices enhance working memory and exert an impact on long-term memory by improving control over the acquisition and retrieval of procedural knowledge. However, they have emphasized the need for further research to establish conclusive results.

The central theme of this study revolves around attention, as mindfulness primarily involves directing one's focus towards both internal and external factors in the present moment. Attention, in this context, refers to the conscious awareness and concentration on these aspects, making mindfulness a potent influencer of cognitive abilities. Generally, two primary forms of meditation are used to enhance mindfulness (Verhaeghen, 2020) and attention regulation (Sumantry & Stewart, 2021). Firstly, focused attention (FA) meditation, involving intentional and sustained attention on a selected object, generally one's own breath. The second type is open monitoring (OM), characterized by non-reactive observation of one's own experience (emotions, thoughts, memories…) moment by moment (Travis & Shear, 2010). While these two types of meditation can be distinctly defined, there is a functional overlap and they are often used together in practices; nevertheless, the studies are not sufficient to differentiate between focused attention and open monitoring (Sumantry & Stewart, 2021). When discussing attention, as with all cognitive abilities, it is crucial to acknowledge its multidimensional nature, characterized by a spectrum of versatile functions. In the article of Posner and Petersen (1990), attention was identified by three different but interconnected subsystems, specifically termed as alerting, orienting and executive control. The "alerting" represents temporal readiness for any novel stimuli and it is also responsible for sustained attention. The "orienting" subsystem directs attention to specific locations, while the "executive control" functions as a conflict resolver in information processing and regulates attentional resources (Sumantry & Stewart, 2021). Taking into account these three subsystems, during mindfulness meditation, one can effectively sustain focused attention, inhibit concurrent distractions, and enhance attention regulation. The practice may contribute to emotion regulation through the cultivation of bodily awareness combined with non-judgmental acceptance. Additionally, it is proposed to improve self-regulation through better attentional control (Tang et al., 2015). By facilitating sustained attention alongside the ability to shift attention, it modulates executive control, consequently influencing working memory.

The meta-analysis conducted by Sumantary and Stewart (2021) revealed that meditation, regardless of focused attention (FA) or open monitoring (OM) techniques, resulted in enhanced attentional capabilities; albeit with a small effect size; particularly, the alerting attentional network and the inhibition aspect of executive control demonstrated benefits related to meditation, while meta-analysis for orienting and shifting reported null results. Additionally, Verhaeghen (2021) points out that the improvement in attention is more noticeable in long-term meditators than in meditation - naïve participants.

Due to the significant role of attention in mindfulness practices, mindful attention and cognitive control have become important topics in the research community. Bishop et al. (2004) present a two factor model that describes two main features of mindfulness based meditations: self-regulation of attention and orientation to experience. According to this model, participants can maintain their sustained attention to stay aware of the current experience and they can also switch their attention to the present moment by utilizing focal points such as their breath or specific body parts and they can inhibit elaborative processing, preventing potential distractions that might divert their focus from the present moment (Im et al., 2021).

Due to its potential advantages, mindfulness has gained prominence in diverse clinically and non-clinically oriented programs that could be beneficial for some conditions include medical illness such as ADHD and cancer, anxiety, stress, managing chronic pain, depression (Im et al., 2021), alcohol and substance consumption, decreased blood pressure (Chiesa et al., 2010).

Sample size, meditation experience, and variations in mindfulness types can result in diverse and conflicting study outcomes. However, more significant findings are needed to understand the impact of mindfulness on cognitive abilities. As indicated in the literature, attention functions as a gateway when considered alongside other cognitive abilities. Mindfulness and mindfulness-based meditation practices, particularly in their capacity to maintain attention in the present moment, the emphasis on being aware of emotions, thoughts and bodily sensations have a direct influence on sustained attention. Discovering robust evidence for its positive effects on attention may also lead to favorable outcomes for other cognitive abilities. Studies showed that 8-week mindfulness programs and long-term meditators have similar structural and functional changes in the brain (Gotink et al., 2016).

Furthermore, we are inquisitive about the influence of a brief mindfulness induction on cognitive abilities. Some studies, such as Erisman and Roemer (2010), indicate that brief mindfulness exposure leads to more adaptive emotion regulation. Leyland et al. (2019) further support this by suggesting that brief mindfulness induction can indirectly enhance executive functions by improving emotional regulation, thereby decreasing mental burden and enhancing concentration capacity. However, a recent systematic review and meta-analysis by Gill et al. (2020) found that a single session of brief mindfulness does not significantly enhance cognitive performance in tasks requiring attentional and executive functioning. Due to its role as a gateway and the confounding results regarding the effects of brief mindfulness on attention, we have selected sustained attention and focused attention mindfulness induction as the types of mindfulness to be explored in our study.

1.1.2 Neural Correlates of Mindfulness and Sustained Attention

The changes meditation induces in the brain have been studied for a long time. While studies reveal the effects of long-term meditation, neuroimaging studies show that brief mindfulness induction (less than 30 days) also causes structural and functional changes in the brain (Tang et al., 2020). Mindfulness prompts alterations in gray and white matter in the brain, and it is also associated with an increase in neural activation in the insula, prefrontal and anterior cingulate cortex which are related to higher-order cognitive functions such as attention (Young et al., 2018).

Converging evidence also indicates mindfulness is related to functional connectivity in the default mode network (DMN; eg, posterior cingulate cortex, dorsomedial prefrontal cortex [FPC]), frontoparietal (FPN; dorsolateral PFC) and salience network (SN; eg, dorsal anterior cingulate cortex, insula) (Sezer et al., 2022). However, studies focusing on the functional connectivity of mindfulness also incorporate inconsistent findings. The experimental investigation of mindfulness is challenged by discrepancies between research questions and study designs, variations in meditation types (mindfulness meditation, guided meditation, Zen meditation etc.) difficulties in implementing meditation protocols, individual differences among practitioners, and the impracticality of conducting double-blind, placebo-controlled studies (Caspi & Burleson, 2007). Hence, there is a need for more controlled studies to achieve consensus in the field.

Sustained attention is a critical cognitive function that underlies other forms of attention (divided and selective) and also fundamental for other cognitive abilities such as memory and learning (Slattery et al., 2022). It provides staying focused on goal directed behavior, while suppressing distractions such as irrelevant thoughts and feelings, thereby preventing mind wandering. And these two key elements of the sustained attention are represented in the brain by two networks: the central executive network (CEN; bilateral DLPFCs and bilateral parietal cortices) which typically shows greater activation during attention-demanding tasks and the default mode network (DMN) which is more activated in resting state (Bauer et al., 2020). The synchrony between these two systems contributes to the maintenance of sustained attention (Hellyer et al., 2014).

Although trait levels of mindfulness and uncontrollable individual differences make it challenging to achieve clear and generalizable results in studies examining the behavioral and neural effects of mindfulness, the study by Dickenson et al. (2013) observed that brief mindfulness induction in novice participants resulted in a decrease in BOLD signal in the default mode network and an increase in the fronto-parietal attention network in fMRI images.

Based on the assumption that the dorsolateral prefrontal cortex (dlPFC) plays a common role in both top-down control of attention, guiding focus based on goals and intentions (Yen et al., 2024), and processes associated with mindfulness and mind wandering, we designed this study with the hypothesis that an increase in dlPFC activation would enhance performance in task requiring sustained attention. Accordingly, brief mindfulness induction and dlPFC stimulation were chosen as the independent variables for this research.

