Polarity Effects of HD-tDCS in a Gaming Setting: Investigating the Effect of Cathodal and Anodal Stimulation in a Visuospatial Working-Memory Task

by

Gina L. Haccou

Faculty of Behavioural Management and Social Sciences,
University of Twente

Master Thesis Conflict, Risk and Safety (201400214)
First Supervisor: Dr. Maximilian A. Friehs
Second Supervisor: Dr. Ir. Jan-Willem van ‘t Klooster
Date: August 19th, 2024

Contents

Abstract

Visuospatial working memory is essential to everyday functioning, for example, when navigating the natural world and for complex everyday tasks like driving. Therefore, tools for investigating and enhancing visuospatial working memory could be relevant for learning, e.g. cognitive enhancement or treatment, e.g. cognitive rehabilitation. The associated brain area with visuospatial working memory is the dorsolateral prefrontal cortex (DLPFC), which can be influenced using transcranial direct current stimulation (tDCS). This is a noninvasive brain stimulation technique that modulates neuronal activity. Typically, tDCS focuses on anodal with excitatory effects, increasing performance, and cathodal stimulation as inhibitory, decreasing performance. This study investigates the relationship between polarity effects, e.g. online anodal, online cathodal and sham effects, and visuospatial working memory via stimulation of the right DLPFC. The study includes a within-subjects factorial design with repeated measures. HD-tDCS was applied to 26 participants across five sessions. The Super Hexagon Task was used as a gamified measure of the player's dynamic visuospatial working memory performance. Results showed mostly insignificant polarity effects on average performance and player behaviour strategies. However, a significant positive effect of anodal stimulation on maximum duration was found. In addition, a small to moderate positive correlation was found between average performance and average rotations (player behaviour). The study illustrates that anodal stimulation can facilitate peak performances in challenging settings and a connection between player behaviour and performance. Overall, the study confirmed the possibilities of cognitive enhancement of visuospatial working memory. Nevertheless, improvements could be made for future studies, e.g., by implementing neuroimaging measures.

Keywords: transcranial direct current stimulation, prefrontal cortex, cognitive enhancement, visuospatial working memory, gaming

1. Introduction

1.1 General Introduction

Working memory is essential for everyday cognitive functioning (Fanari et al., 2019); it is the ability to sustain attention to specific information relevant to engaging in a prospective action (for a comprehensive overview, see Fuster, 2015a). It plays a vital role in acquiring new knowledge and manipulating and temporarily storing information to guide decisions and behaviour (Logie, 2003). One subset of working memory is visuospatial working memory, which stores spatial information, e.g. spatial locations and sequences, and keeps it readily available (Fanari et al., 2019). Bocchi et al. (2020) describe it as the acquisition, storage, and retrieval of object locations and their changing positions. Hence, visuospatial working memory is essential for all activities requiring spatial awareness and visual processing (Fanari et al., 2019; Llana et al., 2021; Scheunemann, 2019).

Understanding working memory and the connected brain regions could be specifically relevant for cognitive enhancement, e.g., when learning and in educational settings, and also in clinical settings, e.g., cognitive rehabilitation or enhancing cognitive abilities in atypically developing brains. For instance, the component of visuospatial working memory is involved in everyday tasks like driving. Such everyday tasks (e.g. driving) involve complex processing of visuospatial attentional demands and high cognitive load. Therefore, deficits in visuospatial working memory can cause difficulties in daily tasks (Scheunemann, 2019).

So, although visuospatial working memory is vital in everyday activities, it is prone to limitations. For example, when faced with high cognitive load (Scheunemann, 2019) or in populations with cognitive impairments, e.g. atypical brains (Berryhill & Martin, 2018; Luckhardt et al., 2021). One way to investigate how to address the limits of visuospatial working memory is by testing the possibilities of visuospatial working memory enhancement. Transcranial Direct Current Simulation (tDCS) is a noninvasive brain stimulation method that has become a promising tool in research on modulating cognitive functions, including visuospatial working memory (Alam et al., 2016; Kuo et al., 2013; Masina et al., 2012; Mikkonen et al., 2019; Reckow et al., 2018). tDCS can modulate targeted brain areas by applying a constant current that, to some extent, penetrates the skull and enters the brain, directly influencing the neural circuits (Masina et al., 2021; Moreno-Duarte et al., 2014). Therefore, tDCS can be used for neuromodulation with polarity-specific effects. Typically, research focuses on anodal excitation effects and cathodal inhibitory effects on neuronal activity (Alam et al., 2016; Kuo et al., 2013; Masina et al., 2012; Mikkonen et al., 2019; Reckow et al., 2018). Studies found that tDCS stimulation over areas like the right dorsolateral prefrontal cortex (rDLPFC) can potentially improve visuospatial working memory performance by enhancing the brain's ability to process and retain visuospatial working memory (Wang & Ku, 2018; Wu et al., 2014). Consequently, analysing visuospatial working memory in complex and dynamic environments is a critical basis for improving visuospatial cognitive functioning and, hence, cognitive rehabilitation in everyday life. Therefore, the research question is*: How do anodal and cathodal stimulation effects influence players' gaming performance and player behaviour in a visuospatial working memory task?* This will be explored through a literature review, explaining the current study and its methods and results. Then, the main findings, implications, limitations, and recommendations are discussed, ending with a conclusion.

1.2 Neurophysiological Correlates of Visuospatial Working Memory

Visuospatial working memory is the system that temporarily holds and manipulates visual and spatial information (Fanari et al., 2019). It is essential to everyday functioning, like interacting with and navigating the physical world, e.g., recognising object location and movement sequences (Garden et al., 2001; Logie, 2003). The aim is to understand how visuospatial working memory operates at the neural level. Therefore, the anatomical position needs to be estimated. According to Fuster (2015a), like almost all cognitive functions, spatial working memory relies on a network of areas. A review by Llana et al. (2021) indicates that visuospatial working memory might be bilaterally localised in the fronto-parietal circuits. More precisely, the prefrontal cortex (PFC), specifically the right PFC, is a super important node in this network (Fuster, 2015a). This is supported by literature on lesions and brain activity. For example, lesions to the prefrontal cortex significantly impact all working memory modalities (Fuster, 2015a). Furthermore, when examining brain activity while performing working memory tasks using positron emission tomography (PET), working memory is associated with activation in the PFC (Fuster, 2015b). As confirmation, Li et al. (2016) also found activation of the PFC when engaging in a working memory task, specifically for attention control in visual working memory tasks. Moreover, Tanoue et al. (2013) applied cathodal stimulation (inhibitory) to the PFC and the posterior partial cortex during a visual working memory task. They found a greater negative influence on the task when stimulating the PFC compared to other brain regions. All suggest an association between the PFC and working memory, specifically visuospatial working memory.

To specify the location even further, research by Li et al. (2016) and Wang et al. (2018) investigated working memory using fMRI. These studies suggest the involvement of the dorsolateral prefrontal cortex (DLPFC). In support, Lucas et al. (2020) and Kronovsek et al. (2021) also found that the DLPFC plays a central role in working memory. To become more specific, using functional near-infrared spectroscopy (fNIRS), Geissler et al. (2020) found lateralisation of activity in the right hemisphere in visuospatial working memory tasks. This is confirmed in a review by Llana et al. (2021) that reports the predominance of right hemisphere activation when investigating visuospatial functions. Moreover, right hemisphere damage has been connected to visuospatial working memory impairments (review: Llana et al., 2021).

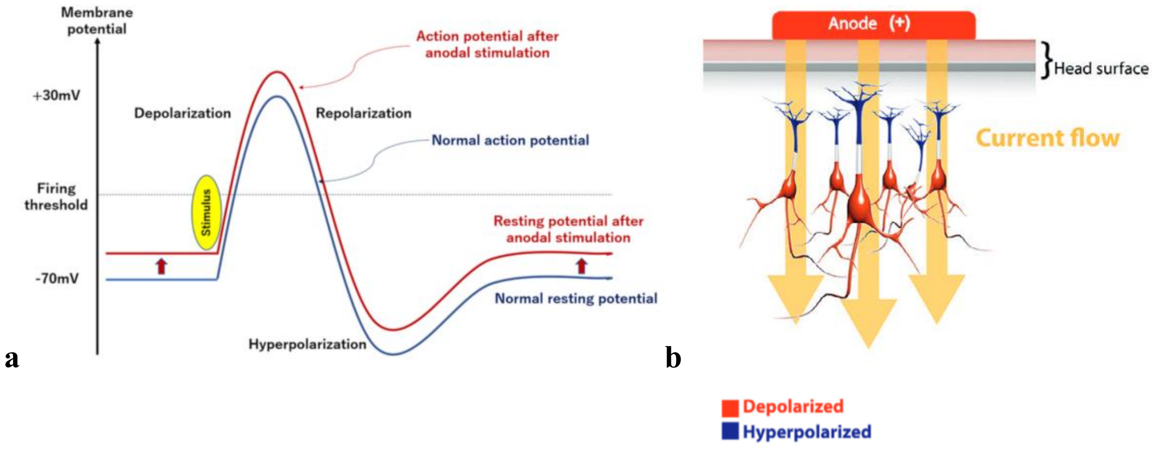
1.3 Cognitive Enhancement through Transcranial Electrical Stimulation

1.3.1 tDCS and Polarity Effects

A common noninvasive method for cognitive enhancement is Transcranial Electrical Stimulation (tES). The most widely used tools are tDCS and transcranial alternating current stimulation (tACS) (Farah et al., 2013). To start, tDCS is used to neuromodulate targeted brain areas by applying a constant current (Masina et al., 2021; Moreno-Duarte et al., 2014). Typical intensities for tDCS range up to 3mA and can cause sensations such as tingling and burning (Reckow et al., 2018). Although weak, the electrical current in tDCS produces an electric field that can enhance or suppress spontaneous neuronal activity and, as a result, the responsiveness to synaptic input, which can influence the firing rate of individual neurons. (Alam et al., 2016; Moreno-Duarte et al., 2014). The effect depends on the polarity of the current. According to Moreno-Duarte et al. (2014), the anode causes a positive inward current flow at the brain (of positive ions, e.g., NA+), see Figure 1b. For this reason, stimulation typically involves the depolarisation of neurons. Subsequently, the membrane potential becomes less negative (closer to zero), making the threshold to trigger an action potential closer and easier, see Figure 1a. Thus increasing the likelihood of neurons firing. In contrast, cathodal stimulation generates an outward current flow (see Figure 2b), leading positive ions out of the neuron (efflux) and causing hyperpolarisation (surplus of negative ions, e.g., Cl-). Hence, the membrane potential becomes more negative, making it harder to reach the threshold for firing an action potential, resulting in a lower frequency of action potentials (see Figure 2a). The so-called inhibitory effect (Moreno-Duarte et al., 2014; Yamada & Sumiyoshi, 2021). Similarly explained by Roy et al. (2014) as well. These effects are consistent with animal work, motor manipulations and predominantly in verbal tasks (Bergmann & Hartwigsen, 2021; Fitz & Reiner, 2014; Roy et al., 2014)

Figure 1

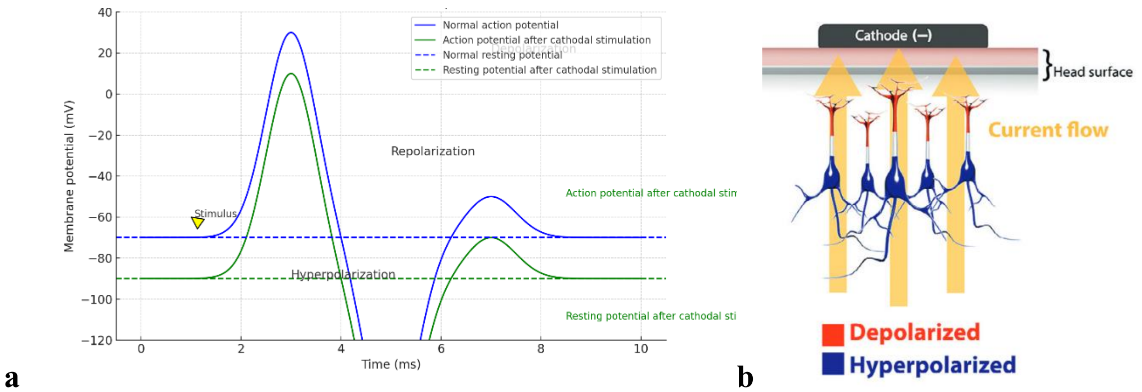
Current Flow and Changes in Neuron Potential by Anodal tDCS



Note. **a** by Yamada & Sumiyoshi (2021) depicts the increased neuronal excitability (depolarisation; becomes less negative) and how it moves closer to an action potential threshold (lowering the distance to the threshold). **b** by Moreno-Duarte et al. (2014) displays the inward current flow that depolarises the resting membrane potential

Figure 2

Current Flow and Changes in Neuron Potential by Cathodal tDCS



Note. **a** visualises the decrease in excitability and the hyperpolarisation (becomes more negative) of the resting membrane potential, e.g. moving further away from the firing threshold (visual: inspired by Yamada & Sumiyoshi, 2021). **b** by Moreno-Duarte et al. (2014) shows the inward flow that hyperpolarises the resting membrane potential

Conventional tDCS involves two big (20-35 cm²) saline-soaked sponges and connected electrode units, with the stimulating electrode-sponge positioned above the scalp (stimulation area) and the return placed on another location (e.g. skull, shoulder or upper arm)

(Moreno-Duarte et al., 2014). The spread of the electric field was limited in focality in conventional tDCS (Masina et al., 2021), with activation somewhere between the anode and cathode and not directly under the stimulating electrode as initially suggested (Pisoni et al., 2017). Thus, approaches were developed to focalise stimulation. Smaller gel-based electrodes already generated more focused electric fields (Kuo et al., 2013; Mikkonen et al., 2019), yet still insufficiently focal. As a response, a new technique, termed 'High-Definition-tDCS' (HD-tDCS), was introduced to increase the focality of the stimulation (Kuo et., 2013; Masina et al., 2021; Mikkonen et al., 2019; Roy et al., 2014). HD-tDCS produces a more constricted and well-contained electric field (Bergmann & Hartwigsen, 2021; Kuo et al., 2013), enabling better targeting of brain regions (Roy et al., 2014). The set-up consists of a concentric-ring electrode configuration, where the active electrode is positioned directly above the target area at the centre. The return electrodes are positioned in a ring surrounding the active electrode, containing the stimulation. Mikkonen et al. (2019) investigated the best-suited allocation and optimal number of electrodes and found that a 4x1 HD-tDCS montage creates the most focal electrical field. Adding additional return electrodes, in turn, would broaden the stimulation area, again decreasing focality to some extent.

In addition, HD-tDCS improves the stimulation magnitude (Mikkonen et al., 2019) and diminishes uncomfortable sensations usually perceived with conventional tDCS (Kuo et al., 2013). Nonetheless, Mikkonen et al. (2019) critique HD-tDCS because of the anatomical interindividual variability and differences in produced e-fields between individuals. However, this issue can be addressed with individual monitoring. Moreover, Bergmann and Hartwigsen (2021) emphasise that all tDCS should be combined with neuroimaging techniques like EEG to draw more transparent inferences.

1.3.2 Comparing tDCS and tACS

However, as mentioned above, another form of tES is Transcranial Alternating Current Stimulation tACS, which also induces changes in cortical excitability (Hermann & Strüber, 2017; Moreno-Duarte, 2014b). Whereas tDCS modulates cortical excitability by applying a constant current, tACS operates through pulses of current to the brain that periodically change in polarity (Moreno-Duarte, 2014b). tACS involves rhythmic stimulation at a repeated frequency, which affects the endogenous brain oscillation (Hermann & Strüber, 2017). The oscillations refer to the natural rhythmic activity in the brain, which is critical for cognitive and motor functions. During the peak of an oscillation, the membrane potential is closer to the threshold of firing an action potential. Applying tACS produces external oscillatory input and can manipulate endogenous oscillations. This occurs through rectangular or, most commonly, sinusoidal waves (for a review, see Baltus & Hermann, 2016; Hermann & Strüber, 2017; Moreno-Duarte, 2014b). Both tDCS and tACS are tools for drawing causal inferences between brain regions and cognitive functions (Grover et al., 2023) and promising techniques for improving cognitive abilities in mild cognitive impairments (for a comparison, see Kim et al., 2021). Abellaneda-Pérez et al. (2020) investigated the effects of both tDCS and tACS on working memory. tDCS tends to influence cognitive functioning both online, during the application, and offline, persisting over time, whilst tACS modulation occurs mainly online. Based on functional magnetic resonance imaging (fMRI), which can visualise and map the changes in brain activity in tES experiments, it can be tested whether changes induced by tES are robust and reproducible.

Using fMRI, Abellaneda-Pérez et al., 2020) found that tDCS can enhance connectivity, thus regulating or facilitating cognitive capabilities; these findings tend to be more robust across experiments and tasks. For tACS, the effects, however, might be more context-specific. The variability in the application of tACS requires more strict stimulation parameters (Abellaneda-Pérez et al., 2020). Moreover, although some studies found that tACS can enhance working memory more than tDCS, this seems to be restricted to low working loads (Röhner et al., 2018). When looking at complex tasks that require greater memory loads, e.g. closer to real life, tDCS outperforms tACS (Röhner et al., 2018; Wu et al., 2014). Therefore, this paper will investigate causal relationships between brain regions and working memory through applying tDCS.

Overall, tDCS allows the exploration of causal relationships between specific brain areas and cognitive and motor functions (Bergmann & Hartwigsen, 2021; Wang et al., 2018). A greater understanding of cognitive functioning would significantly contribute to later applications in clinical settings (Kuo et al., 2013; Roy et al., 2014) and could, thus, according to Masina et al. (2021), be a promising tool for treating clinical conditions. Currently, tDCS is popular in a variety of treatments, for example, neuropsychiatric disorders, motor learning and rehabilitation, depression, chronic pain, stroke, and addiction (Masina et al., 2021; Reckow et al., 2018; Roy et al., 2014). One example that emphasises the helpfulness of tDCS in rehabilitation is its application to motor rehabilitation. Treatment of stroke after-effects in motor rehabilitation has already been paired with tDCS. Orrù et al. (2019) reviewed the efficacy of stroke recovery combined with tDCS and found that, especially in the early stages, tDCS can promote the recovery process. However, tDCS is not only beneficial for the rehabilitation of motor function but can also be useful for the treatment of cognitive functions (Orrù et al., 2019). Research into the application of tDCS in learning disabilities has shown that tDCS can reduce symptoms of atypical brain development (Berryhill & Martin, 2018; Krause et al., 2014; Luckhardt et al., 2021). The application of tDCS even enabled some individuals to exceed the cognitive limit imposed by their learning difficulties (Krause & Kadosh, 2012).

Additionally, with a focus on healthy participants, research into improvements in implicit learning, motor memory, and also working memory has been done (Alam et al., 2016; Mikkonen et al., 2019; Moreno-Duarte et al., 2014; Reckow et al., 2018). Investigating cognitive functioning in healthy participants can also be helpful for clinical application. Although much research focuses on tDCS effects on motor responses, findings on tDCS effects in cognitive enhancement are still quite untransparent, e.g., there is no coherent pattern of polarity effect findings. In motor areas, anodal stimulation tends to be excitatory, and cathodal stimulation tends to be inhibiting. Nevertheless, the results of anodal or cathodal stimulation on cognition are still very mixed (for a review, see Jacobson et al., 2012; Wang et al., 2018). The findings of healthy participants are valuable for understanding complex cognitive processes and can be applied to both cognitive enhancement and rehabilitation.

1.3.3 Cognitive Enhancement

Cognitive enhancement describes the improvement of cognitive capacities. Usually, this refers to neurotypical healthy individuals. However, in some cases, it is connected to the treatment of cognitive disorders, e.g. dementia (Farah et al., 2013). Research on cognitive enhancement considers different approaches. In a focus article, Farah et al. (2013) examine neurocognitive enhancement through both drugs, e.g. stimulants (methylphenidate, e.g. Ritalin) or brain stimulation, e.g. tDCS. tDCS effects are usually more lasting than drugs, promoting enhanced learning and working memory. Pisoni et al. (2017) claim that brain stimulation-related cognitive enhancement occurs through anodal tDCS for healthy and clinical populations. Especially for working memory, similar effects were found (Hoy et a., 2013). These results are reflected in the increase in theta oscillations associated with better performance, especially as task demands increase. Additionally, increases in alpha oscillations were found; they are connected to the inhibition of external noise, e.g. task-irrelevant details. This supports the idea that cognitive enhancement in healthy individuals can be achieved using tDCS (Pisoni et al., 2017).

1.4 Polarity-Specific Effects of tDCS on Visuospatial Working Memory

Few studies have analysed the application of tDCS over the right DLPFC. Although there is a common consensus that anodal stimulation facilitates performance and cathodal stimulation suppresses performance, this trend is not always persistent concerning stimulation effects on working memory. When investigating the effects of tDCS on cognitive abilities, cathodal stimulation sometimes leads to better performance (Fitz & Reiner, 2014). Some studies suggest that cathodal stimulation over the DLPFC causes inhibitory effects (Fitz & Reiner, 2014; Wang & Ku, 2018), whereas other studies found opposite effects (for a review on this, see Jacobson et al., 2011). For instance, for overall working memory, Wang et al. (2018) conducted a study investigating the effect of tDCS on the right DLPFC. They found that cathodal stimulation enhanced working memory performance.

On the other hand, when focusing only on visuospatial working memory, Wu et al. (2014) found that anodal stimulation over the right DLPFC in a specific visuospatial memory task quickened reaction time and even, with increased task difficulty, improved visuospatial working memory capacity. In addition, Wang and Ku (2018) examined the role of the right DLPFC on visuospatial working memory using a combination of tDCS and Electroencephalography EEG. The study reconfirmed the causal role of the right DLPFC in visuospatial working memory and found that anodal stimulation improved the visuospatial working memory capacity, e.g. holding and manipulating visual information in mind. The improvement was significant for participants (n = 40) with initially higher cognitive abilities, as they could perform better on more difficult tasks.

In contrast, other findings on visuospatial working memory have also suggested reverse-polarity effects. Wang et al. (2018) found that, when applying tDCS to the right DLPFC, anodal stimulation reduced performance, whilst cathodal stimulation improved performance in the difficult condition (n = 30). To be more precise, neither stimulation protocol influenced the performance of updating working memory, but cathodal stimulation increased performance for maintenance. Combined with EEG, this can be explained by decreased alpha oscillations related to inhibiting task-irrelevant information. Nevertheless, it should be mentioned that this was dependent on task difficulty. For the same difficulty, anodal stimulation significantly decreased maintenance performance (Wang et al., 2018). Another suggested explanation of the reverse-polarity effects in cognitive tasks is a compensation process. Especially for cognitive functioning, such as visuospatial working memory, as this is typically supported by richer brain networks than motor responses (review: Jacobson et al., 2011).

Theoretically, it is important to analyse the influence of anodal and cathodal effects on the performance of visuospatial working memory tasks. For anodal stimulation, the excitatory effects could facilitate the maintenance and updating of task-relevant information, leading to the greatest enhancement. Meanwhile, cathodal stimulation might suppress information.

However, for some tasks, information suppression may be beneficial and possibly suppress predominantly interfering noise, thus also promoting performance slightly above the control condition (review: Jacobson et al., 2011).

1.5 From Laboratory Measurements to Real-Life Tasks: Gamified Visuospatial Working Memory Task

1.5.1 Visuospatial Working Memory Tasks

Visuospatial working memory involves interaction with the environment (review: Llana et al., 2021). There are many different and adapted visuospatial working memory tasks. According to Miyake et al. (2001), standard designs to study visuospatial working memory focus on different subprocesses. The first factor is spatial visualisation, which involves the apprehension, encoding, and mental manipulation of spatial forms. These tasks are highly complex, requiring multiple steps and extensive cognitive processes. Typical tasks are the Paper Folding test and the Space Relations test. Required abilities are visualising mental transformations and problem-solving, e.g. folding or rotating. During the task, the participants must imagine folding a paper or a box and predict the resulting pattern; 3D thinking. A second factor tests the spatial relations, e.g., the speed of mental rotation. The tasks only involve single-step rotations, or spatial transformations, of a 2D object. However, quick judgment on simple rotations is asked. Tasks are the Card Rotation task and Flags test, where a picture is presented, and the participant needs to decide whether another rotated picture is the same. A third factor is the visuospatial perceptual speed; these tests focus on quickly recognising visual patterns. Tasks are the Identical Picture and Hidden Patterns tests, requiring the participant to match and recognise a specific pattern in other shapes. Other factors are also often tested. For example, closure flexibility, when knowing the target pattern beforehand, and closure speed, when needing to identify the pattern, are used to measure the speed and accuracy of identifying shapes, often combined with other distracting stimuli. A test would be the Hidden Figure test, where the participant needs to recognise an object in a complex and distracting background. Nevertheless, these factors are all highly correlated, as they all tap into the same underlying construct and involve similar operations, e.g. temporary visual storage or spatial transformations and executive functioning. Therefore, drawing clear, distinct inferences tends to be difficult, depending on the participant's task difficulty and skill level (Miyake et al., 2001).

Another task, developed in 1971, is the Corsi Block-Tapping task, which measures spans of spatial memory (Busch et al., 2005; Toril et al., 2016). For the task, the researcher taps a sequence of 3D-looking blocks, and the participant is instructed to repeat the sequence

(Cocchi et al., 2007; Hamilton et al., 2003) or, in the Logie and Pearson (1997) version, recognise missing taps when the researcher repeats the sequence. Therefore, it is a visual motor task, including observation of the order, planning, and execution of the motor action, e.g. tapping. However, the additional motor component adds some complexity and makes isolating the visuospatial working memory component hard. Additionally, it is hard to analyse whether problems are due to sequence memory, spatial memory or motor control issues, making interpretation complex (Hamilton et al., 2003). Hence, Hamilton et al. (2003) introduced a different version to measure the visuospatial working memory with reduced motor demands, in turn reducing complexity and unrelated cognitive load. This includes a figure illuminated by yellow and green spots, whilst the participants must memorise the locations of the green spots. Then, the figure is hidden and reintroduced, and the participants must decide orally whether the green spots changed locations (Hamilton et al., 2003). This task is also very similar to another task, the spatial variant of the n-back task, where the participant also reproduces a pattern of locations several trials (n) after its presentation (Geissler et al., 2020). This task was, for example, used by Geissler et al. (2020) to infer an association between visuospatial working memory and the right DLPFC.

However, another distinction for visuospatial working memory can be made between dynamic and static visual information. The abovementioned tasks mainly include static mental processes and focus on simple cognitive load. The more complex mentioned tasks are spatial visualisation and spatial relations tasks due to the mental processes that involve mental manipulation or movement. However, task design should increase complexity to challenge and measure the limits of visuospatial working memory (Cocchi et al., 2007). Nevertheless, the task difficulty and cognitive load must be balanced appropriately so as not to exceed visuospatial working memory capacity. Such elements could be moving targets that require sustained attention and involve mental manipulations to predict future positions, e.g. testing visual tracking abilities and continuous updating of spatial information. Thus, Cocchi et al. (2007) implemented a dynamic task with physically moving targets containing a moving ball. The participants need to memorise and recognise the correct flight path. This involves continuous tracking and predicting the direction whilst observing the different positions in space to reconstruct the full flight afterwards. Reconstruction then occurs by chunking together the different segments of spatial positions (Cocchi et al., 2007)

Although the previously discussed tasks have been fundamental in understanding visuospatial working memory, providing transparent and replicable measures of visuospatial working memory capacity and function, they mainly examine isolated cognitive processes of visuospatial working memory (Cocchi et al., 2007; Hamilton et al., 2003; Miyake et al., 2001). Nevertheless, complexity is also one essential characteristic of visuospatial working memory, and the isolated tasks may not reflect how visuospatial working memory operates in everyday life (Kemps, 2014). Therefore, addressing complex and high cognitive load is important to improve ecological validity, especially when applying the research to the complexity of real-world tasks like driving (Scheunemann, 2019). Geissler et al. (2021) investigated the complex workload required in simulated driving. The results showed that driving in a demanding environment, e.g., a city, is connected to high cognitive load. More specifically, the right anterior DLPFC was highly active during this complex task, indicating the high demand for visuospatial working memory in such a complex but real-life task (Geissler et al., 2021). Therefore, such tasks, e.g. simulated driving, are assumed to function similarly to other visuospatial working memory tasks but in measuring complex visuospatial skills. A method to introduce such complex and dynamic visuospatial working memory tasks can be achieved in a gamified approach. Studies have found a correlation between gaming and visuospatial working memory enhancement (Waris et al., 2019). Therefore, research on gamified tasks is not only used as an assessment tool for visuospatial working memory but also its enhancement. Thus, gaming has been used solely to improve visuospatial working memory, indicating its effectiveness in cognitive training and enhancement (Toril et al., 2016; Waris et al., 2019).

1.5.2 Relevance of Using a Gamified Task

Traditional visuospatial working memory tasks typically focus on isolated visuospatial working memory mechanisms. Addressing only specific cognitive loads, however, the functions of visuospatial working memory all tend to be tightly correlated and hard to isolate (Miyake et al., 2001). Thus, this gamified approach, called the Super Hexagon Task, will address multiple visuospatial working memory functions in one task. Imitating the complex and high cognitive load of real-life situations involving simultaneous information processing. The memory processes assumed to be prominent in the Super Hexagon Task will be mostly continuous updating of visual stimuli, their spatial location and the player's own position. Therefore, addressing different subprocesses of visuospatial working memory than, for example, Wang et al. (2018), who focused only on updating and maintenance.

1.5.2.1 Increased Motivation

Gamified tasks often involve greater motivation compared to other cognitive interventions. Thus, it ensures that participants or patients fully complete a task (Bergmann et al., 2023). Moreover, games implement fun and entertainment in the task, which increases the player's investment (Eggemeier et al., 2020b), making it an effective research tool that also adds enjoyment for the player.

1.5.2.2 Life-like Complexity

Real-life situations like driving tend to be very complex, draw on visuospatial working memory and require high cognitive loads (Geissler et al., 2021; Scheunemann, 2019). Video games also include various cognitive processes, and their complexity affects the player's performance in the game. Moisala et al. (2016) suggest that a player's brain activity and performance vary depending on the task's difficulty. Gamers performed better in tasks demanding higher cognitive load because of their experience in other complex gaming situations from a gaming environment (Moisala et al., 2016). Thus, a gamified visuospatial memory task can also implement and mirror such real-life complexities. The idea is that gaming tasks resemble complex real-world situations. Subsequently, complex gaming tasks that demand high cognitive load can be generalised to real-world settings (e.g. driving: Geissler et al., 2021; Scheunemann, 2019). Both scenarios require coordinating multiple cognitive processes, meaning a high cognitive load, making a gamified task highly ecologically valid.

The mental workload can be defined as the processing capacity and resources an individual requires to effectively execute a task (Eggemeier et al., 2020a). For driving, this would include all variables that influence the difficulty of the driving environment; one important factor is the visual stimuli and the storage of spatial locations (Geissler et al., 2021). Gaming also includes visual stimuli and spatial locations; gamers tend to better remember and encode spatial locations. Hazarika and Dasgupta (2018) used an EEG set-up to analyse neural responses of gamers versus non-gamers during a visuospatial working memory task, the Corsi Blocks task. Brain oscillations behaved differently between groups, with gamers experiencing better theta synchronisation, which facilitates cognitive processes—suggesting that experience with gaming can enhance specific cognitive processes (Hazarika & Dasgupta, 2018). Overall, this supports the idea that gaming involves a high cognitive load on visuospatial working memory and is closely related to complex real-life demands on working memory.

1.5.2.3 Association between Gaming and Enhanced Visuospatial WM

Toril et al. (2016) investigated video game training enhancement of visuospatial working memory. However, not only did the video game performance increase, but follow-up visuospatial working memory tasks, e.g., the Corsi Blocks task, revealed significant improvements when comparing the gaming group to the control group. Moreover, other parts of working memory were also enhanced, sustaining until a three-month follow-up test. This proves that such learning tasks can promote enduring effects by increasing neuroplasticity in the brain (Toril et l., 2016), similar to offline tDCS stimulation. Moisala et al. (2016) add that gaming enhancement effects are most effective for tasks requiring high cognitive demand and related to increased activation of the fronto-parietal cortical network, specifically the DLPFC. As a result, computerised cognitive exercises have already been implemented into computer-assisted cognitive rehabilitation programmes for working memory and visuospatial skills (Davarani et al., 2020). Amini Masouleh et al. (2022) even found that combining anodal tDCS (enhancing excitability of the cortical network) with computerised cognitive rehabilitation facilitates the efficacy of cognitive rehabilitation programmes.

Therefore, cognitive enhancement appears tightly related to video gaming, most prominently in visuospatial cognition. The enhancements in players are hypothesised to result from repeated strain on the cognitive system, producing plastic changes in the neural substrates. Consequently, updating working memory, goal-directed multi-component behaviour, encoding speed of visuospatial working memory, and cognitive resource allocation improve, enhancing performance (Waris et al., 2019). The necessary gaming environments for such an effect are fast-paced, high perceptual, cognitive demands focusing on peripheral vision, divided attention and constant predictions (Green & Bavelier, 2012).

As a result, gamified tasks are valuable because they overcome task specificity, promote more general learning beyond the training environment (Green & Bavelier, 2012) and are highly motivating (Bergmann et al., 2023). A gaming setting is ecologically valid for investigating complex cognitive load but is also a first step to creating cognitive rehabilitation tools. tDCS is a tool that can facilitate such learning but also help in exploring the underlying mechanism (Amini Masouleh et al., 2022; Green & Bavelier, 2012; Waris et al., 2019)

1.6 Current Study

This research addresses a gap in comprehending how tDCS can enhance cognitive functions in complex, real-world situations. Using a complex gamified approach, the study aims to gain insight into cognitive enhancement and offers a foundation for potential applications in cognitive rehabilitation. The focus lies on visuospatial working memory associated with the right lower DLPFC.

The current study design closely adheres to Villamar et al. (2013)'s recommendations for an effective HD-tDCS set-up. It also includes a new gamified task that addresses the complex cognitive load of visuospatial working memory, e.g. the Super Hexagon Task. Consequently, anodal stimulation is hypothesised to increase gaming performance and enhance efficient behaviour strategies the most compared to the other conditions, e.g. to sham and cathodal stimulation. Nevertheless, the cathodal stimulation protocol is still hypothesised to perform better than the control group, Sham, because of the rich compensatory networks in cognitive tasks that can counteract the inhibitory effects. Overall, the study incorporates a within-subjects factorial design with repeated measures and is part of a larger project that analysed both polarity and timing effects. This is why the design includes five conditions. The conditions are online anodal, online cathodal, offline anodal, offline cathodal and sham stimulation. Nevertheless, this paper will focus on and present the findings regarding the effects of polarity in online conditions. In order to exclude the possibility of uncontrolled modulating effects from motivation, attention or gender (Li et al., 2017), additional measures and analyses were included.