1.1.3 Psychophysiology of Mindfulness

Many mindfulness-based intervention programs emphasize the modulating effect of mindfulness on the balance of the autonomic nervous system (Scavone et al., 2020). The autonomic nervous system plays a crucial role in maintaining homeostasis, regulating the body's fight-or-flight response through the sympathetic system and promoting recovery and maintenance through the parasympathetic system (McCorry, 2007). While it is generally crucial in the study of stress, it gains particular significance in investigating mindfulness effects on stress reduction, anxiety and emotion regulation, assessed through measures like skin conductance and heart rate variability. These two subsystems of the ANS work in an opposite manner, such that the activity of one increases while the other decreases (Scavone et al., 2020).

Skin conductance, which measures electrodermal activity, reflecting the activity of sweat glands regulated by the sympathetic nervous system. Skin conductance response is used for observing the connection between skin conductance response (SCR) and cognitive and emotional activations, although there is not a consistent association between mental processes and SCR (Hinterberger et al., 2018). Studies exploring the connection between mindfulness and skin conductance (SC) have generated mixed results, leaving an unsolved question about whether mindfulness traits, states, or interventions have an impact on sympathetic activation. According to Scavone et al. (2020), individuals who reported higher levels of mindfulness showed reduced sympathetic psychophysiological activation compared to those with lower levels of state mindfulness. However, no differences in psychophysiological activation were detected between individuals with high and low levels of trait mindfulness. In a pilot study conducted by Lassander and colleagues in 2022, although they identified differences between mindfulness intervention and relaxation-based groups, they did not achieve statistically significant results.

1.1.4 Mindfulness and Virtual Reality

The role of technology in our lives is increasing significantly day by day. Virtual reality, beyond its role in gaming and entertainment, has become one of the technologies we encounter continually today due to its increasing use in education and healthcare, offering practical and beneficial outcomes. In the realm of mindfulness, VR offers various mindfulness designs that aid the user's focus on bodily sensations through a heightened sense of immersion and presence. These designs may involve guided meditations or audio and visual cues that enhance awareness by directing the individual's attention.

Due to its immersive nature, virtual reality stimulates all perceptual channels of the individual, exhibiting potential favorable features to facilitate mindfulness practice. The review by Arpaia et al. (2022), indicates that this enhances participant's motivation in meditation not only by stimulating perceptual channels but also by using gamification features. Argüero-Fonseca et al., (2022) identified a significant difference in attention and memory between the experimental and control groups while using virtual reality through the application TRIPP. Mitsea et al., (2022) suggested that combining mindful breathing with virtual reality enhances sustained attention, reaction time, and attentional control by facilitating the involuntary allocation of attentional resources.

Considering this evidence and the feasibility of brief mindfulness meditation in the laboratory setting, we have decided to implement a VR environment in our research that incorporates gamification, as well as brief mindfulness induction containing attention-guiding breathing exercise.

1.2 Mind Wandering

Mind-wandering refers to the spontaneous and involuntary shifting of thoughts from the present task or events toward unrelated thoughts and feelings (Christoff et al., 2016). Due to its characteristic feature of attention decoupling, mind-wandering negatively affects various cognitive performances that require cognitive control and attention (Mooneyham & Schooler, 2013). While the mind wandering is a normal psychological process that can occur anytime and anywhere, about 30-50% of our daytime (Kawagoe et al., 2019), it has a negative impact on tasks that require executive control. In this study, mind wandering was not used as an additional variable, nor was there a mind wandering intervention for the experimental groups. Although there are overlapping regions with focused mindfulness meditation (Christoff et al., 2009), and it's crucial to strike balance between the two processes (Smallwood & Schooler, 2015), this study did not specifically examine mind wandering and its underlying processes. Instead, it was used as a control condition for the mindfulness intervention group.

1.3 TDCS

TDCS is a non-invasive technique that uses mild electrical currents on the scalp to adjust the activity of the neural circuits below (Molina et al., 2020). The type of stimulation affects the modulation direction: cathodal stimulation, which hyperpolarizes neurons, generally leads to a decrease in cerebral excitability (Nitsche & Paulus, 2000) while the anodal stimulation induces neuronal depolarization, thereby enhancing excitability (Molina et al., 2020). Evidence suggests that tDCS stimulation can transiently boost prefrontal functioning (Miler et al., 2018) and enhanced excitability can occur right after the stimulation and may endure for up to 30-90 minutes following the conclusion of the stimulation (Pantovic, 2022). As indicated in the literature, stimulation intensity up to 2mA and a duration of approximately 30 minutes are generally regarded as safe (Wörsching et al., 2016).

Although tDCS can produce after-effects lasting up to an hour and single session can enhance cognitive abilities, the electrode size, placement, stimulation intensity, duration, and individual differences contribute to inconsistent and conflicting outcomes (Brunoni et al., 2012). Therefore, further investigations and controlled conditions over different cortical areas are necessary for optimizing tDCS parameters (Hunter et al., 2018).

1.3.1 tDCS and dlPFC Related Cognitive Functions

Cognitive functions could include a wide range of mental processes ranging from decision making, social cognition and moral reasoning, which involve emotional and motivational components, to attention, memory, inhibition and problem solving, which are less influenced by emotional factors. The prefrontal cortex (PFC) is the key region within the network of both hot and cold cognitive functions. Specifically, the dorsolateral prefrontal cortex (dlPFC) is identified as being responsible for these functions, including both emotional and non-emotional aspects (Lindquist et al., 2012). According to the review of Salehinejad et al., (2021), dlPFC has been predominantly associated with cold cognitive functions, yet its involvement in some aspects of emotional processing complicates the ability to make a clear and precise distinction among the brain areas.

Stimulating the dlPFC with tDCS seems to enhance cognitive performance in both healthy individuals and patients with neurological conditions. These positive effects can last for days to up to 3 months, showing promise for improving cognitive abilities (Bashir et al., 2019). Anodal tDCS applied to the left dlPFC has been observed to positively impact task performance on attentional task requiring sustain attention and inhibitory control in both healthy subjects and those with ADHD (Nelson et al., 2014; Soff et al., 2017; Sotnikova et al., 2017).

Alongside findings that suggest tDCS stimulation on dlPFC enhances cognitive abilities in both healthy and clinical subjects, single session tDCS remains a highly debated topic in the literature (Frings et al., 2021). Horvath et al. (2015), in their review, argue that tDCS has a zero effect on cognitive outcomes, indicating that it is not yet possible to draw generalizable conclusions.

Taking into account the research findings indicating the prefrontal cortex, particularly the dorsolateral prefrontal cortex (dlPFC), as a key area for the functional connectivity of mindfulness, coupled with the results showing that transcranial direct current stimulation (tDCS) applied to the dlPFC enhances sustained attention, it can be inferred that non-invasive stimulation applied to this region in conjunction with focused mindfulness meditation may lead to a greater increase in attentional abilities.

1.4 Rationale for Research

In the light of the need for further exploration into the effects of both transcranial direct current stimulation (tDCS) and mindfulness meditation on neuropsychophysiological processes associated with cognitive performance enhancement, this study aims to significantly contribute to current knowledge in this field.