1.6.1 Research Question and Hypotheses

Drawing upon the above-mentioned literature and theoretical work, this research aims to answer the central question of how anodal and cathodal stimulation effects influence players' gaming performance and player behaviour in a visuospatial working memory task. The following hypotheses were formulated to analyse the interplay between polarity and visuospatial working memory, testing whether there are significant differences in the player's performance and behaviours across conditions.

Q1: *Does anodal stimulation enhance gaming outcomes compared to cathodal stimulation?*

Hypothesis 1 Anodal stimulation causes significantly higher (a) performance scores and more efficient (b) gaming behaviour than cathodal stimulation.

Q2: *Are gaming outcomes of anodal stimulation better than those of the control condition?*

Hypothesis 2 Anodal stimulation causes significantly (a) higher performance scores and more efficient (b) gaming behaviour than sham stimulation.

Q3: *Does cathodal stimulation improve gaming outcomes compared to the control condition?*

Hypothesis 3 Cathodal stimulation causes significantly higher (a) performance scores and more efficient (b) gaming behaviour than sham stimulation.

Q4: *Is gaming performance related to gaming behaviour in the Super Hexagon Task?*

Hypothesis 4 Rotation variables are positively correlated to the performance variables.

Q5: *Do different stimulation polarities influence gaming behaviour in the Super Hexagon Task?*

Hypothesis 5 There is a significant difference in gaming behaviour between anodal, cathodal and sham stimulation protocols.

2. Methods

The current study was ethically approved under the IRB approval code 231146 by the Ethics Committee of Behavioural, Management and Social Sciences (BMS) of the University of Twente.

2.1 Sample

Twenty-six students (17 male, 9 female) aged 18 to 29 (mean age: 23 ± 2.857) participated, mainly Germans (see Appendix B. Sample Characteristics Table). Twenty-five participants were right-handed, and one was left-handed. Recruitment occurred via the personal network and the online platform SONA of the University of Twente (https://utwente.sona-systems.com/). Therefore, convenience sampling and volunteer sampling were chosen to ensure a cost and time-efficient sampling. Exclusion criteria for partaking in the study were acute injuries to the head or skin, pregnancy, epilepsy in close family, prior psychological illnesses, CNS-active medication, and cochlea implants see Appendix E). During the study, participants had normal or corrected-to-normal vision adjusted to the study design. Everyone gave written and informed consent.

Before the data collection, to compute the required sample size, an a priori power analysis was conducted in G*Power 3.1 (Faul et al., 2009). Based on previous research on tDCS (Friehs & Frings, 2019), the aim was an effect size of $f = .333$ and the correlation among repetitive measures within each group as $r = .4$. To obtain a desired power of at least $1 - \beta = .95$ and $\alpha = .05$, the sample should have included at least 25 participants (actual power $1- \beta = .9766$).

2.2 Materials and Measures

2.2.1 tDCS

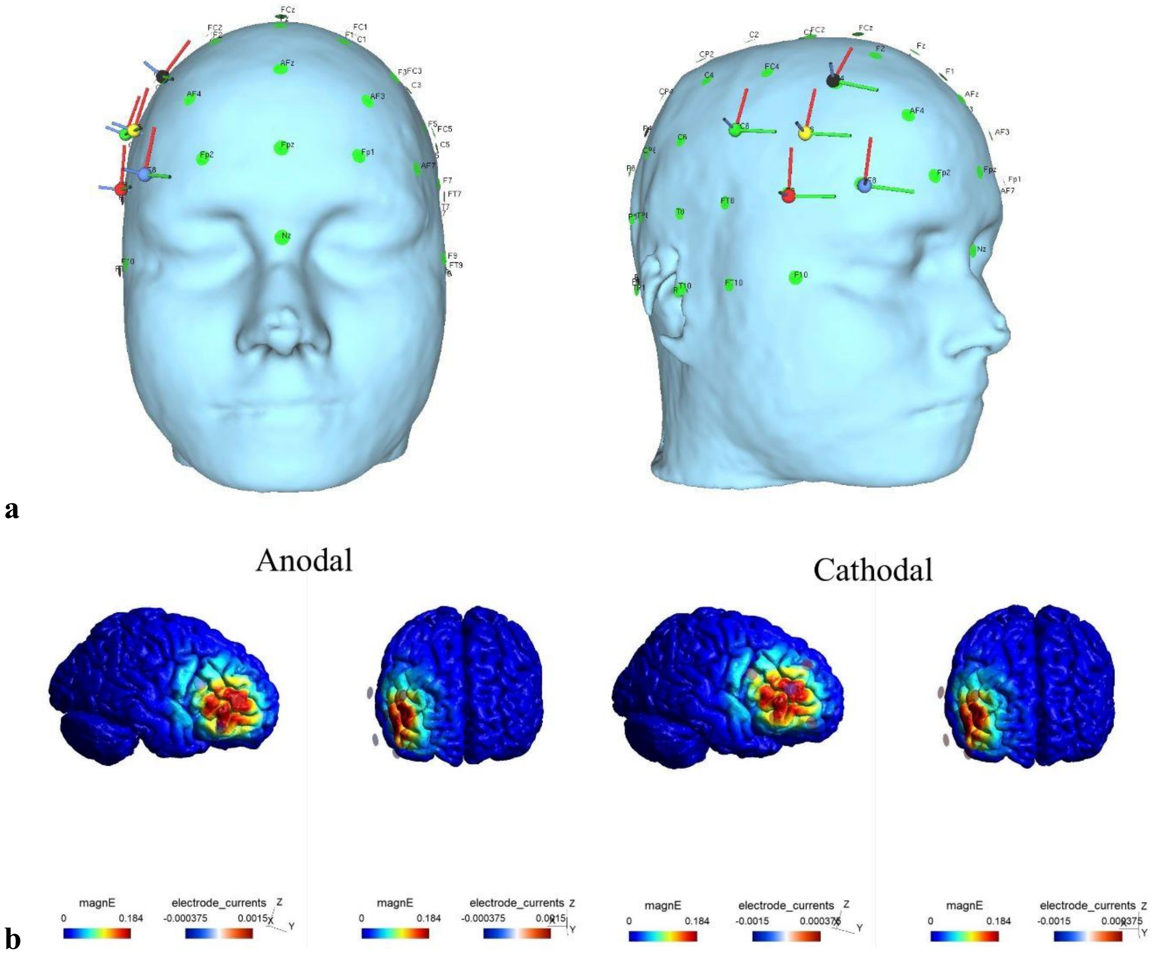
For this study, the battery-driven Starstim tES (eight-channel stimulator by Neuroelectrics, Barcelona, Spain) was used. Besides, the provided NIC headcaps were placed on the head. Before placement, the vertex Cz, the central point of the skull, was measured, localising the crossing point of the distance from the nasion to the inion and the distance between the left and right pre-auricular points. NG Pistim electrodes with a π cm² circular contact area were placed in a 4x1 high-definition (HD) montage on the right lower DLPFC using electrode gel to improve skin conductivity. The ring centre distance from the active electrode was approximately a 5.5-6.5 cm radius. The central active electrode was placed at position F6 (Frontal 6), surrounded by the return electrodes at positions AF8 (Anterior Frontal 8), F8 (Frontal 8), F4 (Frontal 4) and FC6 (Frontal Central 6), all according to the standard 10-10 system (see Figure 3a). Appendix A displays the approximated Talairach coordinates of the EEG positions according to SimNIBS 4 (n.d.).

The stimulation intensity of 1.5 mA was chosen based on a pilot study, analysing intensities, discomfort and side effects to ensure no participant will withdraw. The stimulation intensity generates an electric field of approximately 0.45 V/m. For all conditions, anodal, cathodal and sham, a constant current of 1.5 mA was applied with a current density of .477 mA/cm² for the stimulating electrode and 0.119 mA/cm² per return electrode. The stimulating electrode was used as an anode for the anodal stimulation, and the return electrodes were a collective cathode, each returning 25% of stimulation intensity. For the cathodal stimulation protocol, it is the other way around, with the stimulating electrode being the cathode and the return electrodes as anodes. The positioning was the same for the sham condition, but the current was only applied in the beginning and ending to simulate the same experience of ramping up and down. Stimulation occurred for 16 minutes, including a ramp-up and ramp-down period for each 30s. The device was controlled using the NIC2 software for designing and executing tES protocols.

Figure 3b shows the calculated current flow, modelled in SimNIBS 4 (https://simnibs.github.io/simnibs/build/html/index.html). For the anodal stimulation, the larger positive value indicates a stronger current delivery into the tissue, with minor reverse currents. Therefore, the anode injects the current into the brain tissue. On the other hand, larger negative values in the cathodal stimulation reflect a stronger current withdrawal from the tissue, meaning that the current is extracted from the brain tissue.

Figure 3

Electrode Placement and Calculated Current Flow



Note. Picture **a** depicts the electrode placement over the right lower DLPFC. **b** shows the calculated current flow for both the anodal and cathodal conditions. The current flow was calculated based on the materials and set-up of the present study (e.g. electrode size, gel base, and positions).

2.2.2 Super Hexagon Task

The game was designed as a visuospatial working memory task. This study used the Super Hexagon Task developed by Colby Johanson (University of Saskatchewan, Canada) in the Unity game engine based on an original commercial game Super Hexagon (Cavanaugh, 2012). It involves a rotating task of a triangle rotating centrally around a hexagon (Johanson et al., 2019). The player is instructed to avoid the triangle from touching the rotating obstacles during the game through clockwise and anti-clockwise movements of the triangle. The obstacles spawn, starting on the outside and moving towards the centre hexagon. In addition to the surrounding obstacles, the camera rotates constantly. Over time, the camera rotation speed increases, and the design of the different obstacles becomes more complicated, resulting in a higher difficulty. Upon hitting an obstacle, the timer and game reset, including the difficulty. Performance and rotation data were automatically collected during the game, creating various duration and player-movement variables. The task involves perceptually complex stimuli and some simple motor reactions. Figure 4 shows a screenshot of the Super Hexagon Task.

Figure 4

Super Hexagon Task

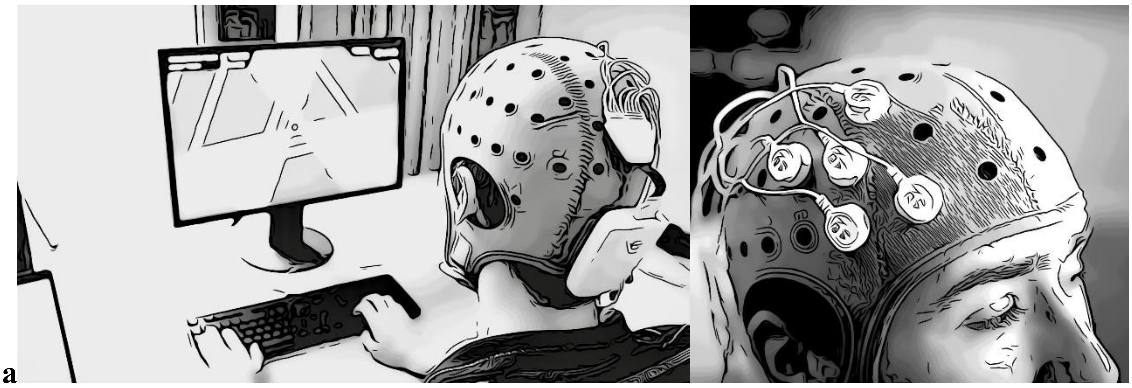
The Super Hexagon Task includes a dynamic design that addresses complex cognitive load, requiring constant spatial manipulation of objects and quick reaction time. The player has to be aware of the changing positions of the objects (Bocchi et al., 2020) and predict where to move next. Moreover, constant monitoring and mental updating are required through continual adjustments in response to the overload of perceptual stimuli (Johanson et al., 2019). The game includes mental transformations to estimate rotation paths, prevent barriers, and make quick decisions about rotating the player's position. Nonetheless, the motor component is minimal to prevent significant interference with the task. Still, adding a motor component makes it more life-like.

2.2.3 Set-Up

Participants were instructed only to use their right hand to play. They were placed in a silent room with a monitor and a keyboard. The electrodes were placed by using a NIC neoprene headcap with a predefined positioning grid in a standard 10-10 EEG system (see Figure 5a. The game was controlled by the left-arrow and right-arrow keys (see Figure 5b). The keys determined the direction of rotation, e.g. by the left-arrow key (anti-clockwise movement) and right-arrow key (clockwise movement)

Figure 5

Study Set-Up and Player Set-Up



a

Note. Part **a** shows the set-up, including the device, the Super Hexagon Task and headcap (including electrode placement).

2.2.4 Questionnaires

First, a one-time demographic questionnaire was conducted to gather information regarding the sample characteristics (gender, age, nationality and handedness). In addition, a short sub-questionnaire regarding attention (concentration and shifting attention) was conducted based on the self-report Attention Control Scale ATTC (Derryberry & Reed, 2002). After every session, each participant was also requested to fill in a repeated questionnaire. This questionnaire investigated the motivation and discomfort of the participant during that session and tested blinding efficacy (see Appendix C). For transparency, it should be mentioned that the repeated questionnaire was only added after the fifth participant completed session 1. Starting with participant six, the questionnaire was answered for each session, whilst for participants one to five, the questionnaires were only added by session two. For the missing values, averages of the other four sessions were computed to exclude the missing values and provide estimates. All data was analysed and securely stored to ensure confidentiality.

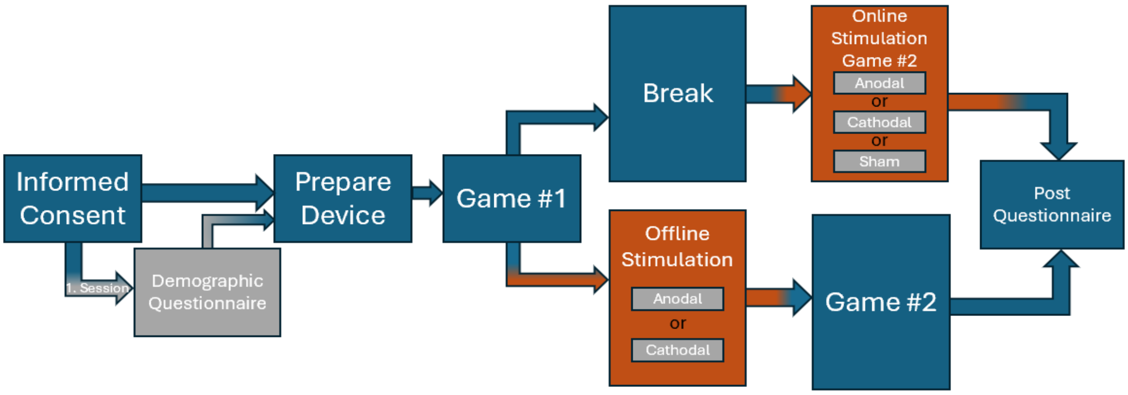
2.3 Design and Procedure

The study was a within-subjects design and included five groups, each measured five times. Each group participated in the five different conditions: 1) sham online, 2) online anodal, 3) online cathodal, 4) offline anodal and 5) offline cathodal. Nevertheless, the order of the conditions was different for each group to prevent order effects (Bergmann & Hartwigsen, 2020); this was handled in a counterbalanced method (see Appendix F). Participants were randomly allocated to each group based on the time of recruitment. This simple randomisation used a repeated list numbered from one to five. Newly registered participants were added to the list and assigned to one of the groups.

Data collection occurred in five separate sessions. The rule was a minimum of five full resting days, a washout period, between sessions to reduce possible learning effects. Each session had a similar sequence but with different stimulation protocols. Each session consisted of preparing the device and cap, a baseline gaming session (2x 5mins), a 15-minute break and a treated gaming session (2x 5mins). Procedure-wise, the stimulation occurred at different times during the procedure. For online stimulations, the participants first experienced a 15-minute break followed by a stimulation protocol plus the treated gaming session. Offline stimulations meant that the stimulation protocol was applied during the 15-minute break. The stimulation was either anodal, cathodal or sham. After preparation of the cap, the participant wore it the entire session, regardless of the stimulation timing, only taking it off after the treated gaming session. The first session started with informed consent and a demographics questionnaire and ended with a short questionnaire. The other four sessions only included revising the consent and ended with a short questionnaire. Figure 6 shows the sequence of events.

Figure 6

Procedure



Note. The sequence only differed when testing timing effects. Both online and offline stimulation occurred anodal and cathodal, while sham only occurred online.

2.4 Data Analysis

2.4.1 Data Reduction and Preparation

Data was gathered through four separate datasets including, the results of the 1) beginning demographics questionnaire and 2) repeated questionnaire, 3) performance dataset and 4) rotation dataset (see Figure 7). A short overview of the data preparation can be found in Figure 8. For the beginning demographics, the dataset was cleaned. For the ATTC sub-questions the item loadings were reverse scored for specified items following Derryberry & Reed's (2002) framework and values were calculated by averaging the ATTC scores. After calculating the scores, the participants were allocated into categories ranging from one to four. The repeated questionnaire was also cleaned from all tests and filtered by excluding unnecessary columns (e.g. Start Date, End Date, IP address, Recipient's first name, Recipient's email) and unfinished questionnaires. Variables of interest were the blinding efficacy, motivation, perceived stimulation intensity and discomfort. A simple yes/no question evaluated effective blinding and the other variables were calculated by taking averages.

Figure 7

Example of Raw Rotation Data

eventType	sessionNumber	trialNumber	trialTime	gameTime	playerRotation	rotationInput	cameraRotationSpeed	playerRotationRate	patternName	eventRadius	patternOuterRadius	patternInnerRadius
CheckpointTrigger	0	0	2903171	370573	34929	0	81	300	hex_3_hole	169626	4696259	169626
MoveStart	0	0	2907331	370924	34929	166	81	300		0	0	0
PatternIsOffScreen	0	0	2926481	372839	29166	3842	81	300	hex_3_hole	0	100	100
MoveEnd	0	0	2927281	372919	28935	0	81	300		0	0	0
PatternSpawned	0	0	2932321	373423	28935	0	81	300	hex_zigzag_1way_x3_15u	0	1509087	1179087
PatternIsAtPlayer	0	0	2975751	377766	28935	0	81	300	hex_spiral_size_5_1_loop	0	5788987	4889932
CheckpointTrigger	0	0	2992321	379424	28935	0	81	300	hex_spiral_size_5_1_loop	150965	5450959	150965
TouchedPattern	0	0	3070681	387273	28935	0	82	300	hex_spiral_size_5_1_loop	5452041	3845205	-1454791
PatternSpawned	0	1	0	41733	28935	0	30	300	hex_intro2	0	93	50
PatternSpawned	0	1	149	417479	28935	0	30	300	hex_3_hole	0	1132165	1102165
PatternSpawned	0	1	6107001	423437	28935	0	30	300	hex_3_hole	0	1232634	1202634
PatternSpawned	0	1	17703	435033	28935	0	30	300	hex_3_hole	0	1233002	1203002
PatternIsAtPlayer	0	1	2535801	442688	28935	0	30	300	hex_intro2	0	4795751	495753
CheckpointTrigger	0	1	2718101	444554	28935	0	30	300	hex_intro2	1712589	4471258	1712589
PatternSpawned	0	1	2914502	446475	28935	0	30	300	hex_2_hole_b	0	1234888	1204888
TouchedPattern	0	1	3616802	453572	28935	0	30	300	hex_intro2	5680524	286805	-143195
PatternSpawned	0	2	0	483518	28935	0	30	300	hex_intro2	0	93	50
PatternSpawned	0	2	148	483666	28935	0	30	300	hex_3_hole	0	1132322	1102322
PatternSpawned	0	2	6075	489593	28935	0	30	300	hex_3_hole	0	12336	12036
PatternSpawned	0	2	17677	501195	28935	0	30	300	hex_3_hole	0	123441	120441
PatternIsAtPlayer	0	2	25434	508952	28935	0	30	300	hex_intro2	0	4794564	4945605
CheckpointTrigger	0	2	27273	510853	28935	0	30	300	hex_intro2	1682814	4468286	1682814
PatternSpawned	0	2	29237	512755	28935	0	30	300	hex_2_hole_b	0	1234537	1204537
TouchedPattern	0	2	3627501	519871	28935	0	30	300	hex_intro2	5659286	286593	-1434074
PatternSpawned	0	3	0	549826	28935	0	30	300	hex_intro2	0	93	50
PatternSpawned	0	3	152	549978	28935	0	30	300	hex_3_hole	0	1132235	1102235

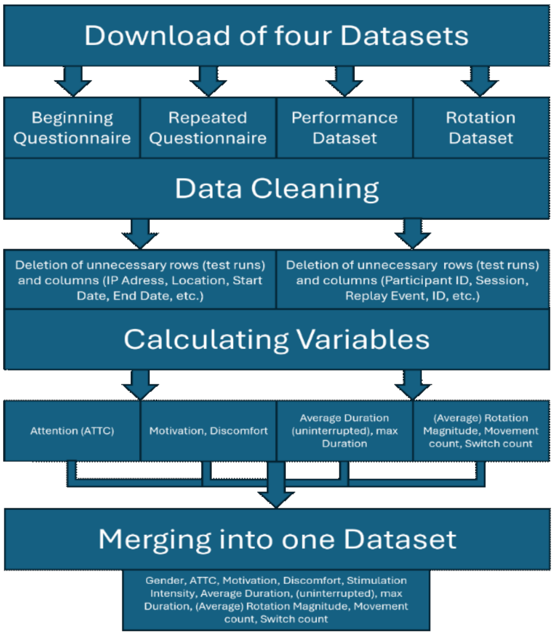
To prepare the performance data, the dataset was cleaned from testing data and unnecessary columns (e.g. system-given participant ID and session). The fitting participant ID and session numbers were reallocated to the data. The data was inspected for possible extreme differences in the variables, such as frames per second and trials without movements, to remove possible extreme outliers that could bias the data. Initially, the dataset included pre- (baseline) and post measures (treated). These columns were filtered by creating new variables based on the improvement from pre to post through simple subtraction (post–pre). So-called change scores, subtracting the baseline from post-stimulation measurements. The new variables created were average duration, average duration uninterrupted, max duration, obstacles cleared, and valid obstacles cleared.

For the rotation data tests and unnecessary columns (e.g. Replay Event ID) were deleted. Additionally, coded data from before the game started was deleted. A dummy variable was created for later analysis that summed the different rotation directions (clockwise and anticlockwise). This was calculated by counting every rotation direction at the start of a new movement. Also, the rotation magnitude was calculated. For this, the game time from the start and end of a movement was used to calculate the duration of the movement, which was multiplied by the player's rotation speed. Averages for all movements within a game were calculated and averaged, and then the difference between the pre and post-game was calculated (like for the performance data). Another variable, the switch frequency, was calculated based on the rotation direction dummy by assessing the switches from clockwise to counterclockwise from one row to the next. For this, the change scores, e.g., the difference within a session, were also calculated.

In the end, a completely new dataset was created that combined the descriptive output, ATTC, motivation and discomfort scores, perceived stimulation intensity, average duration, average duration uninterrupted, max duration, average rotation magnitude and rotation switches. All data cleaning and calculations were done in Microsoft Excel and R 4.0.3. For more details, see Figure 8 (overview) and Appendix D (details on excluded data, extreme values and outliers).

Figure 8

Procedure of Data Preparation



2.4.2 Exploratory Analysis

A first look at the data involved generating descriptive statistics, including mean, standard deviation, minimum and maximum for the variables of interest. The performance variables were average duration (average playing time without hitting obstacles), average duration uninterrupted (excluding the last try in the game that was cut off due to time limits) and max duration (highest score achieved during the game, without hitting obstacles). The rotation data variables were switch frequencies (sum of direction switches) and average rotation (distance travelled, in degrees).

2.4.2.1 Assumptions Testing

A Shapiro-Wilk test was conducted to assess the normality of the variables across conditions. Additionally, histograms and Q-Q plots were generated to display normality. A Box's M test was used to test the assumption of equal covariance matrices across groups. A Levene's Test followed this to check for the equality of error variances for each dependent variable. Moreover, boxplots were generated for each variable, displaying outliers across conditions. To further analyse, the extreme values were printed and looked at.

2.4.3 Statistical Analyses

All MANOVAS, follow-up univariate ANOVA's and visualisations were conducted using the statistics programme IBM SPSS Statistics 29.0.1. Later follow-up repeated measures ANOVA's were conducted using R 4.03.

2.4.3.1 Performance Data

To investigate whether there are significant differences across conditions, a general linear model was used to perform a MANOVA. 'Conditions' and 'Session' were included as factors, as well as their interaction. The performance variables were included as dependent variables. The multivariate tests produced multiple test statistics (e.g. Pillai's Trace, Wilks-Lambada). Moreover, repeated measures ANOVAs were performed for each dependent variable. Also, multiple bar plots and graphs were plotted. This was all done, including all 26 participants and five sessions. Upon analysing the plots, an additional analysis was conducted in the same fashion but including different data. As the plots showed a plateau for the first two sessions, when people seemed to still get adjusted to the game, the analysis was conducted excluding the first two sessions. So, the same factors and dependent variables were included, but for 'Sessions,' only the data from sessions three to five were included. In contrast, an analysis of only sessions one to three was also done. For these measures, follow-up univariate ANOVA's were derived from the MANOVA that had been conducted before. Lastly, a third analysis was included that only focused on polarity effects, excluding the timing effect by only including online stimulation effects for anodal, cathodal, and sham. For this, also repeated measures ANOVA's were added as a follow-up. In case of significant findings, to determine pairwise differences between conditions a Tuckey's Honestly Significant Difference (HSD) was conducted, as well as a paired t-test was conducted.

2.4.3.2 Rotation Data

The rotation data describes the player's behaviour during the game. To test whether the performance variables and the rotation data are correlated a Spearman Correlation test was conducted, suitable for non-normally distributed data. Scatterplots were also generated to visualise the relationship. Subsequently, a general linear model was used to conduct a MANOVA and separate repeated measures ANOVA's. Finally, the data was visualised using bar plots and graphs.

2.4.3.3 Additional Variables

Additional variables were derived from the questionnaires to identify possible biases. Therefore, gender and attention control (ATTC categorised) were further investigated by conducting a MANOVA and a follow up univariate ANOVA. These variables were also plotted in box plots and bar plots. Moreover, data on average discomfort and motivation was also plotted across conditions and tested by running a MANOVA and univariate ANOVA.

3. Results

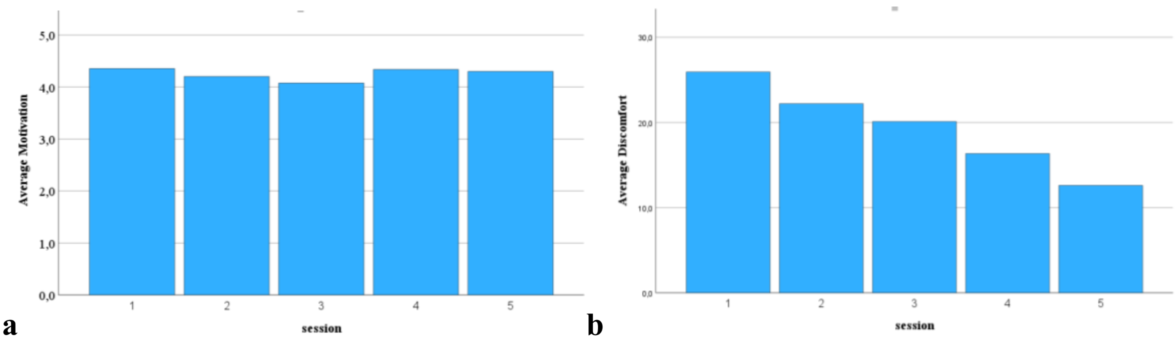
3.1 Sample Characteristics

Additional possibly confounding variables of the sample characteristics were also analysed and checked for extreme values. Attention was tested using the ATTC on a four-point scale. Higher values indicate ease in concentrating and shifting attention. Overall, the results showed that most participants could frequently concentrate well, with a mean of 2.375 (*SD* = 0.189). For more, see Appendix D. This means there were no severe troubles with concentration in the sample.

Furthermore, the majority felt very motivated, with a mean of 4.254 (*SD* = 0.735) on a scale from one to five, with high scores indicating high motivation. The motivation was consistently high across sessions (see Figure 9a). Conversely, the average discomfort was relatively low at 19.67 (*SD* = 18.493). Higher scores reflect greater discomfort as it was measured on a scale ranging from zero (nothing) to 100 (very intense). Figure 9b shows the tendency for the discomfort to decrease across sessions. The discomfort was very similar across conditions, including the control condition, sham. However, it was the highest for online cathodal. Moreover, the majority (87.69%) believed they were actively stimulated, also when being in the control condition (84.62%). For more information on blinding efficacy and discomfort across conditions, see Appendix C and M.

Figure 9

Average Motivation and Average Discomfort by Session



a b

Note. **a** shows the average motivation across sessions and **b** shows the average discomfort across sessions. Both were measured in the repeated questionnaire.

3.2 Assumptions

The normality of the data was assessed using the Shapiro-Wilk test and Q-Q plots for each dependent variable across conditions (and sessions). The Shapiro-Wilk test suggested that the average duration scores were normally distributed, average duration uninterrupted was abnormally distributed for conditions ONA and ONC, max duration was abnormal for OFA, ONA and ONC, the switching frequency was abnormally distributed for ONC, and average rotation was abnormal for the condition ONA (see Appendix N). The Q-Q plots reflected these findings. Nevertheless, the data points fell approximately along the reference line for most conditions. To test the assumption of equal covariance matrices across groups a Box's M test was conducted. The results also showed significant differences, Box's M = 370.228, $p < .001$, $F(144, 5295) = 1.806$, violating the assumption of homogeneity of covariance matrices. Thus, further analyses will focus on Pillai's trace criterion, as it is more robust to departures from assumptions. Lastly, Levene's test was conducted to test the assumption of homogeneity of variance across groups. The values were calculated based on the median, due to deviations from normality. Levene's test was not significant for all three performance variables, suggesting that the variance of the dependent variables does not differ significantly between groups. For average duration $F(24, 105) = 0.752$, $p = .786$, average duration uninterrupted $F(24, 205) = 0.771$, $p = .764$, and max duration $F(24, 205) = 0.622$, $p = .910$. For rotation data, Levene's test was non-significant. The results showed, switch frequencies $F(24, 103) = 0.791$, $p = .740$, and average rotation $F(24, 103) = 0.664$, $p = .875$.

3.3 Inferential Statistics: Hypothesis Testing

3.3.1 Performance Data (a)

The performance data includes data on average performance per session and maximum duration within a session, e.g., the high score. The average performance variables, average duration and average duration uninterrupted, refer to the mean level of performance across multiple games across one session, providing an estimate of the player's overall skill level and consistency. Maximum duration describes the highest performance a player could achieve within one session. It demonstrates the maximum capability of the player in that specific task. The following hypotheses regarding stimulation effects on performance were tested.

Hypothesis 1 Anodal stimulation causes significantly higher (a) performance scores than cathodal stimulation.

Hypothesis 2 Anodal stimulation causes significantly (a) higher performance scores than sham stimulation.

Hypothesis 3 Cathodal stimulation causes significantly higher (a) performance scores than sham stimulation.

3.2.1.1 Average Duration (Uninterrupted): Examining Condition Effects

MANOVA: 5 Sessions

Average duration and average duration uninterrupted both describe the average performance level of the player. The uninterrupted performance captures the entire session and its fluctuations. In contrast, the other variable excludes potentially biased scores (both high-score and low-score games affected by the cut-off). Including both variables for analysis accounts for the individual variability and the randomness of the cut-offs. Moreover, comparing both average performance variables is more reliable, as the patterns should remain similar. A MANOVA demonstrated that the effect of condition on the combined dependent variables (average duration, average duration uninterrupted, and max duration) was not significant, Pillai's Trace = 0.153, $F(12, 315) = 1.410$, $p = .160$, $\eta^2 = .051$. A follow-up repeated measures ANOVA was conducted to examine the effect of the condition on each dependent variable separately. For the average duration, the analysis revealed a non-significant effect of condition, $F(4,100) = 1.999$, $p = .100$, $\eta^2 = .059$. For average duration uninterrupted, the effect was also not significant $F(4,100) = 1.891$, $p = .118$, $\eta^2 = .055$. However, Mauchly's test indicated that the assumption of sphericity was violated, $W = 0.331$, $p = 0.002$. After applying the Greenhouse-Geisser correction, the results were still insignificant, $F(2.535, 63.384) = 1.891$, $p = .149$.

Descriptive statistics showed that for the online anodal stimulation, the mean improvement of the average duration was the highest (*M* = 9.653, *SD* = 8.773), closely followed by online cathodal stimulation (*M* = 9.613, *SD* = 10.291) and the lowest improvement in sham (*M* = 4.474, *SD* = 9.154). However, looking at the average duration uninterrupted, the biggest improvement occurred in the online cathodal group (*M* = 4.914, *SD* = 5.881), then online anodal (*M* = 4.855, *SD* = 4.299) and lastly, sham (*M* = 2.223, *SD* = 4.184). Table 1 shows the different mean improvements. This is also reflected in Figure 10, which shows the differences in performance across conditions. For average duration (uninterrupted), the conditions ONA and ONC scored the highest. For Sham, the Figure illustrates the lowest improvement scores.