With this study we aim to further understand the impact of brief focus mindfulness meditation and single session tDCS on cognitive and psychophysiological processes, as well as exploring the interplay among these distinct levels of analysis. Furthermore, the study seeks to investigate the underlying mechanisms through which brief mindfulness induction and single session tDCS influence attention and inhibitory control. Additionally, the research will further contribute to the field by examining the correlation between mindfulness, tDCS, prefrontal activity, and cognitive functioning across individuals with varying levels of trait mindfulness. Within this framework, we anticipate that participants exposed to both tDCS active and focus mindfulness meditation (MM) will exhibit superior sustained attention abilities measured through the SART compared to those exposed solely to either tDCS active or MM, with no significant increase expected in mind-wandering and tDCS sham groups. We hypothesize that the group exposed to MM will experience a decrease in arousal compared to other groups, regardless of tDCS activation.

2. MATERIALS AND METHODS

2.1 Ethics

The project was complied with the GDPR, the Ethical Principles of the Chapter of Fundamental Rights of the EU, the Declaration of Helsinki, the American Psychological Association, the European Code of Conduct for Research Integrity, and the Portuguese College of Psychologists and was approved by the Ethical Committee of the Faculty of Psychology and Educational Sciences of the University of Coimbra. Privacy was protected by anonymized procedures. All methods employed are non-invasive, therefore physical, psychological, financial, or legal risks for participants are minimal. Participants were informed about the research process and voluntary nature of participation, all of the risks associated with their participation and their rights to withdraw from research any time. Additionally, consent was obtained from all participants after they were fully informed.

2.2 Recruitment

The participants were recruited from the psychology department voluntarily, and they were given extra credit for their participation. The participants ranged in age from 18 to 46 years (*M*=20.9y, *SD*=5y) and were required to have a satisfactory level of proficiency in English comprehension to understand the tasks in the experiment. The exclusion criteria were defined as follows: age over 50, current or previous history of psychiatric or neurological disorders, ongoing use of psychopharmacological medication, history of epilepsy, current or previous metal implants (excluding titanium) in the brain or skin, current or previous metal equipment in the body (such as a pacemaker), current or previous head injuries and/or resulting disorders of consciousness, skin problems, history of syncope, pregnancy or potential pregnancy, and uncorrected vision or color blindness. Two hours before the experiment, participants were instructed to: (i) refrain from smoking and consuming alcohol, tea, coffee or energy drinks; (ii) abstain from engaging in meditation or participating in sporting activities. Informed consent was provided to participants before the experiment.

The current study was designed as a double-blind study, ensuring that both participants and researchers were unaware of the experimental group assignments and the groups were divided into five groups based on experiencing either active tDCS or sham conditions, mindfulness or mind-wandering conditions, and finally, a control group that did not undergo any interventions. Initially, the study included a total of 112 participants. However, five participants were excluded from the final analysis due to non-compliance with the experimental conditions. Specifically, one participant was excluded due to cardiac concerns, another participant had smoked within two hours before the experiment, one participant did not have sufficient English proficiency to follow the instructions, and two participants reported not feeling well during the experiment. Consequently, the final sample size for the analyses was reduced to 107 participants (26 male, 81 female).

2.3 Procedures

Prior to acquainting themselves with the experimental setting, participants were requested to fill out a self-report sociodemographic questionnaire developed by the research team. This procedure was executed on the LimeSurvey platform with the aim of ascertaining the eligibility of participants for engagement in the study. Candidates were determined to be eligible were organized for in-person sessions and were randomly assigned to one of the five experimental groups:

Group 1: Participants received 20 minutes of active transcranial Direct Current Stimulation (tDCS) over the left dorsolateral prefrontal cortex (DLPFC) combined with a focused mindfulness meditation scenario.

Group 2: Participants received 20 minutes of active tDCS over the left DLPFC along with a mind-wandering scenario.

Group 3: Participants received 20 minutes of sham tDCS over the left DLPFC and participated in a 20-minute focused mindfulness meditation scenario.

Group 4: Participants received 20 minutes of sham tDCS over the left DLPFC and engaged in a 20-minute mind-wandering session.

Group 5: Participants did not receive any intervention and served as the control group.

The experimental sessions were conducted in a quiet room to create an environment conducive to attention. Prior to the initiation of the intervention, participants were instructed to complete Mindful Attention and Awareness Scale (MAAS), the Depression Anxiety and Stress

Scale (DASS-21), and the Difficulties in Emotional Regulation Scale (DERS) assessments on LimeSurvey. In the preparation stage, every participant was administered the Trail Making Test A (TMT-A) and Trail Making Test B (TMT-B) in order to establish a baseline for participants' cognitive performance. Furthermore, participants completed the 2 minutes virtual reality habituation phase, regardless of whether they were assigned to the mindfulness or mind-wandering group, to familiarize them with the environment and ensure they were not experiencing any discomfort. Following the completion of all questionnaires and the assessments for cognitive baseline and habituation, participants were proceeded to the intervention phase of the study.

Skin conductance (SC) and transcranial direct current stimulation (tDCS) data were concurrently collected as participants engaged in the virtual reality (VR) experience which incorporated either a mindfulness or a mind-wandering scenario. Participants exposed to the focused mindfulness meditation engaged in gamified activities with verbal instructions aimed at maintaining focus and sustained attention. Meanwhile, mind-wandering sessions lacked auditory cues, involving observation of naturalistic scenes within virtual landscapes.

Following the completion of the VR scenario, the VR headset was removed, and the administration of tDCS was concluded, along with the cessation of skin conductance measurements. Subsequently, participants completed the Toronto Mindfulness Scale (TMS) to measure "state-like" experiences during VR experience and the Adverse Side Effects Questionnaire for tDCS and VR. In the concluding stage of the experiment, participants underwent neuropsychological assessments, including the Emotional Stroop Task for inhibitory control and emotion regulation and the Continuous Performance Test for sustained attention (SART). However, this study primarily concentrates on sustained attention and given that the SART provides insights into vigilance and inhibitory control, the outcomes are the primary focus of my analyses. The results presented in this thesis do not include the outcomes of the Emotional Stroop task. While this task and its outcomes were conducted concurrently, they will be explored in another thesis dedicated to that spesific topic. This setup provided the means to examine the effects of the brief focused mindfulness induction and the tDCS on cognitive performance.

2.4 Measures

2.4.1 Self – Report Questionnaire

Sociodemographic questionnaire. The sociodemographic questionnaire was developed by the research team to assess participants' demographics (e.g., age, gender, educational level, mental health history, recent caffeine use, lifestyle) and to learn participants' previous experience of mindfulness.

MAAS. Trait mindfulness was measured using the 15-item-single-factor MAAS (Mindfulness Attention Awareness Scale) (MAAS; Gregório & Pinto-Gouveia, 2013; Brown & Ryan, 2003), which had been translated into Portuguese and adapted for use. Items are scored on a 6-point Likert scale (1 = almost always; 6 = almost never) , with Cronbach's alpha values of 0.82 and 0.87. This scale encompasses cognitive, emotional, physical, interpersonal, and general domains of trait mindfulness, with higher scores indicating a greater level of trait mindfulness. Total score on the MAAS was used in the current study as a measure of self-reported mindfulness and to understand participants' trait mindfulness level.

DASS. The Depression Anxiety and Stress Scale (DASS-21; Pais-Ribeiro et al., 2004; Lovibond & Lovibond, 1995) consists of three subscales that assess depression, anxiety, and stress symptoms experienced in the past two weeks. In this study, the 21-item short version of the DASS was employed with seven items allocated to each category, based on a four-point rating scale (0 = 'did not apply to me at all'; 3 = 'applied to me very much, or most of the time'). To align the scores with the full Depression Anxiety and Stress Scale, each seven-item scale was doubled. The Cronbach's alpha values for these subscales are reported as 0.85, 0.74, and 0.81, respectively.