Table 1

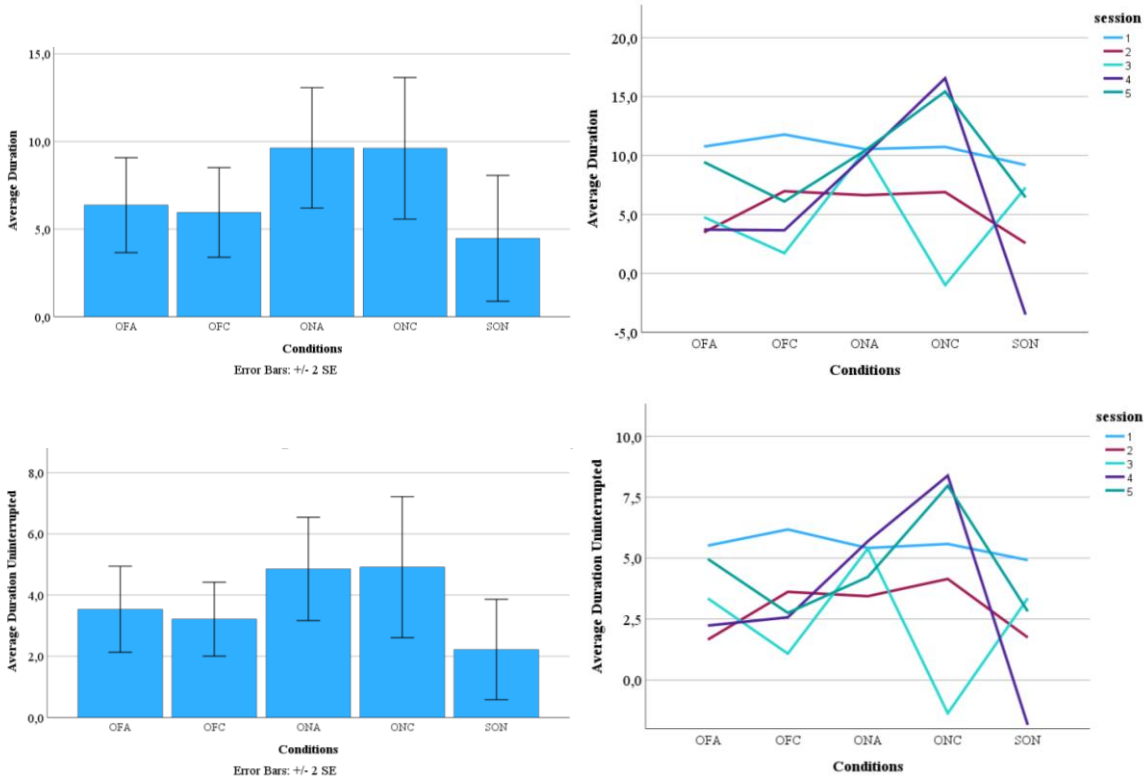
List of Improvements of Average Gaming Performance per Condition and Their Significance

Condition	Mean Improvement of Scores (standard deviation)	Minimum, Maximum
Average Duration		
OFA	6.369 (6.900)	-3.883, 21.270
OFC	5.953 (6.516)	-8.980, 20.062
ONA	9.635 (8.773)	-5.030, 30.965
ONC	9.613 (10.291)	-18.239, 34.961
SON	4.475 (9.154)	-8.656, 29,214
Average Duration Uninterrupted		
OFA	3.537 (3.583)	-1.829, 11.844
OFC	3.215 (3.081)	-1.798, 9.885
ONA	4.855 (4.299)	-0.262, 15.758
ONC	4.914 (5.881)	-13.766, 17.505
SON	2.223 (4.184)	-4.014, 11.942

Note. Average duration (uninterrupted) reflects the endurance during the game, the uninterrupted value only includes the games that were not cut off due to time restraints when playing the game, e.g. excluding the last game before a break or ending. Higher values indicate an improved gaming performance for the second game within one session, compared to the baseline game. Lower scores show a declined gaming performance.

Figure 10

Average Performance Across Conditions

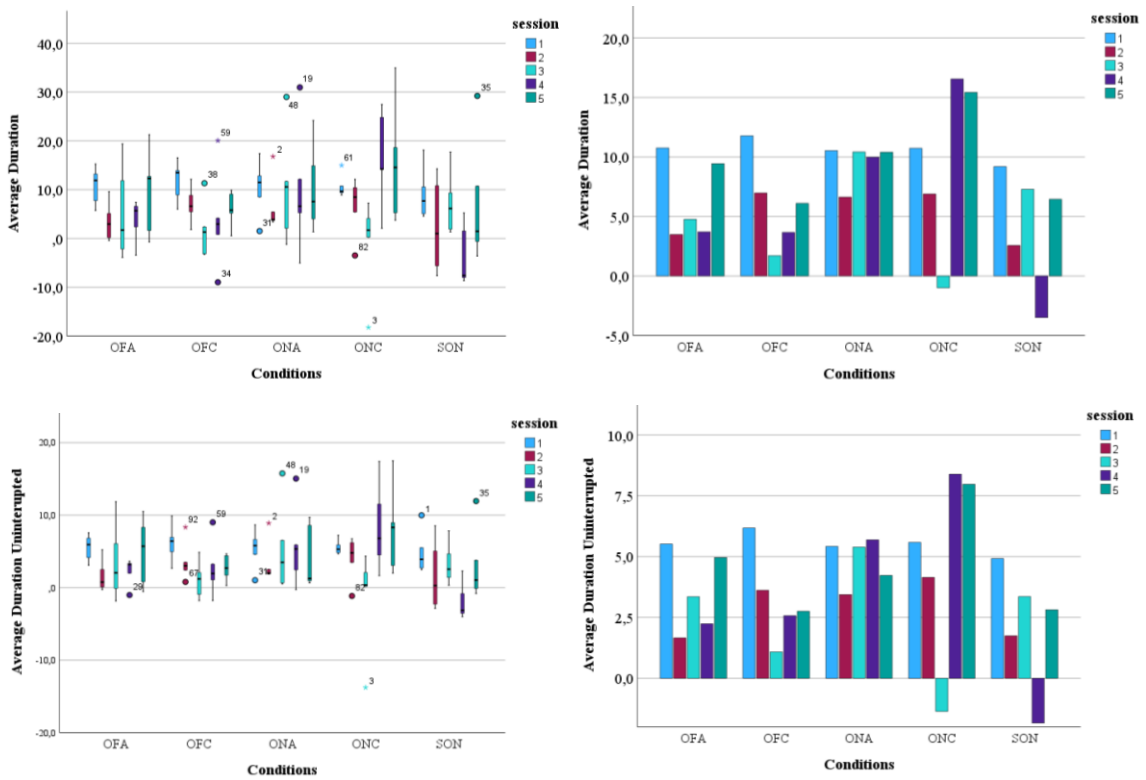


MANOVA: 3 Sessions

Boxplots and bar diagrams were created to visualise the relationship of average performance across sessions. Figure 11 shows how the participants performed throughout the sessions, including a filter by condition. For the first session, the differences are not yet very prominent across conditions, especially for the average duration (uninterrupted). By session three, the differences per condition grow more extreme (see Appendix G for a line graph). Due to this observation, the performance data was analysed again. Another analysis was conducted only including sessions three to five, as visually, the differences were suggested to be more extreme. Also, an analysis that included only sessions one to three was conducted to compare the results.

Figure 11

Average Performance Data per Condition Across Sessions



A second analysis, which only included the data from sessions three to five, also did not find significant effects. The MANOVA was not significant Pillai's Trace = 0.251, $F(12, 189) = 1.440$, $p = .151$, $\eta^2 = .084$. Followed by the non-significant result of the univariate ANOVA with the average duration $F(4) = 1.978$, $p = .109$, $\eta^2 = .112$ and average duration uninterrupted $F(4) = 1.898$, $p = .122$, $\eta^2 = .108$ Additionally, an analysis that only included the data from sessions one to three to compare was conducted. The MANOVA of this general linear model demonstrated non-significant effects. The effect of the conditions on the combined performance variables was non-significant with Pillai's Trace = 0.142, $F(12, 189) = .780$, $p = .671$, $\eta^2 = .047$.

MANOVA: Online Polarity-Effects

With a focus on polarity effects (online), a third analysis, which only included conditions SON, ONA, and ONC, was conducted as a general linear model. The effect of the condition on the combined variables was non-significant, Pillai's Trace = 0.128, $F(6, 148) = 1.704$, $p = .124$, $\eta^2 = .065$. The repeated measures ANOVA for average duration $F(2,50) = 2.36$, $p = .10$, $\eta^2 = .06$ and average duration uninterrupted $F(2, 50) = 2.32$, $p = .11$, $\eta^2 = .07$ were non-significant. For average duration uninterrupted the Mauchly's test indicated a violation of sphericity, $W = 0.72$, $p = .02$. Using Greenhouse-Geisser correction the adjusted values were still insignificant *F*(1.78, 35.91) = 2,32, *p* = .109. Thus, no significantly different effects of stimulation protocols were confirmed for the average performance variables, partially refuting H1, H2 and H3.

3.3.1.2 Maximum Duration: Examining Condition Effects

MANOVA: 5 Sessions

The maximum duration is the highest time achieved during the session, measured in its improvement. The previously conducted MANOVA already showed that the effect of condition on the combined dependent variables (average duration, average duration uninterrupted, and max duration), including all five sessions and five conditions, was not significant, Pillai's Trace = 0.153, *F*(12, 315) = 1.410, *p* = .160, η^2 = .051. Nor significant for a follow-up repeated measures ANOVA after Greenhouse Geisser correction due to violated sphericity, W = 0.370, p = .006*. It investigates the effect of all five conditions on max duration after correction insignificant results were found: *F*(2.841, 70.276) = 2.626, *p* = .060, (before correction: *F*(4,100) = 2.626, *p* = .039*, η^2 = .068).

MANOVA: 3 Sessions

The second analysis of sessions three to five also demonstrated non-significant results of a univariate ANOVA investigating max duration, *F*(4) = 2.074, *p* = .095, η^2 = .116. Similarly, analysing the effect of all five conditions but only including sessions one to three resulted in an insignificant univariate ANOVA of max duration, *F*(4) = 2.079, *p* = .094, η^2 = .117.

MANOVA: Online Polarity-Effects

Nevertheless, a third analysis focused only on online polarity effects (SON, ONA, ONC) displayed a significant effect of the three conditions on maximum duration (repeated measures ANOVA of *F*(2,50) = 3.49, *p* = .038*, η^2 = .085). Mauchly's test suggested sphericity *W* = 0.922, *p* = .378. A Tuckey's HSD post hoc test was conducted to compare the mean test scores between conditions and assess the effect of different stimulation conditions on gaming performance, max duration. The results suggested that the mean maximum duration for the condition SON (*M* = 3.480, *SD* = 7.452), with the lowest score improvement, was significantly different from ONA (*M* = 9.287, *SD* = 8.765), the highest score improvement, with a mean difference of 5.739, *SE* = 2.207, *p* = .030*, 95% CI [.463, 11.016]. However, SON (*M* = 3.48, *SD* = 7.452) was not significantly different from ONC (*M* = 5.540, *SD* = 7.587) with a mean difference of 1.993, *SE* = 2.207, *p* = .640, 95% CI [-3.284, 7.269]. For the descriptives, view Table 2. For ONA and ONC, the results also showed no significant differences, a mean difference of 3.47, *SE* = 2.207, *p* = .213, 95% CI [-1.530, 9.023]. The online effects are visualised in Figure 12, highlighting the significant performance increase under anodal stimulation. To compare online and offline across sessions, view Appendix H.

This partially confirms H2: anodal stimulation causes significantly higher (a) performance scores (maximum duration levels) than cathodal stimulation. Additionally, a paired t-test was conducted to compare the maximum duration between conditions, and the findings are consistent, confirming a significant difference between ONA and SON. No significant differences were revealed between ONA and ONC or ONC and SON conditions. Comparing ONA and SON, there was a significant difference with $t(25) = 2.711$, $p = .012$*. For ONA and ONC, $t(25) = 1.505$, $p = 0.145$. Finally, for ONC and SON, $t(25)$, $p = .325$.

Table 2

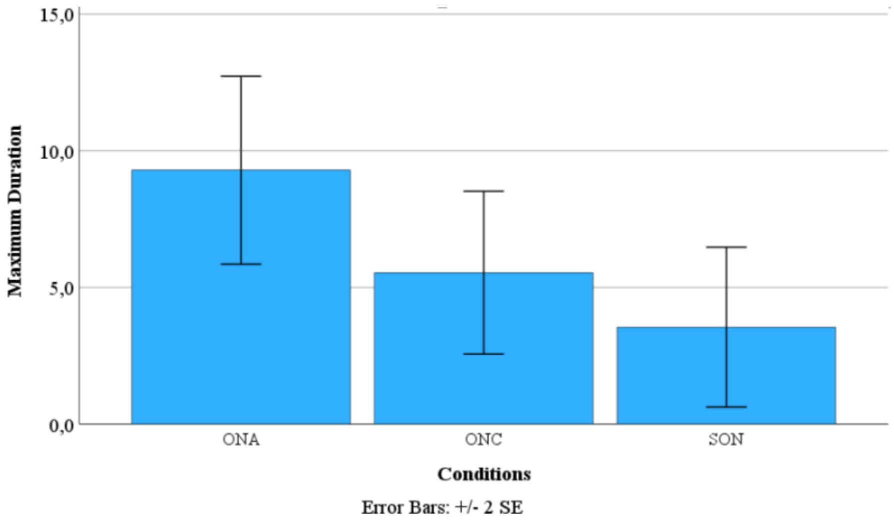
List of Improvements of Maximum Performance per Condition and Their Significance

Condition	Mean Improvement of Scores (standard deviation)	Minimum, Maximum
Maximum Duration		
OFA	5.068 (4.444)	-1.660, 16.580
OFC	5.989 (6.627)	-3.540, 17.640
ONA	9.287 (8.765)	-0.520, 26.970
ONC	5.540 (7.587)	-8.030, 24.860
SON	3.548 (7.452)	-11.580, 22.150

Note. Higher values indicate a higher improvement in maximum duration for the second game within one session.

Figure 12

Maximum Duration across Conditions: Investigating Polarity



3.3.1.3 Hypotheses Performance Data

Based on these findings, H1a, anodal stimulation causes significantly higher performance scores than cathodal stimulation, can be refuted. No significant differences exist between the performance data of anodal and cathodal stimulation. For H2a, no significant effects of condition on the performance variables: average duration (uninterrupted) were found, partially refuting the hypothesis as the conditions are statistically equal. However, anodal stimulation causes significantly higher performance scores on max duration than sham stimulation; the post hoc test found a significant difference when focusing only on online polarity data. Anodal stimulation increased the maximum duration compared to the sham condition, meaning that the condition ONA (M = 9.287, SD = 8.765) performs greater high scores than condition SON (M = 3.548, SD = 7.452), with a mean difference of M = 5.807. The paired t-test reconfirmed this highlighting significant differences in maximum duration between ONA and SON ($t(25) = 2.711$, $p = .012$*). Partially confirming the initial second hypothesis. H3a, which hypothesised that cathodal stimulation causes significantly higher performance scores and more efficient gaming behaviour than sham stimulation, can also be refuted due to non-significant differences found between conditions ONC and SON

3.3.2 Gaming Behaviour (b)

The rotation data describes the player's behaviour during the game. E.g. the reactions and strategies in response to the obstacles. This includes the variable switch frequencies, the sum of direction changes, and average rotation, the magnitude of rotation in degrees. The rotation data is thought to be an indicator of efficiency in gaming behaviour. Hence, there are two underlying assumptions.

Assumption 1: More rotation transitions are considered more effective. (e.g. high switch frequency).

Assumption 2: Shorter rotation paths are considered more efficient (e.g. average rotation

Based on these assumptions, efficiency was analysed. The correlations and condition differences were assessed to test the following hypotheses.

Hypothesis 4 Rotation variables are positively correlated to the performance variables.

Hypothesis 5 There is a significant difference in gaming behaviour between anodal, cathodal and sham stimulation protocols.

e.g. Hypothesis 1 Anodal stimulation causes significantly more efficient (b) gaming behaviour than cathodal stimulation.

Hypothesis 2 Anodal stimulation causes significantly more efficient (b) gaming behaviour than sham stimulation.

Hypothesis 3 Cathodal stimulation causes significantly more efficient (b) gaming behaviour than sham stimulation.

3.3.2.1 Correlation

Spearman's rho correlation was computed to examine the relationship between the performance and the rotation data. There was a small to moderate positive correlation between average duration and average rotation, r (128) = .25, p = .004*. Also, for average duration and average rotation, a small to moderate correlation was found, r (128) = .27, p = .002*. The analysis did not reveal correlations between switch frequency and the chosen performance variables. See Table 3. For visuals, see Appendix I, a displays the small to moderate correlations between average rotation and average duration (uninterrupted). In addition, the relationship between switch frequency and the performance data is depicted in b. This partially confirms H4.

Table 3

Spearman's Rho Correlations Among Variables

Variable	Average Duration	Average Duration Uninterrupted	Max Duration	Switch Frequency	Average Rotation
Average Duration	1.000	.970*	.335*	.031	.254*

		(<.001)	(<.001)	(.725)	(.004)
Average Duration	.970*	1.000	.357*	.020	.271*
Uninterrupted	(<.001)		(<.001)	(.822)	(.002)
Max Duration	.335*	.357*	1.000	.106	.092
	(<.001)	(<.001)		(.232)	(.300)
Switch Frequency	.031	.020	.106	1.000	.060
	(.725)	(.822)	(.232)		(.499)
Average Rotation	.254*	.271*	.092	.060	1.000
	(.004)	(.002)	(.300)	(.499)	

Note. The table shows the correlation coefficient and (p-value). N = 130 for correlations involving performance data (average duration (uninterrupted) and max duration); N = 128 for correlations of rotation data (switch frequency and average rotation). $p < .05$ (2-tailed) is marked with *.

3.3.2.2 Average Rotation: Examining Condition Effects

MANOVA: 5 Sessions

The Average Rotation describes the average of the difference in rotation magnitude between sessions, initially coded in degrees of rotation. Shorter rotation paths were assumed to be more efficient. A MANOVA found no statistically significant effect of the condition on gaming behaviour, e.g. the combination of average rotation and switch frequency, Pillai's Trace = 0.103, $F(8, 206) = 1.405$, $p = .196$, $\eta^2 = .052$. An additional repeated measures ANOVA revealed non-significant effects for each dependent variable. With values for average rotation of $F(4, 100) = 0.849$, $p = .497$, $\eta^2 = .029$. The lowest increase in rotation path was found for the sham condition ($M = 1.489$, $SD = 7.134$), followed by ONC ($M = 3.148$, $SD = 6.870$), and the biggest increase for ONA ($M = 5.929$, $SD = 9.186$) see Table 4. The average rotation depicted per session can be found in Appendix J which reflects that the lowest average rotation values were found for sham.

Table 4

List of Improvements of Average Rotation per Condition and their Significance

Condition	Mean Improvement of Scores (standard deviation)	Minimum, Maximum
Average Rotation		
OFA	3.867 (7.174)	-8.061, 21.052
OFC	3.404 (4.930)	-4.759, 14.366
ONA	5.929 (9.186)	-6.462, 34.935
ONC	3.148 (6.870)	-5.442, 18.417
SON	1.489 (7.134)	-9.881, 19.900

Note. The values show the average difference (or improvement) within a condition between the first and second games, displaying either a decrease or an increase.

MANOVA: 3 Sessions

The plateaus were analysed as well. When analysing the relationship for sessions three to five, there was no significant effect of conditions on rotation data Pillai's Trace = 0.171, $F(8, 124) = 1.451$, $p = .182$, $\eta^2 = .086$. For separate analysis with a follow-up univariate ANOVA, there were also no significant results for average rotation $F(4) = .993$, $p = .418$, $\eta^2 = .060$. Further, no significant effects were found when including only sessions one to three. Analysing the effect of condition on both rotation variables was non-significant Pillai's Trace = 0.124, $F(8, 122) = 1.440$, $p = .433$, $\eta^2 = .062$. Also, when analysing condition effects on average rotation, no significant results were found $F(4) = 1.037$, $p = .395$, $\eta^2 = .064$.

MANOVA: Online Polarity-Effects

A third analysis focused on polarity (excluding OFA and OFC) revealed the following. The main effect of the condition on the combined dependent variables (switch frequency and average rotation) was not significant, Pillai's Trace = 0.078, $F(4, 148) = 1.503$, $p = .204$, $\eta^2 = .039$. A repeated measures ANOVA for the effect of condition on average rotation. Mauchly's test indicated a violation of sphericity, $W = 0.519$, $p < .001$, thus Greenhouse Geisser correction was applied; the effect also proved to be non-significant, $F(1.35, 33.77) = 0.90$, $p = .412$, Partially refuting H5, e.g. also H1, H2 and H3.

3.3.2.3 Switch Frequency: Examining Condition Effects

MANOVA: 5 Sessions

The variable Switch Frequency describes the frequency of direction changes. High switch frequency was assumed to be more efficient. The previously conducted MANOVA already found non-significant effects of Condition on the combined gaming variables, average rotation and switch frequency. An additional repeated measures ANOVA investigating the effect of condition on switch frequencies found non-significant results, even after Greenhouse Geisser correction ($W = 0.380$, $p = 0.007$*). Switch frequency was non-significant with the values $F(2.788, 68.829) = 1.129$, $p = .341$. The highest switch frequency improvement was found for ONA ($M = 3.190$, $SD = 32.523$), followed by SON ($M = -4.200$, $SD = 46.737$) and the lowest count for ONC ($M = -16.810$, $SD = 67.070$). See Table 5 for more. The proportions of travelling either clockwise or anticlockwise can be found in Appendix K. The figures show a tendency for players to turn anticlockwise, most prominent for the sham stimulation protocol, then online cathodal, and the lowest for online anodal stimulation.

Table 5

List of Improvements of Switch Frequency per Condition and Their Significance

Condition	Mean Improvement of Scores (standard deviation)	Minimum, Maximum
Switch Frequency		
OFA	1.620 (25.235)	-46, 53
OFC	6,480 (27.301)	-59, 57
ONA	3.190 (32.523)	-79, 58
ONC	-16.810 (67.070)	-320, 52
SON	-4.200 (46.737)	-98, 78

MANOVA: 3 Sessions

When analysing possible plateau effects. The univariate ANOVA showed no significance when only including sessions three to five, switch frequency $F(4) = 1.606$, $p = .184$, $\eta^2 = .094$. Also, including sessions one to three led to insignificant findings, with switch frequency $F(4) = .977$, $p = .427$, $\eta^2 = .060$.

MANOVA: Online Polarity-Effects

The third analysis focused on polarity. Here, a repeated measures ANOVA for the effect of condition on switch frequency (Mauchly's test: $W = 0.890$, $p = .247$) also showed insignificant values, $F(2, 50) = 1.02$, $p = .367$, $\eta^2 = .027$. Thus, H5 can be fully rejected.

3.3.2.4 Hypotheses Gaming Behaviour

No significant condition effects were found, refuting H5 (e.g. H1b, that anodal stimulation results in more efficient gaming behaviour than cathodal stimulation, and refuting H2b, that anodal stimulation causes significantly more efficient gaming behaviour than sham stimulation. Also, refuting H3b, that cathodal stimulation leads to more significant gaming behaviour than sham). This means that all conditions facilitate statistically similar gaming behaviour strategies. To answer the question of whether gaming behaviour performance is related, positive correlations between average duration (uninterrupted) and average rotation were found. However, no correlations between switch frequency and performance variables were found. Therefore, H4 can only be partially confirmed.

3.3.3 Additional Variables and Gaming Performance

Additional variables and trends were analysed to dismiss any possible confounding biases. Appendix D provides an overview of the descriptive statistics.

3.3.3.1 Gender and Attention

A MANOVA showed a significant effect of gender on gaming performance with Pillai's Trace = 0.062, $F(3, 124) = 2.727$, $p = .047$*. For attention, no significant effect was found with Pillai's Trace = 0.002, $F(3, 124) = 0.077$, $p = .972$. A follow-up univariate ANOVA revealed significant values for the effect of gender on max duration $F(1) = 6.677$, $p = .011$ and non-significant effects for the average duration $F(1) = 2.362$, $p = .127$, and the average duration uninterrupted duration $F(1) = 3.519$, $p = .127$. This was also reflected in the highest scores per participant, as most were set up by male participants. Nevertheless, these results might only reflect the bias of male participants in this study. For visualisations, view Appendix L.

3.2.3.2 Motivation and Discomfort

For motivation and discomfort, another MANOVA was executed. Results were not significant for either. For motivation, the values were, Pillai's Trace = 1.424, $F(27, 30) = 1.004$, $p = .493$ and for discomfort with Pillai's Trace = 2.699, $F(270, 30) = 0.995$, $p = .536$. For visuals look at Figure 10 and Appendix D.

4. Discussion

4.1 Main Findings and Interpretations

This study investigated the polarity effects of tDCS on players' gaming performance in a visuospatial working memory task. The results indicate that the only significant polarity effect was found for the maximum duration when comparing anodal stimulation to sham stimulation. This implies that anodal stimulation enhanced the maximum performance achieved by the player compared to sham. No other significant effects were found, neither for the other performance variables nor for the rotation variables. Additionally, the study demonstrates a partial correlation between performance and rotation variables. A small to moderate correlation exists between average duration (uninterrupted) and average rotation.

Anodal stimulation of the right lower part of the DLPFC only enhanced the maximum duration performance but not the average duration or average duration uninterrupted. One assumption is that average performance is too consistent and might not be very sensitive to short-term neuromodulation as maximum duration. However, another assumption is that neuromodulation was the most effective for high task demand, e.g. during peak performance events. Anodal tDCS of the right lower DLPFC might facilitate critical moments, for example, in peak performance when the player already achieved a certain threshold of gaming difficulty. As these critical moments already require high concentration and allocation of cognitive resources, this is then facilitated by anodal stimulation. These findings suggest that the enhanced neural activation of the right lower DLPFC promoted better visuospatial working memory performance in moments of high demand, generating higher scores. This would confirm the idea that the DLPFC is tightly connected to visuospatial working memory, as well as other higher-order cognitive functions (review: Llana et al., 2021; Li et al., 2016; Wang et al., 2018). Meanwhile, average performance might be influenced by a wide variety of other factors, such as motivation or fatigue (Johanson et al., 2019). Further, the study also found quite steep learning effects that could have masked the stimulation effects and, thus, likely affected the measured effect size on average duration.

The positive correlation between average duration (uninterrupted) and average rotation indicates that average performance also increases as the extent of rotation increases. This is the opposite of Assumption 2, hypothesising that shorter rotation paths would be connected to better performance. A greater extent of rotation tasks could correlate with higher engagement levels and better positioning in the game, thus consistently increasing performance levels.

Additional variables were also investigated to rule out effects based on motivation, discomfort, or gender. However, gender seemed to significantly influence the maximum duration. This was also observed in real life throughout the study, as male participants usually set the highest scores. Therefore, there was a trend of males achieving higher scores, but there were also more males in the sample (65.4%). However, this may be confounded with stereotypical gaming experience. In addition, other variables that possibly interacted with the stimulation effects, such as the order effects, should be considered. Depending on the order of the different conditions, specific training effects might already have been present for certain conditions.

4.2 Implications

The Super Hexagon Task included continuous and highly demanding cognitive processes for the player, e.g. constant monitoring, updating and predictions (Johanson et al., 2019; Waris et al., 2019). High difficulty of the task means that the participants tend to allocate more cognitive resources to it (Wang et al., 2018). Moreover, tDCS effect models suggest that the functional effects of tDCS are most influential on the more active areas during the stimulation protocol (Pisoni et al., 2017; Silvanto et al., 2008). Further, for complex tasks with greater memory load, tDCS effects are more significant (Röhner et al., 2018; Wu et al., 2014). This could explain why peak performance was influenced only by anodal stimulation in these findings. The higher scores likely involved a more complex cognitive load due to the higher task demands. Studies have shown that higher task demands often make the active brain area more susceptible to tDCS effects (Pisoni et al., 2017). Hence, to sum up, the higher the task difficulty, the higher the effect of tDCS. This explains why, for maximum performance, there is a significant difference between anodal stimulation and sham, with enhanced performance in the anodal stimulation group. Hence, the suggestion is that, as tDCS tends to reach the more active brain areas more effectively, active engagement and focus during high-level performance in more complex tasks (peak performance) likely facilitated the tDCS effects. This also supports the strength of using tDCS as a research tool for complex tasks.

Multiple theories support these findings, namely, that higher difficulty, resulting in higher availability of cognitive resources in such situations of high demand, promotes higher scores, therefore facilitating the anodal stimulation effect. For the stimulation effect, anodal tDCS increases the excitability of neurons in the targeted brain area associated with visuospatial working memory. Specifically, under challenging conditions, the facilitation of better neural processing allowed participants to sustain higher performance levels. On the one hand, as the Super Hexagon Game was very complex, it is likely that a bottleneck effect was present for regular playing and average playing performance, meaning that the number of cognitive processes that can be processed simultaneously is limited (Borst et al., 2010; Cunff, 2022). As a result, performance often tended to plateau at an average level regardless of the stimulation protocol, as the cognitive demands might have reached the limits of the bottleneck (Cunff, 2022). In contrast, for high scores, the anodal condition facilitated exceeding the bottleneck. Hence, the effects of anodal stimulation on high scores suggest that the anodal stimulation alleviated the bottleneck, possibly by enhancing the brain's capacity to process more information, improving performance during the high demand situation. Hence, the idea is that anodal stimulation might reduce the overload, allowing for higher scores. Specifically for high-demanding tasks near the upper limits of cognitive capacity, where bottlenecks tend to occur.

On the other hand, independent of the complexity of the game, the cognitive engagement was likely different for high-score situations, promoting the facilitatory effects of anodal stimulation. Different theories support the notion that performance improvements are more pronounced under challenging conditions—for instance, the Capacity Theory (Cowan et al., 2005; Just & Carpenter, 1992) and the Yerkes-Dodson Law (Broadbent, 1965; Khazaei et al., 2021). First, the Capacity Theory states that cognitive resources are limited, and their allocation depends on the task demands and the subsequent activation (Just & Carpenter, 1992), e.g. the adjustable attentional focus of the cognitive resources (Cowan et al., 2005). The plateau in average playing performance would then be explained by the low engagement of the brain on simple tasks. This means that, during average playing performance, the brain might not allocate all available resources towards the task because the low to moderate difficulty indicates that the task does not require it. However, as soon as a task becomes more challenging, e.g. surpassing a specific score or difficulty level in the game, the brain responds to the increased demand by allocating more cognitive resources. Subsequently, the brain operates at a higher information-processing capacity, which might cause improved performance. Therefore, when the task becomes more challenging, the player becomes fully engaged, operating at full capacity, and initiates a more efficient use of cognitive resources. Additionally, the performance can be enhanced even further when the anodal stimulation influences the high score. Thus, possibly, the anodal stimulation effects are only present in high-score situations because the resources are already highly engaged, and the neural reactivity becomes more responsive to the additional stimulation.

Similarly, the Yerkes-Dodson Law describes an inverted U-shaped relationship between arousal and performance (Broadbent, 1965; Khazaei et al., 2021). To apply the theory to cognitive processes such as visuospatial working memory, the idea is a U-inverted relationship between the interaction of challenge and cognitive effort, as explained before, and performance. The theory suggests that for low arousal, thus low challenge, performance tends to be lower, as the tasks do not highly engage the player and do not trigger optimal levels of cognitive effort. However, for moderate to high challenges, the level of arousal tends to be optimal (Khazaei et al., 2021). Therefore, as the task difficulty increases, the performance improves, due to higher engagement, which is the point where performance tends to be optimised, likely facilitated even more during anodal stimulation. Nevertheless, when the game becomes too challenging, the performance decreases due to overloading the cognitive demands (Broadbent, 1965; Khazaei et al., 2021). Consequently, anodal stimulation would only increase performance at the optimal point of player engagement and not throughout the entire game, e.g., average performance.

Other factors could also be relevant to explain why stimulation affected maximum duration. Studies found an interaction effect of achievement motivation, task difficulty and invested mental effort, with approach-driven participants performing better, especially for more difficult tasks (Capa et al., 2008). High achievements might produce higher levels of motivation when faced with high task difficulty, whereas average or low achievements tend to be demotivating (Miller, 2003). Hence, peak performance might be related to surpassing a specific threshold of task difficulty, e.g., a particular score, which could have increased motivation to continue and invest in mental effort.

Nevertheless, determining the stimulation effects of tDCS and cognition can be very hard. The combination of tDCS and cognitive tasks is highly vulnerable to external noise, and cognitive functioning is often a bilateral interaction. Additionally, brain areas involved in cognitive tasks are usually highly activated, thus in high competition with stimulation effects (review: Jacobson et al., 2011). Furthermore, compensatory mechanisms can be involved, especially for such rich networks (Hartwigsen & Bergamnn, 2020; review: Jacobson et al., 2011). The findings also showed that for maximum duration, although non-significant, the performance in the cathodal stimulation group exceeded the performance level of the Sham group. This suggests that compensatory mechanisms might have been active in the cathodal condition for this study. As visuospatial working memory is a bilateral cognitive resource, the down-regulation of the brain activity in the right DLPFC might have led to compensatory measures by other regions, thus facilitating optimal performance more than players' that were not stimulated, e.g. Sham.

This study provided insights into applying tDCS to the right lower DLPFC, investigating effects on visuospatial working memory. The findings confirm that in some cases, anodal stimulation can increase neuronal excitability in the right lower DLPFC, improving visuospatial working memory in high-stakes situations and enabling higher scores. Sela and Lavidor (2014) claim that the anodal enhancement of working memory is due to the alteration of theta and alpha bands. In support, Masina et al. (2021) also found that tDCS stimulation affected alpha and beta power, as measured by EEG. Possibly, anodal stimulation can help the player update and maintain information more effectively during peak performances of the Super Hexagon Task. Nevertheless, when focusing on cognitive enhancement, it could be that tDCS is only a tool for high-stakes events and does not consistently improve skill- levels. When analysing the players' behaviour, the extent of average rotation could be an indication of overall skill. It attempts to analyse the role of the right lower DLPFC in visuospatial WM to investigate further cognitive enhancement that can be relevant for education and clinical treatments.

4.3 Limitations

Nonetheless, including neuroimaging measures in the experiment would have been more informative. This helps draw more precise inferences because only the behavioural output was now measured. Neuroimaging could be added to assess whether the right DLPFC was activated. Other confounding factors include individual differences, e.g. prior gaming experience or gender. This study did not control for cognitive, physiological or anatomical individual differences. Consequently, cognitive differences and prior experience could have biased the results and anatomical differences. HD-tDCS does increase focality, but at the cost of inter-individual differences (Mikonnen et al., 2019). In addition, anatomical variability, e.g. conductance, can cause differences in the current flow and could cause varying electrical fields (conductivity of skull, scalp and cerebrospinal fluid) and different localisations of brain areas (Masina et al., 2021). Also, the found gender bias is attributed to individual and sex-specific differences, e.g. spatial abilities (Voyer et al., 2017). It is hard to disentangle the gender effects from the tDCS effects, as gender is assumed to be related to other factors, such as vulnerability to tDCS or motivation, fatigue, failure to maintain attention (Johanson et al., 2019) or cognitive predispositions in visuospatial factors (Voyer et al., 2017). Moreover, Voyer et al. (2017) assessed sex differences in visuospatial working memory and found a significant male advantage in spatial abilities, which supports our findings. This indicates that gender might play a role in gaming or visuospatial working memory.