DERS. Difficulties in Emotion Regulation Scale (DERS-SF; Moreira et al., 2020; Kaufman et al., 2015) was used to gather information on participants' difficulties in regulating their emotions. Brief version of the scale had 18 items, scored on a 5-point severity/frequency scale. Cronbach's alpha values range from 0.65 to 0.84, where higher scores reflect more challenges in employing effective emotional regulation strategies. This scale also was adapted for the Portuguese sample.

Adverse Side Effects Questionnaire for Virtual Reality and tDCS. The adverse side effects questionnaires were developed by the research team to observe whether participants experienced any side effects following VR and tDCS. Values range from 1 ("indicating absent") to 10 ("indicating severe") for each of the items.

TMS. The Portuguese version of Toronto Mindfulness Scale (TMS; Lau et al., 2006; Portuguese version by Mateus et al., 2024) was used for assessing state mindfulness. The instrument consists of 13 items divided into two subscales: curiosity and decentering. Each item is rated on a 5-point severity/frequency scale. Higher scores on the scale indicate increased levels of curiosity, decentering, and overall state mindfulness.

2.4.2 Neuropsychological Assessments

SART. Sustained Attention Response Task is a form of Continuous Performance Test that consists of detecting and responding to Go-No/Go tasks over a prolonged period of time. It was used for assessing if the sustained attention capacities among participants differed based on the experimental conditions or experiences they were exposed to. In this study, we decided to select a Continuous Performance Task (CPT) because of predominant characteristics in the literature, which primarily assess the subjects' capability to concentrate and sustain vigilance over time, as well as its initial purpose of identifying deficits in sustained attention (Shalev, Ben-Simon & Mevorach et al., 2011). Specifically, SART was chosen for this study due to its specific suitability in terms of duration, extensive history as a neuropsychological tool for measuring mind wandering, well-established neural and behavioral correlates (Morrison, Goolsarran & Rogers et al., 2014). Furthermore, the SART was used as a measure of response control, making it a valuable instrument for investigating the impact of distraction of the executive control system (Helton, Weil & Middlemis et al., 2010).

The Sustained Attention to Response task, in this study was adapted from Stothart, C. (2015) for PsychoPy version 2023.2.3. During the task, participants were presented with a digit (ranging from 1 to 9) at the center of a black screen for 250 ms, followed by a mask for 900 ms. Their task was to press the space key immediately upon seeing each digit on the screen (target; go trials), except when the digit 3 appeared (non target; no-go trials). A practice stage consisting of 18 trials was included, providing feedback on accuracy (correct/incorrect). In our experiment, participants completed 6 blocks, each comprising 45 trials (5 font sizes × 9 digits), without receiving accuracy feedback. Every unique digit was presented 40 times per block, with the presentation order randomized for each participant. The font size of the digits varied between trials, randomly chosen from a set of five possible font heights: 1.20, 1.80, 2.35, 2.50, or 3.00 cm, with each size used 72 times per block. Response times and accuracy rates were recorded for analysis.

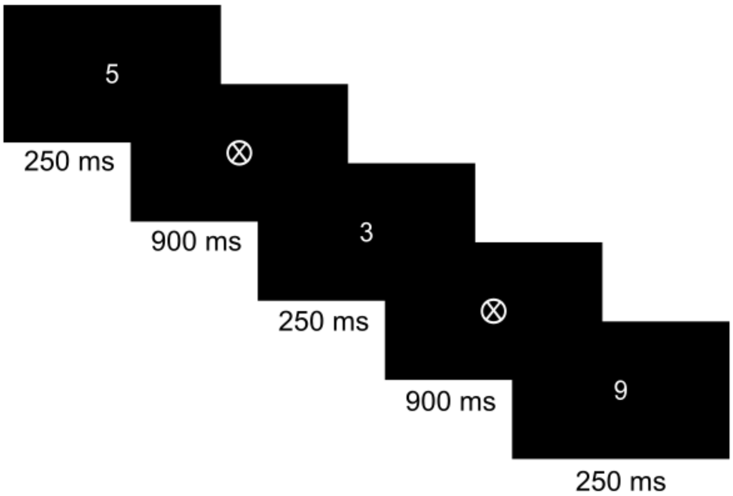

Figure 1. Experimental Paradigm

2.4.3 Electrophysiological Measurement

Skin Conductance Level. Researchers investigating the correlation between mindfulness and skin conductance (SC) remain uncertain regarding whether mindfulness influences sympathetic arousal levels (Scavone, Kadziolka & Miller, 2020). Skin conductance data was collected using a PPG sensor and two galvanic skin response (GSR) sensors of the Shimmer3 GSR + Unit. The GSR sensors were attached to the index and middle fingers of the non-dominant hand, and the PPG sensor was attached to the ear-lobe. The data was collected for each VR scenario of the 20 minutes session with a sampling rate of 128 Hz.

2.4.4 Oculus Rift and TRIPP VR

For this study we make use of the Oculus Rift S. head-mounted display, a product stemming from Oculus VR, a division under Meta Platforms. It aims to provide a fully immersive virtual reality experience for the user, fostering an environment where they can concentrate on the screen devoid of any distractions. TRIPP is a software product available for purchase, created by TRIPP Inc. (TRIPP Inc., Los Angeles, USA, www.tripp.com) that includes guided meditations, breathing exercises, games and sounds with immersive mindfulness teaching. This application allows users to experience their own meditation sessions from a variety of visual and auditory stimulation. For the mindfulness induction, we employed the "Focus" feature within the TRIPP app, integrating attention-stimulating gameplay mechanics. During the mind-wandering sessions participants were exposed to a "Calm" condition, which facilitated immersion in naturalistic scenes while observing virtual landscapes.

2.4.5 tDCS Procedure

For transcranial direct current stimulation (tDCS), participants were administered the Sooma tDCS™ portable device and a proprietary Sooma head cap. A direct current of 2mA was delivered through electrodes with a diameter of 35 cm^2. Specifically, the anode was positioned over the F3 area, while the cathode was placed over the F4 area, following the international 10-20 system used in electroencephalography (EEG) to target the dorsolateral prefrontal cortex (DLPFC). This protocol was administered for a duration of 20 minutes with the VR scenario.

3. Statistical Analyses

Statistical analyses were conducted using RStudio version 4.3.3 for preprocessing the outcomes of the neurobehavioral task (SART) and performing general linear modeling to examine the relationship between the dependent variables and independent variables. Skin conductance data was first converted from .csv to .mat format, preprocessed, and analyzed using MATLAB's Ledalab program version 3.4.9 (http://www.ledalab.de/). Subsequently, group differences were examined using SPSS.

Descriptive statistics were used to characterize the sample with respect to sociodemographic variables, global cognitive functioning, trait mindfulness, emotion regulation difficulties, psychological challenges such as depression, anxiety and stress experienced by participants in the past week. Visual inspections and statistical analyses were conducted to assess data normality and detect outliers. The choice of the parametric or non-parametric test was based on the nature of the variables and the assumptions of normality and homoscedasticity, verified by the Kolmogorov-Smirnov test or Shapiro-Wilk test and the Levene test, respectively. The existence of statistically significant differences between subgroups was analyzed using the chi-squared independence test for categorical variables, and one-way ANOVA for continuous variables when examining five groups. Alpha levels of .05 and .01 were used depending upon the number of variables and type of statistical test used.