Another limitation is that the Super Hexagon Game was played twice per session, baseline and post. However, the game consisted of 11 minutes, with five minutes of playtime, a 60-second break, and again 5 minutes of playtime. Johanson et al. (2019) showed players can improve their performance by taking breaks. This short break could have elevated their performance and increased their learning. Overall. High learning effects were found over the game. Nevertheless, we tried to control these learning effects for statistical analyses by calculating change scores and comparing baseline and post-stimulation measurements.

Although most studies investigating tDCS effects compute change scores (as done here), Masina et al. (2021) claim that different statistical analyses should be used. One disadvantage of change score calculations includes the regression to the mean; for repeated measures, the extreme values become closer to the mean. For example, further improvement is impossible when baseline scores are already high. Especially for the scores of this Super Hexagon Task, the overall improvement, learning, and baseline scores were higher than initially expected, independent of the great difficulty of the game. Therefore, a limitation of this study. Besides, calculating the averaged change scores was done by taking the average of the data, which was already a combined average due to the 2x5-minute sessions within one game, which could have caused minor deviations from the actual variables. Nevertheless, all values were computed like this and should not change the results of this study.

4.4 Strengths

Despite the limitations, this study shows many factors that were well implemented, making up the strengths of this research. For example, the game was tightly related to visuospatial WM, similar to complex, every day, cognitively demanding situations. The game incorporates multiple subprocesses of visuospatial working memory into one task involving high complexity, as seen in real-life situations. To compare, Miyake et al. (2001) suggest that measures of complex working memory tasks tend to predict the outcomes of complex cognitive functions better (Miyake et al., 2001). Therefore, simplifying the visuospatial working memory would make it hard to draw real-life inferences for settings outside of the laboratory. Subsequently, using gamified tasks such as the Super Hexagon Task is more generalisable when examining complex cognitive processes, like in the real world. Furthermore, studies showed that gaming is tightly connected to visuospatial working memory development and enhancement (Moisala et al., 2016; Toril et al., 2016; Waris et al., 2019) and also to higher task-related motivation (Bergmann et al., 2023; Eggemeier et al., 2020b), suggesting that the game is a good measure for cognitive enhancement, whilst motivating the participants to play actively. Even further, the Super Hexagon Task is very task-specific, which is important when implying cause and effect (Hartwigsen & Bergmann, 2020), e.g. tracing the behaviour to the correct cognitive function. Also, blinding was very well executed as no participant could distinguish better than chance level.

In addition, The stimulation intensity was adjusted, and no participant stopped due to sensations that were too discomforting. Like discomfort, the study also examined possible other confounding variables to enable transparent and clear hypothesis testing. Therefore, questionnaires on demographics, attention, motivation, pain tolerance, and distractions were also added.

Also, the set-up of the current study design closely adhered to Villamar et al. (2013)'s recommendations for an effective HD-tDCS set-up. HD-tDCS is also beneficial for blinding because of its high tolerability and lower side effects than conventional tDCS (Reckow et al., 2018). Further, this study considers feasible suggestions by Bergmann and Hartwigsen (2020) to limit the influences of residual effects, such as the standardised set-up. For example, to enable subject comparability for the Electrode positions, the headcap was worn based on a standardised measurement of Cz (10-10 system of EEG positions), promising within-subject consistency and approximating between-subject consistency in the stimulated target. Other strengths include the randomisation using a counterbalanced order, including baseline measures, to best prevent a bias from learning effects, high blinding efficacy and using a large sample size (as calculated by G-Power (Faul et al., 2009)) to account for within-subject variability. Bergmann and Hartwigsen (2020) also mention that tDCS-induced electric fields starting at 0.2-1V/m already generated significant effects which should have been given in the present study, as the induced electric field with a current of 1.5 mA is approximately 0.45 V/m (calculated based on Moreno-Duarte et al., 2014).

Although it was a longitudinal repeated measures study that lasted at least 30 days, the sample size was good. The study's high actual power of 0.976 ensures that the study design was sensitive enough to detect even small effects or differences between conditions. All in all, 26 participants were recruited and completed the study (130 data points), fulfilling the a priori calculated goal and resulting in a comparable effect size to other tDCS studies ($f = 0.333$). Participants also reported enjoying the study, specifically the Super Hexagon Task. Thus, future use of the Super Hexagon Task in gaming or visuospatial working memory assessment is highly recommended. Further, the effect between maximum duration and anodal stimulation provides evidence that the game is associated with visuospatial working memory.

Another important variable that is often forgotten in tDCS is state-dependency effects. Often, the brain state influences the potential effect of tDCS (Bergmann, 2018; Masina et al., 2021; Silvanto et al., 2008). Bergmann and Hartwigsen (2020) also highlight that the current state of the brain should be considered. Because the neural impact of tDCS also depends on the initial activation state of the targeted brain region (Silvanto et al., 2008). The results on maximum duration show that, to some extent, the targeted brain regions were involved in the task demand.

Lastly, the gathered data is part of a more extensive study. It also includes data on timing effects in tDCS (online vs. offline) and other performance and gaming behaviour variables. Thus, further analyses could be conducted based on the data. Further, the rotation data, e.g., player behaviour, is coded in detail, enabling the replication of past games in Unity using the dataset as a script. Such data is very new and can be valuable for in-depth analyses. This study initiated the first attempt at implementing and connecting performance and player behaviour variables.

4.5 Recommendations and Future Directions

Overall, based on the strengths and limitations mentioned above, parts of similar future studies can be adjusted to draw more precise conclusions. E.g. using a more variable sample size, adjusting the playing time, adding questionnaires measuring other confounding variables, or using different statistical calculations. One way to better understand the player's behaviour is to analyse the different response strategies through distributional analyses (Bergmann & Hartwigsen, 2020). In order to categorise the speed of the reaction and its effectiveness, one way could be measuring the time between the spawn of a new object and the first movement of the player in response to that object. All of this data was coded automatically while playing the game. Additionally, individualised e-field modelling, neuroimaging, and EEG can greatly contribute to making more transparent inferences between cognition and measured behaviours, such as when examining state dependency. All in all, future research into tDCS effects on cognition is recommended—for example, the use of cognitive enhancement effects to counter malfunctioning cognition.

In light of this potential, it is vital to explore how cognitive enhancement can also be applied to fields of cognitive dysfunction. For instance, by providing treatments for neurodevelopmental disorders (autism spectrum disorder (ASD)) and neurocognitive disorders (Alzheimer's dementia), as well as counteracting decreases in cognitive abilities from simple ageing (Berryhill & Martin, 2018; Luckhardt et al., 2021; Prehn & Flöel, 2015). ASD is an example of abnormal brain function. It is associated with altered brain activity patterns and task-related functional connectivity between brain regions. Further, some evidence suggests a disbalance in neuronal excitation and inhibition for ASD. Consequently, individuals experience difficulties in communication and working memory, which psychotherapy can only mildly treat. A review by Luckhardt et al. (2021) found that tDCS stimulation can relieve ASD symptoms, increasing functional connectivity and alpha oscillations. Increased alpha oscillations are often associated with higher working memory speed and capacity. In support of this, van Steenburgh et al. (2017) focused on anodal stimulation of the DLPFC and found positive effects on working memory in ASD (van Steenburgh et al., 2017). Therefore, tDCS seems to be an effective tool for compensating abnormal brain patterns in ASD, especially in combination with a concurrent task. Krause and Kadosh (2013) suggest similar benefits for the treatment of attention-deficit hyperactivity disorder (ADHD). Combining cognitive training with tES can enhance cognition and facilitate beneficial neuroplastic changes in brain connectivity, making them long-term. This can occur through the modulation of cortical excitability. Anodal tDCS lowers the neuronal threshold, and at the same time, the cognitive training repeatedly activates the network, strengthening the connections of the atypical and deficient network (Krause & Kadosh, 2013).

Overall, using tDCS can help overcome learning- and memory-related deficits (Prehn & Flöel, 2015), making it a valuable tool for cognitive rehabilitation as well as enhancement (Berryhill & Martin, 2018). Besides its cost efficiency, the application creates minimal side effects, making it a safe tool (Luckhardt et al., 2021). Moreover, because of the enduring effects of tDCS, improved cognitive functions can be sustained beyond the stimulation duration (Orrù et al., 2019), and effects can even increase over time (Luckhardt et al., 2021).

5. Conclusion

To conclude, this research aimed to investigate how cathodal or anodal tDCS stimulation influences a student's gaming performance and behaviour in a visuospatial working memory task. Stimulation occurred on the right lower DLPFC, as prior research identified this brain region's correlation to visuospatial working memory. The task was a challenging, dynamic game with moving visual components, addressing complex cognitive load. Findings specifically for the Super Hexagon Task suggest that higher rotation duration, e.g. average rotation, positively affects performance. In addition, based on this within-subjects factorial design with repeated measures, one can conclude that anodal stimulation of the right lower DLPFC can be beneficial for reaching high scores on visuospatial working memory tasks. This means that anodal stimulation especially affects complex and highly difficult tasks. Nevertheless, anodal stimulation did not enhance the average performance, including all gaming attempts. Theories like Kahneman's Capacity Model of Attention and the Yerkes-Dodson Law suggest that moments of high task difficulty, e.g. surpassing a specific score in the game, require high engagement and put a high demand on cognitive load. Consequently, when reaching the threshold of optimal arousal, the high neural activity by anodal stimulation can facilitate performance above average.

Although some studies found the effects of cathodal stimulation to be inhibiting, this cannot be confirmed for stimulation over the right lower DLPFC. The difference was insignificant, but the scores of cathodal stimulation were higher than those of the control group, sham. A possible explanation would be through compensatory mechanisms, as the cognitive network is bilateral and can counteract the decreased excitability of the right DLPFC. Additionally, this study investigated the players' behaviour during the game and found that higher average performance scores were related to a higher extent of rotation movement. Also, the findings reflect a male advantage in visuospatial abilities.

Hence, this research provided new insights into the effects of tDCS on visuospatial working memory, including multiple components of working memory to imitate the complexity of real-life situations. These results illustrate that anodal stimulation can enhance cognitive performance, e.g. visuospatial working memory. Therefore, it confirms the potential of using tDCS as a cognitive enhancement tool in educational settings and as a cognitive rehabilitation tool in clinical settings. Further research is needed to investigate the relationship between tDCS stimulation and cognitive enhancement. Such research could be done with combined measures of neuroimaging and tDCS. Moreover, different approaches to statistical analyses could be tested.

References

Abellaneda-Pérez, K., Vaqué-Alcázar, L., Perellón-Alfonso, R., Bargalló, N., Kuo, M., Pascual-Leone, A., Nitsche, M. A., & Bartrés-Faz, D. (2020). Differential TDCS and TACS effects on working Memory-Related neural activity and Resting-State connectivity. *Frontiers in Neuroscience*, *13*. https://doi.org/10.3389/fnins.2019.01440

Alam, M., Truong, D. Q., Khadka, N., & Bikson, M. (2016). Spatial and polarity precision of concentric high-definition transcranial direct current stimulation (HD-tDCS). *Physics in Medicine & Biology/Physics in Medicine and Biology*, *61*(12), 4506–4521. https://doi.org/10.1088/0031-9155/61/12/4506

Amini Masouleh, M., Chalabianloo, G., & Abdi, R. (2022). Comparison of Cognitive Rehabilitation efficacy based on Computer-Assisted Cognitive Rehabilitation With and Without Transcranial Direct Current Stimulation (TDCS) on improving the working memory of stroke patients. *Neuropsychology*, *8*(28), 41–53. https://doi.org/10.30473/clpsy.2020.51573.1516

Baltus, A., & Herrmann, C. S. (2016). The importance of individual frequencies of endogenous brain oscillations for auditory cognition – A short review. *Brain Research*, *1640*, 243–250. https://doi.org/10.1016/j.brainres.2015.09.030

Bergmann, M., Wollbrandt, I., Gittel, L., Halbe, E., Mackert, S., Philipsen, A., & Lux, S. (2023). Effects of a video game intervention on symptoms, training motivation, and visuo-spatial memory in depression. *Frontiers in Psychiatry*, *14*. https://doi.org/10.3389/fpsyt.2023.1173652

Bergmann, T. O. (2018). Brain State-Dependent brain stimulation. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.02108

Bergmann, T. O., & Hartwigsen, G. (2021). Inferring Causality from Noninvasive Brain Stimulation in Cognitive Neuroscience. *Journal of Cognitive Neuroscience*, *33*(2), 195–225. https://doi.org/10.1162/jocn_a_01591

Berryhill, M. E., & Martin, D. (2018). Cognitive effects of transcranial direct current stimulation in healthy and clinical populations. *Journal of ECT/˜ the œJournal of ECT*, *34*(3), e25–e35. https://doi.org/10.1097/yct.0000000000000534

Bocchi, A., Palermo, L., Boccia, M., Palmiero, M., D’Amico, S., & Piccardi, L. (2018). Object recognition and location: Which component of object location memory for landmarks is affected by gender? Evidence from four to ten year-old children. *Applied Neuropsychology. Child*, *9*(1), 31–40. https://doi.org/10.1080/21622965.2018.1504218

Borst, J. P., Taatgen, N. A., & Van Rijn, H. (2010). The problem state: A cognitive bottleneck in multitasking. *Journal of Experimental Psychology Learning Memory and Cognition*, *36*(2), 363–382. https://doi.org/10.1037/a0018106

Broadbent, D. E. (1965). A REFORMULATION OF THE YERKES-DODSON LAW. *British Journal of Mathematical and Statistical Psychology*, *18*(2), 145–157. https://doi.org/10.1111/j.2044-8317.1965.tb00338.x

Busch, R. M., Farrell, K., Lisdahl-Medina, K., & Krikorian, R. (2005). Corsi Block-Tapping task performance as a function of path configuration. *Neuropsychology, Development, and Cognition. Section a, Journal of Clinical and Experimental Neuropsychology/Journal of Clinical and Experimental Neuropsychology*, *27*(1), 127–134. https://doi.org/10.1080/138033990513681

Capa, R. L., Audiffren, M., & Ragot, S. (2008). The interactive effect of achievement motivation and task difficulty on mental effort. *International Journal of Psychophysiology*, *70*(2), 144–150. https://doi.org/10.1016/j.ijpsycho.2008.06.007

Cocchi, L., Schenk, F., Volken, H., Bovet, P., Parnas, J., & Vianin, P. (2007). Visuo-spatial processing in a dynamic and a static working memory paradigm in schizophrenia. *Psychiatry Research*, *152*(2–3), 129–142. https://doi.org/10.1016/j.psychres.2006.02.004

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*(1), 42–100. https://doi.org/10.1016/j.cogpsych.2004.12.001

Cunff, A. L. (2022, June 23). *Cognitive bottlenecks: the inherent limits of the thinking mind*. Ness Labs. https://nesslabs.com/cognitive-bottlenecks

Davarani, M. N., Darestani, A. A., Hassani-Abharian, P., Vaseghi, S., Zarrindast, M., & Nasehi, M. (2020). RehaCom rehabilitation training improves a wide-range of cognitive functions in multiple sclerosis patients. *Applied Neuropsychology. Adult*, *29*(2), 262–272. https://doi.org/10.1080/23279095.2020.1747070

Derryberry, D., & Reed, M. A. (2002). Anxiety-related attentional biases and their regulation by attentional control. *Journal of Abnormal Psychology*, *111*(2), 225–236. https://doi.org/10.1037/0021-843x.111.2.225

Eggemeier, F. T., Wilson, G. F., Kramer, A. F., & Damos, D. L. (2020a). Workload assessment in multi-task environments. In *CRC Press eBooks* (pp. 207–216). https://doi.org/10.1201/9781003069447-12

Eggemeier, F. T., Wilson, G. F., Kramer, A. F., & Damos, D. L. (2020b). Workload assessment in multi-task environments. In *CRC Press eBooks* (pp. 207–216). https://doi.org/10.1201/9781003069447-12

Fanari, R., Meloni, C., & Massidda, D. (2019). Visual and spatial working memory abilities predict early math skills: a longitudinal study. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02460

Farah, M. J., Smith, M. E., Ilieva, I., & Hamilton, R. H. (2013). Cognitive enhancement. *Wiley Interdisciplinary Reviews. Cognitive Science*, *5*(1), 95–103. https://doi.org/10.1002/wcs.1250

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/brm.41.4.1149

Fitz, N. S., & Reiner, P. B. (2014). The perils of using electrical stimulation to change human brains. In *Elsevier eBooks* (pp. 61–83). https://doi.org/10.1016/b978-0-12-404704-4.00003-x

Friehs, M. A., & Frings, C. (2018). Pimping inhibition: Anodal tDCS enhances stop-signal reaction time. *Journal of Experimental Psychology. Human Perception and Performance*, *44*(12), 1933–1945. https://doi.org/10.1037/xhp0000579

Friehs, M. A., & Frings, C. (2019). Cathodal tDCS increases stop-signal reaction time. *Cognitive, Affective & Behavioral Neuroscience*, *19*(5), 1129–1142. https://doi.org/10.3758/s13415-019-00740-0

Fuster, J. M. (2015a). Human Neuropsychology. In *Elsevier eBooks* (pp. 183–235). https://doi.org/10.1016/b978-0-12-407815-4.00005-2

Fuster, J. M. (2015b). Overview of prefrontal functions. In *Elsevier eBooks* (pp. 375–425). https://doi.org/10.1016/b978-0-12-407815-4.00008-8