3.1 Sample Size

A priori power calculations indicated that a sample of 90 participants was required to detect a medium effect size of $f = 0.4$ with a power of 85% with a one-way analysis of variance (ANOVA) employing a 5-group design. Power calculation was computed using by G*Power version 3.1.9.7 ($f = 0.4$, $\alpha = 0.05$, $1-\beta = 0.85$). To account for potential drop-outs, difficulties in following the proposed interventions, or data acquisition problems, more participants were included than originally planned.

3.2 Independent Variables

Variables derived from self-report questionnaires and neuropsychological testing served as the independent (predictor) variables to ensure that all participants were at equivalent levels regarding their characteristics, psychological state, and cognitive abilities. The total score on the MAAS was utilized to assess participants' trait mindfulness. The DASS-21 was employed to evaluate participants' emotional states, including anxiety, depression, and stress, ensuring that these psychological factors were not going to influence their cognitive performance on the neurobehavioral tasks. Additionally, the 18-item version of the DERS was used to measure emotion regulation difficulties.

TMT-A and TMT-B are utilized as cognitive baselines, with TMT-A primarily assessing sustained attention ability, while TMT-B focuses on attention, switching and executive functions.

3.3 Dependent Variables

Dependent measures were derived from the SART as a behavioral assessment of sustained attention failures and skin conductance data. Vigilance during SART and failures on this task were determined from the mean reaction time, accuracy, and intraindividual reaction time variability. To compute the mean reaction time (RT) for non-target stimuli, only correct responses were analyzed. To ensure accurate measurement, reaction time less than 110 ms were excluded, as this is considered insufficient for the stimulus to be encoded and the response to be executed (Berger & Kiefer, 2021). Additionally, reaction times over 1000 ms were excluded as they likely reflect attentional lapses or external factors rather than true cognitive processing (Grosjean et al., 2001). Reaction times for responses following incorrect answers were also not included in the analyses. For accuracy, the commission error rate was calculated as the errors on no-go trials divided by the total number of no-go trials, reflecting failures in inhibitory control (Isbel et al., 2020). And the final dependent variable we obtained form SART results in intra-individual reaction time variability (ICV), which indicates fluctuations in sustained attention and serves as an index of mind-wandering (Morrison et al., 2014). ICV is calculated by dividing the standard deviation of participants' reaction times (RTs) by the mean RT for non-target trials (Isbel et al., 2020). Skin conductance results were obtained from both time and amplitude variables.

4. Results

4.1 Sociodemographic Characterization of the Study Sample

Demographic variables relevant to the measures used in this study were collected from a sample of N=107 participants, comprising 81 females and 26 males, with a mean age of 20.94 years (SD = 4.97, range: 18-46). Additionally, participants were queried about their prior experience with meditation training, regularity of meditation practice in their daily routines, and, if applicable, the frequency of engagement in such practices. In our sample, 3 out of 107 participants reported having formal mindfulness training: one participant had MBCT, one participated in MBSR and one indicated other forms of training. Current or recent meditation practice was evaluated on a yes/no basis. A “Yes” response indicates that the participant regularly engages in the practice, while a “No” response signifies the absence of any practice routine. Among the participants, 97.2% reported no regular meditation practice, whereas 2.8% practiced meditation regularly, either daily or several times per week.

Group 1 consisted of 21 participants (16 female, 5 male) who underwent focused mindfulness meditation alongside active transcranial direct current stimulation (tDCS). In contrast, Group 2, comprising 22 participants (16 female, 6 male), underwent active tDCS paired with a mind-wandering scenario, serving as a control condition relative to Group 1. Group 3, with 21 participants (17 female, 4 male), received sham tDCS as a control condition for active tDCS and the focused mindfulness scenario. Group 4, consisting of 22 participants (16 female, 6 male), served as a control condition without any tDCS stimulation, engaging instead in a mind-wandering scenario. Finally, Group 5, with 21 participants (16 female, 5 male), served as the baseline control group, receiving neither tDCS intervention nor the mind-wandering scenario, thereby controlling for all experimental conditions.

After analyzing the nature of the variables and the assumptions of normality and homoscedasticity, the chi-squared independence test and one-way ANOVA were applied to verify the existence of differences between five experimental groups in terms of age and gender. Meditation frequency was excluded as a variable in the chi-squared analysis of group differences because the number of participants who practiced meditation regularly was insufficient for statistical analyses.

Table 1. *Sociodemographic Characterization and Differences of the Study Group*

	Total sample	*FM + tDCS* active	*MW + tDCS* active	*FM + tDCS* sham	*MW + tDCS* sham	No intervention	Differences between groups
N	107	21	22	21	22	21	107
Age							$F(4,102) = 0.57$, $p = 0.69$
$M \pm SD$	20.9 ± 5.0	22.3 ± 7.9	21 ± 5.3	20.7 ± 5.4	20.4 ± 2.0	20.3 ± 1.9	
[Min-Max]	[18 - 46]	[19 - 46]	[18 - 44]	[19 - 44]	[18 - 26]	[19 - 26]	
Gender							$\chi^2(4) = 0.53$, $p = 0.97$
Female (%)	81 (75.7%)	16 (76.2%)	16 (72.7%)	17 (81%)	16 (76.2%)	16 (76.2%)	

Note. N = number of participants in each condition; M = mean; SD = standard deviation; Min = minimum; Max = maximum; F = F-statistics; χ^2 = chi-squared independence test; *p* = statistical significance.

4.2 Descriptives

For descriptive statistics of the questionnaires and neuropsychological measures used as cognitive baselines, all participants (N=107) completed these assessments. One-way analysis of variance (ANOVA) was conducted to assess the success of randomization and examine potential differences among five experimental groups. The descriptive properties of these measurements are explained in detail in this section.

Mindfulness measures. The total score on the Mindful Attention Awareness Scale (*MAAS*) was used to assess participants' trait mindfulness. Scores ranged from 2.07 to 5.87, with a mean of 3.9 (SD= .73). The ANOVA results indicated that there were no significant differences in trait mindfulness levels between groups, $F(4,102) = 1.39$, $p = 0.24$. This suggests that the groups had similar levels of trait mindfulness at baseline, implying that any subsequent effects observed can be attributed to the interventions rather than pre-existing differences in mindfulness level.

Emotion regulation. Participants' overall difficulties in regulating emotions were evaluated using the total score on the Difficulties in Emotion Regulation Scale (*DERS-18*), with scores ranging from 20 to 73 (M = 39.4, SD = 9.4). A significant negative correlation was found between the DERS-18 and MAAS total scores, $r = -0.55$, $p < .01$, indicating that higher difficulties in emotion regulation were associated with lower levels of trait mindfulness. According to the ANOVA results, there were no significant differences between the groups in terms of DERS-18 scores, $F(4,102) = 1.49$, $p = 0.21$.

Stress, Anxiety, and Depression. The Depression, Anxiety, and Stress Scale-21 (*DASS-21*) subscales were used to assess participants' levels of depression, anxiety, and stress. Scores for the stress subscale ranged from 0 to 32, with a mean of 12.1 (SD = 6.6). Anxiety subscale scores ranged from 0 to 28, with a mean of 6.01 (SD = 5.6), and depression subscale scores ranged from 0 to 36, with a mean of 7.3 (*SD* = 6.7). The ANOVA results revealed that there were no significant differences between the groups in terms of anxiety $F(4,102) = 0.82$, $p = 0.51$, stress $F(4,102) = 1.24$, $p = 0.30$ or depression $F(4,102) = 0.90$, $p = 0.46$ levels. The lack of significant differences suggests that the participants' psychological states did not have a meaningful effect on their performance in the sustained attention to response task.

Cognitive baseline. To characterize global cognitive performance, the Trail Making Test Part A (TMT-A) and Part B (TMT-B) were employed. For TMT-A, completion times ranged from 10 to 36 seconds, with a mean of 18.2 seconds (SD = 4.9). For TMT-B, completion times ranged from 14 to 120 seconds, with a mean of 43.48 seconds (SD = 17.6). The ANOVA results for the baseline cognitive level revealed that participants did not exhibit significant differences at the group level in either TMT-A ($F(4,102) = 1.20$, $p = 0.32$) or TMT-B ($F(4,102) = 1.95$, $p = 0.11$).

Table 2 presents the results of each group across these measures, including MAAS, DERS-18, DASS-21 subscales, and TMT-A and TMT-B. Differences between groups are evaluated based on these assessments to ensure consistency and identify significant variations. Considering all independent variables, no significant differences were found that would compromise group homogenity and randomization.

Table 2. *Means and Standard Deviations of Independent Variables Across Experimental Groups*

	FM + tDCS active n=21	*MW + tDCS* active n=22	*FM + tDCS* sham n=21	*MW + tDCS* sham n=22	No İntervention n=21	Differences Between Groups n=107
	M±SD	*M±SD*	*M±SD*	*M±SD*	*M±SD*	
MAAS	4.1 ± 0.6	4.0 ± 0.6	3.7 ± 0.9	4.0 ± 0.7	3.7 ± 0.7	$F(4,102)= 1.39$, $p= 0.24$
[Min-Max]	[2.9-5.4]	[2.9-5.0]	[2.5-5.9]	[2.7-5.7]	[2.1-5.1]	
DASS-21						
Depression	5.8 ± 4.6	6.0 ± 5.2	9.0 ± 7.0	7.8 ± 8.0	8.0 ± 8.1	$F(4,102)= 0.90$, $p= 0.46$
[Min-Max]	[0-18]	[0-24]	[0-28]	[0-28]	[0-36]	
Anxiety	4.5 ± 4.0	5.8±6.0	7.0 ± 4.9	5.6 ± 5.0	7.2 ± 7.6	$F(4,102)= 0.82$, $p= 0.51$
[Min-Max]	[0-16]	[0-20]	[0-22]	[0-14]	[0-28]	
Stress	9.8 ± 5.5	11.9 ± 6.5	11.8 ± 6.5	12.5 ± 7.1	14.3 ± 7.2	$F(4,102)= 1.24$, $p= 0.30$
[Min-Max]	[0-26]	[2-26]	[0-26]	[2-24]	[4-32]	
DERS-18	36.4 ± 7.9	38.1 ± 9.0	43.0 ± 9.7	40.1 ± 11.5	39.3 ± 7.7	$F(4,102)= 1.49$, $p= 0.21$
[Min-Max]	[22-57]	[24-55]	[26-73]	[20-65]	[29-55]	

TMT-A	17.3 ± 4.1	19.4 ± 4.5	17.0 ± 5.1	18.0 ± 4.7	19.3 ± 5.8	F(4,102)= 1.20, p= 0.32
[Min-Max]	[12-27]	[12-27]	[10-34]	[11-34]	[12-36]	
TMT-B	35.4 ± 10.7	50.0 ± 19.4	43.4 ± 21.5	43.9 ± 14.6	44.4 ± 18.2	F(4,102)= 1.95, p= 0.11
[Min-Max]	[18-57]	[24-94]	[14-120]	[20-79]	[26-98]	

Note. MAAS= Mindful Attention Awareness Scale; *DASS-21*= The Depression, Anxiety, and Stress Scale-21; DERS-18= Difficulties in Emotion Regulation Scale; *TMT-A*= Trial Making Test A; *TMT-B*= Trial Making Test B; *n* = number of participants in each condition; *M* = mean; *SD* = standard deviation; Min = minimum ; Max = maximum; F = F-statistics; *p* = statistical significance

4.3 Results of Hypothesis Testing

4.3.1 Differences Between Groups in SART Performance

To examine the differences between matched groups in Sustained Attention to Response Task (SART) performance, we conducted a univariate analysis of variance (ANOVA) for each of the three SART outcome variables: reaction time to correct responses, errors of commission, and intra-individual reaction time variability. This analysis aimed to determine whether the interventions applied to the experimental groups resulted in significant differences in these performance metrics. The results indicated no significant differences in SART performance across the five experimental groups for any of the outcome measures (for Reaction Time, RT $F(4,102)=0.22$, $p=0.93$; for Error of Commission, $F(4,102)=0.42$, $p=0.79$; and for Intra-Individual Coefficient of Variation, ICV $F(4,102)=0.32$, $p=0.86$). To continue analyses with equal groups, we compared the two control groups using an independent t-test, given that Group 5 (no intervention) did not have skin conductance or state mindfulness results. The analysis showed no significant differences in SART performance, including reaction time ($t(41) = 0.23$, $p = 0.23$), commission error ($t(41) = -0.04$, $p = 0.12$), and inter-individual RT variability ($t(41) = 0.77$, $p = 0.36$). For this reason, from now on, the results will be analyzed for the four main experimental groups.

Table 3 presents the performance metrics for each group in the SART, detailing reaction times to correct responses, errors of commission, and intra-individual reaction time variability.

Table 3. *Characterization and Differences of the SART Performance of Five Experimental Group*

	FM + tDCS active	*MW + tDCS* active	*FM + tDCS* sham	*MW + tDCS* sham	No İntervention	Group Differences
n	21	22	21	22	21	107
RT (ms)						F(4,102)=0.22, p=0.93
M ± SD	406.43±84.6	420.88±90.54	403.96±68.93	404.25±75.05	397.7±105.51	
Commission Error						F(4,102)=0.42, p=0.79
M ± SD	0.33±0.19	0.34±0.18	0.38±0.19	0.39±0.19	0.39±0.25	
ICV (ms)						F(4,102)=0.32, p=0.86
M ± SD	265.12±72.09	262.53±73.91	279.38±69.34	276.25±66.36	259.13±79.91	

Note.; RT = mean of reaction time to correct answers; ICV = intra-individual reaction time variability n = number of participants in each condition*; M* = mean*; SD* = standard deviation; Min = minimum ; Max = maximum; F = F-statistics; *p* = statistical significance

Table 4. *Characterization and Differences of the SART Performance of Four Experimental Group*

		FM + tDCS active	*MW + tDCS* active	*FM + tDCS* sham	*MW + tDCS* sham	Differences Between Groups
n		21	22	21	22	86
RT (ms)						$F(3,82)=0.22$, $p>0.05$
	M ± *SD*	406.43±84.6	420.88±90.54	403.96±68.93	404.25±75.05	
Commission Error						$F(3,82)=0.48$, $p>0.05$
	M ± *SD*	0.33±0.19	0.34±0.18	0.38±0.19	0.39±0.19	
ICV (ms)						$F(3,82)=0.29$, $p>0.05$
	M ± *SD*	265.12±72.09	262.53±73.91	279.38±69.34	276.25±66.36	

Note.; RT = mean of reaction time to correct answers; ICV = intra-individual reaction time variability n = number of participants in each condition*; M* = mean*; SD* = standard deviation; Min = minimum ; Max = maximum; F = F-statistics; *p* = statistical significance

4.3.2 Group Differences in Toronto Mindfulness Scale Scores and Skin Conductance Levels

To evaluate the impact of the mindfulness scenario implemented in our experiment and its influence on group differences between those exposed to mindfulness and mind-wandering scenarios, we conducted a focused analysis on the Toronto Mindfulness Scale (TMS) to assess the state of mindfulness level and measured skin conductance levels. Our aim was to determine whether the groups exposed to focused mindfulness exhibited reduced levels of arousal and higher levels of state mindfulness compared to the other experimental groups. Group 5, which did not receive any intervention via VR glasses, was excluded from this comparison as they did not complete the questionnaire and no skin conductance level measurements were taken during the procedure. Descriptive statistics for each group are presented in Table 4. The one-way ANOVA revealed no significant differences between groups on the effect of the intervention, $F(3,82) = 0.18$, $p = 0.91$.

Table 5. *Characterization and Differences of the Toronto Mindfulness Scale and Skin Conductance Level of the Experimental Groups*

	Total sample	*FM + tDCS* active	*MW + tDCS* active	*FM + tDCS* sham	*MW + tDCS* sham	Differences between groups
n	86	21	22	21	22	107
TMS						F(3,82) = 0.18, p= 0.91
M ± SD	35.3±6.7	36.0±5.9	35.6±5.7	34.7±7.2	34.9±8.1	
[Min-Max]	[19-50]	[23-46]	[25-49]	[19-49]	[20-50]	

The skin conductance signals were downsampled to 32 Hz and smoothed using a Gaussian window with a width of 200, following Benedek and Kaernbach (2010). This width was chosen because it is broad enough to capture the slow variations typically associated with mindfulness practices, while still preserving some faster variations critical for data interpretation. Subsequently, peaks in skin conductance were identified for each session, and the average amplitude of these peaks was calculated from the phasic signals derived from the raw data across three specific time points. Tonic activities were estimated using Continuous Decomposition Analysis (Benedek & Kaernbach, 2010) with a smoothing window of 0.2 seconds. Tau values were optimized automatically to reduce errors. The average peak amplitude was determined from the amplitudes of the detected peaks. For statistical comparison, the peak skin conductance responses per minute and their average amplitude across the three VR scenarios were used for each participant. Due to issues with data collection and downsampling during the analyses, 16 participants were excluded from the skin conductance analysis. Across four experimental groups, a decrease in the average amplitude of skin conductance peak was observed in the final scenario of the session. Fig. 2a shows the group differences in the skin conductance responses (peaks) across the three scenarios.

Mauchly's Test of Sphericity revealed a violation of the sphericity assumption, $\chi^2(2) = 7.535$, $p = .023$. Consequently, the Greenhouse-Geisser correction was applied ($\varepsilon = 0.901$). After applying this correction, the repeated measures ANOVA showed no statistically significant main effect for the three scenarios [$F(1.802, 117.130) = 2.413$, $p = .098$, $\eta^2 = .069$]. Furthermore, there was no significant interaction effect between groups and scenarios [$F(5.406, 130.113) = 1.031$, $p = .408$, $\eta^2 = .046$]. Pairwise comparisons revealed a significant difference between the FM + tDCS active group and the MW + tDCS sham group ($p = .016$). No other pairwise comparisons indicated statistically significant differences.

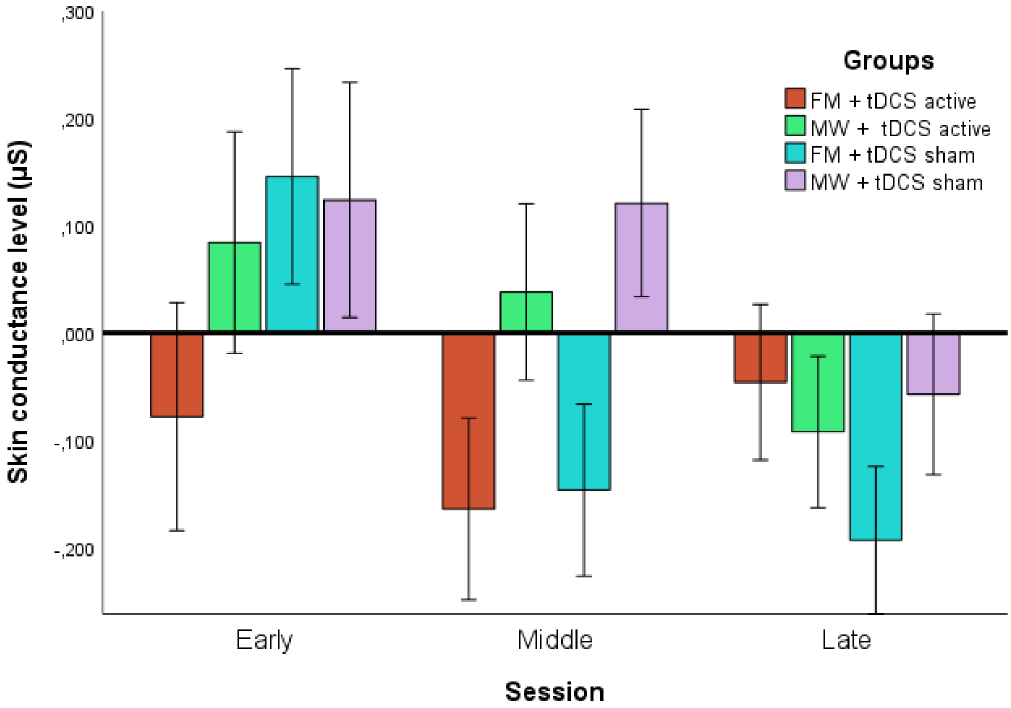

Fig. 2a. Group differences in skin conductance average amplitude of peaks during different stages of the session (Early, Middle and Late). Error bars represent the standard error of the mean (±1 SE).

Figure 2b illustrates the group differences in the average amplitude of skin conductance peaks across the combined three scenarios. A one-way ANOVA revealed a significant difference in the average amplitude between the FM + tDCS active group and the MW + tDCS sham group ($p = .012$).

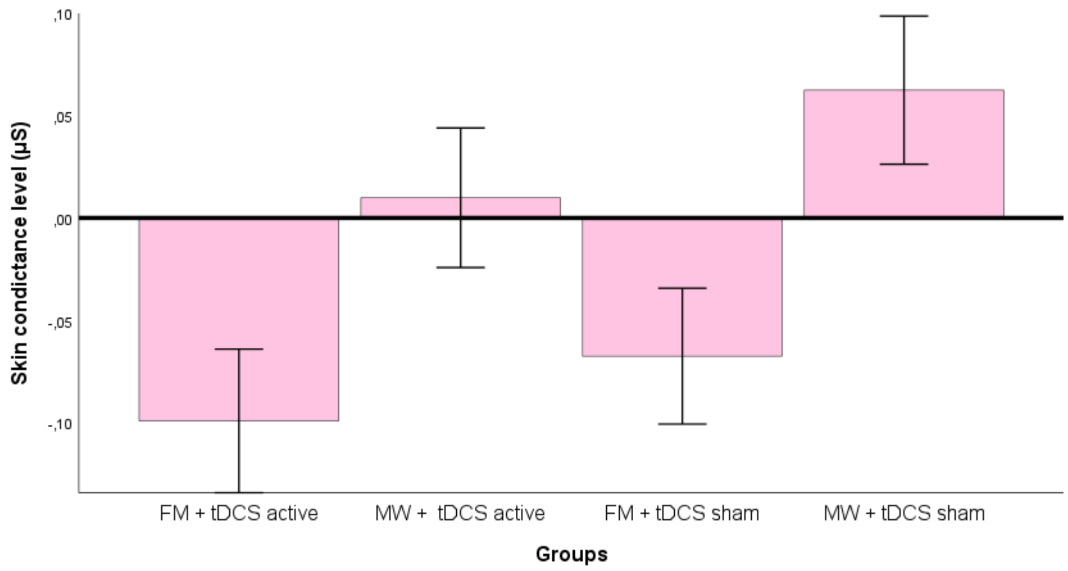

Fig. 2b. Group differences in skin conductance average amplitude of peaks across the entire session. Error bars represent the standard error of the mean (±1 SE).

5. Discussion

The aim of this research project is to investigate the effects of a single session of transcranial direct current stimulation (tDCS), a brief mindfulness meditation intervention, and the combination of both methods on participants' sustained attention performance. Additionally, as a secondary outcome of the Sustained Attention to Response Task (SART), we compared participants' inhibitory control abilities between the different interventions groups. To achieve this, we designed a single-session, factorial, sham-controlled study for tDCS, alongside a mind-wandering control scenario for mindfulness meditation, to investigate the effects of dlPFC neuromodulation and mindfulness intervention on cognitive measures, as well as the physiological responses to brief mindfulness intervention.

To compare cognitive outcomes across five experimental groups, we analyzed three variables: reaction time (RT) to correct answers, accuracy (commission error), and intra-individual reaction time variability (ICV). RT was used to assess participants' sustained attention and awareness, with the understanding that faster response could lead to more mistakes; therefore, we calculated RT specifically for correct answers (Helton et al., 2010). Commission errors were used to evaluate failures in inhibitory control, while ICV was analyzed to observe fluctuations in RT for each participant. Greater variability in ICV serves as an indicator of attentional lapses, which are often attributed to mind-wandering (Isbel et al., 2020). Our results showed no significant differences among the five experimental groups regarding the three cognitive outcomes assessed. This indicates that our interventions did not lead to substantial variations between the experimental methods and the control groups. These findings suggest that neither a brief mindfulness intervention nor a single session of tDCS is sufficient to improve participants' sustained attention abilities in a healthy population. Additionally, combined interventions of both mindfulness and tDCS did not yield significant enhancements in sustained attention, indicating that more extensive or varied approaches may be necessary to achieve notable cognitive improvements in this area.

It is plausible that the lack of significant findings in our study could be attributed to the possibility that brief induction of mindfulness meditation may not exert a robust enough effect compared to longer-term exposures. It is well-understood that executive functions can be influenced differently depending on the duration and intensity of mindfulness practices (Ahne & Rosselli, 2024). However, there is evidence in the literature suggesting that even single sessions of state-induced mindfulness can lead to immediate enhancements in cognitive control (e.g; Larson et al., 2013 conducted a 14-minute mindfulness session using a Kabat-Zinn mindfulness audio; Jaiswal et al., 2020 implemented a 20-minute meditation session with written instructions.

Additionally, Sleimen-Malkoun et al. found that a 10-minute audio meditation guide enhanced cognitive performance regardless of participants' prior meditation experience. Considering these points, it is persistent to discuss whether different modalities of mindfulness meditation could potentially have varying impacts on cognitive outcomes.

Our study also showed that a single session of tDCS on the dorsolateral prefrontal cortex (dlPFC) did not create any significant differences between the control and intervention groups in terms of SART performance. Considering the literature, which indicates that numerous studies with healthy populations report inconsistent results on the cognitive effects of a single session tDCS, our findings align with the existing body of evidence, as Westwood et al. (2017) also reviewed and found that single-session tDCS has null or weak effects on cognitive performance. Yu et al. (2024) meta-analysis indicates that while tDCS applied to the middle temporal cortex (TC) improves athletes' cognitive performance in decision-making and visuomotor skills, tDCS targeting the left dorsolateral prefrontal cortex (DLPFC) or bilaterally did not enhance cognitive improvements; Kaminski et al. (2024) reported no improvement in sequential skill learning with single-session tDCS on the DLPFC, and Elena Giovanazza's thesis found that single-session tDCS protocols, including F4 stimulation, do not offer a significant advantage over placebo in terms of working memory.

To make better inferences about our mindfulness intervention, we considered the Toronto Mindfulness Scale (TMS) results. Upon evaluating the TMS results, we found no significant difference among the four experimental groups that received either a mindfulness or mind-wandering scenario as a control condition, indicating that our mindfulness meditation scenario was not sufficient to change participants' state of mindfulness. Consequently, we must infer that our mindfulness induction did not achieve the desired effect.

Danilewitz et al. (2021) conducted a study that examined the effects of a single session of tDCS targeting the dlPFC (F3-F4) and a yoga session, similar to our research; however, these interventions were applied in separate sessions and also found no significant impact on cognitive outcomes and mindfulness states of participants. In contrast, our study introduces an innovative approach by combining tDCS and mindfulness meditation within a single session.

However, when examining our skin conductance data, we found that the differences in the average amplitude of skin conductance were statistically significant between Group 1 (the group that received focused mindfulness induction and active tDCS) and Group 4 (the group that received mind-wandering scenario and sham tDCS). This indicates that the combination of 20-minutes mindfulness meditation and single session active tDCS may produce distinct physiological effects. This implies that the intervention did induce some form of physiological change, even if it was not reflected in the self-reported mindfulness measures. One possible explanation is that tDCS mediates the effects of the mindfulness intervention, suggesting that the presence of tDCS might facilitate or enhance the physiological changes associated with mindfulness meditation.

Furthermore, our research is pioneering in its focus on sustained attention, an area that has not been extensively explored in prior studies. This design provides a unique contribution to understanding how these interventions simultaneously affect cognitive processes. However, further research is needed to gain a deeper understanding of the mechanisms underlying both mindfulness meditation and tDCS. It would be beneficial to support our findings with neuroimaging data to investigate whether there are any neural changes, even in the absence of differences between our intervention groups. This approach could help reveal subtle or underlying neural alterations that may not be reflected in our measures. Additionally, to increase statistical power of the study, it would be advantageous to design future studies with fewer groups and a larger number of participants.

6. Limitations

One of the limitations of our study is that our sample predominantly consisted of university students, specifically from the psychology department. Although we created baseline homogeneity in terms of meditation experience and trait mindfulness levels, psychology students may have prior knowledge or biases regarding the topics studied. This homogeneity and potential bias may limit the generalizability of our findings to the broader population.

Another limitation is that while we assessed participants' trait mindfulness levels to ensure they were novice in terms of meditation practices, we were unable to compare their state mindfulness levels before and after intervention. Because we were interested in differences at the group level, we can infer from our results that our mindfulness induction did not create any significant differences compared to control conditions. However, we cannot determine whether there were any changes in participants' mindfulness levels before and after the intervention, even if such changes would not have been significant.

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