Garden, S., Cornoldi, C., & Logie, R. H. (2001). Visuo-spatial working memory in navigation. *Applied Cognitive Psychology*, *16*(1), 35–50. https://doi.org/10.1002/acp.746

Geissler, C. F., Domes, G., & Frings, C. (2020). Shedding light on the frontal hemodynamics of spatial working memory using functional near-infrared spectroscopy. *Neuropsychologia*, *146*, 107570. https://doi.org/10.1016/j.neuropsychologia.2020.107570

Geissler, C. F., Schneider, J., & Frings, C. (2021). Shedding light on the prefrontal correlates of mental workload in simulated driving: a functional near-infrared spectroscopy study. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-020-80477-w

Green, C., & Bavelier, D. (2012). Learning, attentional control, and action video games. *CB/Current Biology*, *22*(6), R197–R206. https://doi.org/10.1016/j.cub.2012.02.012

Grover, S., Fayzullina, R., Bullard, B. M., Levina, V., & Reinhart, R. M. G. (2023). A meta-analysis suggests that tACS improves cognition in healthy, aging, and psychiatric populations. *Science Translational Medicine*, *15*(697). https://doi.org/10.1126/scitranslmed.abo2044

Hamilton, C., Coates, R., & Heffernan, T. (2003). What develops in visuo-spatial working memory development? *European Journal of Cognitive Psychology/European Journal of Cognitive Psychology*, *15*(1), 43–69. https://doi.org/10.1080/09541440303597

Herrmann, C. S., & Strüber, D. (2017). What can transcranial alternating current stimulation tell us about brain oscillations? *Current Behavioral Neuroscience Reports*, *4*(2), 128–137. https://doi.org/10.1007/s40473-017-0114-9

Hoy, K. E., Emonson, M. R., Arnold, S. L., Thomson, R. H., Daskalakis, Z. J., & Fitzgerald, P. B. (2013). Testing the limits: Investigating the effect of tDCS dose on working memory enhancement in healthy controls. *Neuropsychologia*, *51*(9), 1777–1784. https://doi.org/10.1016/j.neuropsychologia.2013.05.018

Jacobson, L., Koslowsky, M., & Lavidor, M. (2011). tDCS polarity effects in motor and cognitive domains: a meta-analytical review. *Experimental Brain Research*, *216*(1), 1–10. https://doi.org/10.1007/s00221-011-2891-9

Johanson, C., Gutwin, C., Bowey, J. T., & Mandryk, R. L. (2019). Press Pause when you Play. *Association for Computing Machinery*. https://doi.org/10.1145/3311350.3347195

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, *99*(1), 122–149. https://doi.org/10.1037/0033-295x.99.1.122

Khazaei, S., Amin, M. R., & Faghih, R. T. (2021). Decoding a Neurofeedback-Modulated Cognitive Arousal State to investigate performance regulation by the Yerkes-Dodson Law. *2021 43rd Annual International Conference of the IEEE Engineering in Medicine &Amp; Biology Society (EMBC)*. https://doi.org/10.1109/embc46164.2021.9629764

Kemps, E. (1999). Effects of complexity on visuo-spatial working memory. *European Journal of Cognitive Psychology/European Journal of Cognitive Psychology*, *11*(3), 335–356. https://doi.org/10.1080/713752320

Kim, J., Kim, H., Jeong, H., Roh, D., & Kim, D. H. (2021). tACS as a promising therapeutic option for improving cognitive function in mild cognitive impairment: A direct comparison between tACS and tDCS. *Journal of Psychiatric Research*, *141*, 248–256. https://doi.org/10.1016/j.jpsychires.2021.07.012

Koessler, L., Maillard, L., Benhadid, A., Vignal, J. P., Felblinger, J., Vespignani, H., & Braun, M. (2009). Automated cortical projection of EEG sensors: Anatomical correlation via the international 10–10 system. *NeuroImage*, *46*(1), 64–72. https://doi.org/10.1016/j.neuroimage.2009.02.006

Krause, B., & Kadosh, R. C. (2013). Can transcranial electrical stimulation improve learning difficulties in atypical brain development? A future possibility for cognitive training. *Developmental Cognitive Neuroscience*, *6*, 176–194. https://doi.org/10.1016/j.dcn.2013.04.001

Krause, B., Looi, C. Y., & Kadosh, R. C. (2014). Transcranial electrical stimulation to enhance cognitive abilities in the atypically developing brain. In *Elsevier eBooks* (pp. 455–483). https://doi.org/10.1016/b978-0-12-404704-4.00016-8

Kronovsek, T., Hermand, E., Berthoz, A., Castilla, A., Gallou-Guyot, M., Daviet, J., & Perrochon, A. (2021). Age-related decline in visuo-spatial working memory is reflected by dorsolateral prefrontal activation and cognitive capabilities. *Behavioural Brain Research*, *398*, 112981. https://doi.org/10.1016/j.bbr.2020.112981

Kuo, H., Bikson, M., Datta, A., Minhas, P., Paulus, W., Kuo, M., & Nitsche, M. A. (2013). Comparing Cortical Plasticity induced by Conventional and High-Definition 4 × 1 Ring TDCS: A neurophysiological study. *Brain Stimulation*, *6*(4), 644–648. https://doi.org/10.1016/j.brs.2012.09.010

Li, S., Cai, Y., Liu, J., Li, D., Feng, Z., Chen, C., & Xue, G. (2017). Dissociated roles of the parietal and frontal cortices in the scope and control of attention during visual working memory. *NeuroImage*, *149*, 210–219. https://doi.org/10.1016/j.neuroimage.2017.01.061

Llana, T., Fernandez-Baizan, C., Mendez-Lopez, M., Fidalgo, C., & Mendez, M. (2022). Functional near-infrared spectroscopy in the neuropsychological assessment of spatial memory: A systematic review. *Acta Psychologica*, *224*, 103525. https://doi.org/10.1016/j.actpsy.2022.103525

Logie, R. H. (2003). Spatial and visual working memory: a mental workspace. In ˜ *The œPsychology of learning and motivation/˜ The œpsychology of learning and motivation* (pp. 37–78). https://doi.org/10.1016/s0079-7421(03)01002-8

Logie, R. H., & Pearson, D. G. (1997). The Inner Eye and the Inner Scribe of Visuo-spatial Working Memory: Evidence from Developmental Fractionation. *European Journal of Cognitive Psychology/European Journal of Cognitive Psychology*, *9*(3), 241–257. https://doi.org/10.1080/713752559

Lucas, I., Urieta, P., Balada, F., Blanco, E., & Aluja, A. (2020). Differences in prefrontal cortex activity based on difficulty in a working memory task using near-infrared spectroscopy. *Behavioural Brain Research*, *392*, 112722. https://doi.org/10.1016/j.bbr.2020.112722

Luckhardt, C., Boxhoorn, S., Schütz, M., Fann, N., & Freitag, C. M. (2021). Brain stimulation by tDCS as treatment option in Autism Spectrum Disorder—A systematic literature review. In *Progress in brain research* (pp. 233–257). https://doi.org/10.1016/bs.pbr.2021.03.002

Masina, F., Arcara, G., Galletti, E., Cinque, I., Gamberini, L., & Mapelli, D. (2021). Neurophysiological and behavioural effects of conventional and high definition tDCS. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-87371-z

Mikkonen, M., Laakso, I., Tanaka, S., & Hirata, A. (2020a). Cost of focality in TDCS: Interindividual variability in electric fields. *Brain Stimulation*, *13*(1), 117–124. https://doi.org/10.1016/j.brs.2019.09.017

Mikkonen, M., Laakso, I., Tanaka, S., & Hirata, A. (2020b). Cost of focality in TDCS: Interindividual variability in electric fields. *Brain Stimulation*, *13*(1), 117–124. https://doi.org/10.1016/j.brs.2019.09.017

Miller, S. D. (2003). HOW HIGH- AND LOW-CHALLENGE TASKS AFFECT MOTIVATION AND LEARNING: IMPLICATIONS FOR STRUGGLING LEARNERS. *Reading & Writing Quarterly*, *19*(1), 39–57. https://doi.org/10.1080/10573560308209

Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology. General*, *130*(4), 621–640. https://doi.org/10.1037/0096-3445.130.4.621

Moisala, M., Salmela, V., Hietajärvi, L., Carlson, S., Vuontela, V., Lonka, K., Hakkarainen, K., Salmela-Aro, K., & Alho, K. (2017). Gaming is related to enhanced working memory performance and task-related cortical activity. *Brain Research*, *1655*, 204–215. https://doi.org/10.1016/j.brainres.2016.10.027

Moreno-Duarte, I., Gebodh, N., Schestatsky, P., Guleyupoglu, B., Reato, D., Bikson, M., & Fregni, F. (2014a). Transcranial electrical stimulation. In *Elsevier eBooks* (pp. 35–59). https://doi.org/10.1016/b978-0-12-404704-4.00002-8

Moreno-Duarte, I., Gebodh, N., Schestatsky, P., Guleyupoglu, B., Reato, D., Bikson, M., & Fregni, F. (2014b). Transcranial electrical stimulation. In *Elsevier eBooks* (pp. 35–59). https://doi.org/10.1016/b978-0-12-404704-4.00002-8

Neuroelectrics. (n.d.). *Neuroelectrics: Starstim: tES*. https://www.neuroelectrics.com/solutions/starstim/tes

Orrù, G., Conversano, C., Hitchcott, P. K., & Gemignani, A. (2019). Motor stroke recovery after tDCS: a systematic review. *Reviews in the Neurosciences*, *31*(2), 201–218. https://doi.org/10.1515/revneuro-2019-0047

Pisoni, A., Mattavelli, G., Papagno, C., Rosanova, M., Casali, A. G., & Lauro, L. J. R. (2017). Cognitive enhancement induced by anodal TDCS drives Circuit-Specific cortical plasticity. *Cerebral Cortex*, *28*(4), 1132–1140. https://doi.org/10.1093/cercor/bhx021

Prehn, K., & Flöel, A. (2015). Potentials and limits to enhance cognitive functions in healthy and pathological aging by tDCS. *Frontiers in Cellular Neuroscience*, *9*. https://doi.org/10.3389/fncel.2015.00355

Reckow, J., Rahman-Filipiak, A., Garcia, S., Schlaefflin, S., Calhoun, O., DaSilva, A. F., Bikson, M., & Hampstead, B. M. (2018). Tolerability and blinding of 4x1 high-definition transcranial direct current stimulation (HD-tDCS) at two and three milliamps. *Brain Stimulation*, *11*(5), 991–997. https://doi.org/10.1016/j.brs.2018.04.022

Röhner, F., Breitling, C., Rufener, K. S., Heinze, H., Hinrichs, H., Krauel, K., & Sweeney-Reed, C. M. (2018). Modulation of working memory using transcranial electrical stimulation: A direct comparison between TACS and TDCS. *Frontiers in Neuroscience*, *12*. https://doi.org/10.3389/fnins.2018.00761

Roy, A., Baxter, B., & He, N. B. (2014a). High-Definition transcranial direct current stimulation induces both acute and persistent changes in broadband cortical synchronization: a simultaneous TDCS–EEG study. *IEEE Transactions on Bio-medical Engineering/IEEE Transactions on Biomedical Engineering*, *61*(7), 1967–1978. https://doi.org/10.1109/tbme.2014.2311071

Roy, A., Baxter, B., & He, N. B. (2014b). High-Definition transcranial direct current stimulation induces both acute and persistent changes in broadband cortical synchronization: a simultaneous TDCS–EEG study. *IEEE Transactions on Bio-medical Engineering/IEEE Transactions on Biomedical Engineering*, *61*(7), 1967–1978. https://doi.org/10.1109/tbme.2014.2311071

Scheunemann, J., Unni, A., Ihme, K., Jipp, M., & Rieger, J. W. (2019). Demonstrating Brain-Level interactions between visuospatial attentional demands and working memory load while driving using functional Near-Infrared Spectroscopy. *Frontiers in Human Neuroscience*, *12*. https://doi.org/10.3389/fnhum.2018.00542

Sela, T., & Lavidor, M. (2014). High-Level cognitive functions in healthy subjects. In *Elsevier eBooks* (pp. 299–329). https://doi.org/10.1016/b978-0-12-404704-4.00011-9

Silvanto, J., Muggleton, N., & Walsh, V. (2008). State-dependency in brain stimulation studies of perception and cognition. *Trends in Cognitive Sciences*, *12*(12), 447–454. https://doi.org/10.1016/j.tics.2008.09.004

Tanoue, R. T., Jones, K. T., Peterson, D. J., & Berryhill, M. E. (2013). Differential frontal involvement in shifts of internal and perceptual attention. *Brain Stimulation*, *6*(4), 675–682. https://doi.org/10.1016/j.brs.2012.11.003

Toril, P., Reales, J. M., Mayas, J., & Ballesteros, S. (2016). Video game training enhances visuospatial working memory and episodic memory in older adults. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/fnhum.2016.00206

Van Steenburgh, J. J., Varvaris, M., Schretlen, D. J., Vannorsdall, T. D., & Gordon, B. (2017). Balanced bifrontal transcranial direct current stimulation enhances working memory in adults with high-functioning autism: a sham-controlled crossover study. *Molecular Autism*, *8*(1). https://doi.org/10.1186/s13229-017-0152-x

Villamar, M. F., Volz, M. S., Bikson, M., Datta, A., DaSilva, A. F., & Fregni, F. (2013). Technique and considerations in the use of 4x1 ring High-definition Transcranial Direct Current Stimulation (HD-TDCS). *Journal of Visualized Experiments*, *77*. https://doi.org/10.3791/50309

Voyer, D., Voyer, S. D., & Saint-Aubin, J. (2016). Sex differences in visual-spatial working memory: A meta-analysis. *Psychonomic Bulletin & Review*, *24*(2), 307–334. https://doi.org/10.3758/s13423-016-1085-7

Wang, J., Tian, J., Hao, R., Tian, L., & Liu, Q. (2018). Transcranial direct current stimulation over the right DLPFC selectively modulates subprocesses in working memory. *PeerJ*, *6*, e4906. https://doi.org/10.7717/peerj.4906

Wang, S., & Ku, Y. (2018). 右侧背外侧前额叶在视觉工作记忆中的因果性作用. *Acta Psychologica Sinica*, *50*(7), 727–738. https://doi.org/10.3724/sp.j.1041.2018.00727

Waris, O., Jaeggi, S. M., Seitz, A. R., Lehtonen, M., Soveri, A., Lukasik, K. M., Söderström, U., Hoffing, R. a. C., & Laine, M. (2019). Video gaming and working memory: A large-scale cross-sectional correlative study. *Computers in Human Behavior*, *97*, 94–103. https://doi.org/10.1016/j.chb.2019.03.005

Wu, Y., Tseng, P., Chang, C., Pai, M., Hsu, K., Lin, C., & Juan, C. (2014). Modulating the interference effect on spatial working memory by applying transcranial direct current stimulation over the right dorsolateral prefrontal cortex. *Brain and Cognition*, *91*, 87–94. https://doi.org/10.1016/j.bandc.2014.09.002

Yamada, Y., & Sumiyoshi, T. (2021). Neurobiological mechanisms of transcranial direct current stimulation for psychiatric disorders; neurophysiological, chemical, and anatomical considerations. *Frontiers in Human Neuroscience*, *15*. https://doi.org/10.3389/fnhum.2021.631838

Appendices

Appendix A

Electrode Placement

Table 6

Overview of Mean Talairach Coordinates in Standard 10-10 System

	By SimNIBS 4 x, y, z (in mm)
F6	65.21, 75.44, 36.13
AF8	57,01, 96.90, 14.89
F8	72.10, 71.14, 11.74
F4	52.38, 79.87, 57.34
FC6	75.93, 44.47, 39.50

Note. For SimNIBS, the estimated EEG positions are pre-defined in the programme and were used for the current flow calculations.

Appendix B

Sample Characteristics

Table 7

Sample Characteristics

Variable	Category	Frequency	
Age mean (*SD*)		23 (2,857)	
		n	%
Gender	Female	9	34.6
	Male	17	65.4
Nationality	German	19	73.1
	Dutch	4	15.4
	Other	3	11.5
Dominant Hand			
	Left-Handed	1	3.8
	Right-Handed	25	96.2

Note. N = 26

Appendix C

Questionnaires and Results Blinding Efficacy

Table 8

Blinding Efficacy

	Yes-Actively Stimulated n (%)	No-Actively Stimulated n (%)
OFA*	24 (92.31%)	2 (7.69%)
OFC*	20 (76.92%)	6 (23.08%)
ONA*	25 (96.15%)	1 (3.85%)
ONC*	24 (92.31%)	2 (7.69%)
SON	22 (84.62%)	4 (15.38%)
Total	114 (87.69%)	16 (12.31%)

Note. Response to the question: 'Do you think you were actively stimulated today?', posed in the repeated questionnaire. Conditions marked with * involved active stimulation.

Questionnaire: Beginning Demographics Questionnaire

Participant Number: What is your participant number indicated by the researcher? (example: 1)
Gender: What gender do you identify with?
Age: How old are you?
Nationality: What is your nationality?
Dominant Hand: What is your dominant hand?
Attention Control Scale (ATTC):
Please indicate on a scale from 1 to 4, how much you agree with the following statement.
1 = almost never 2 = sometimes 3 = often 4 = always

1. It's very hard for me to concentrate on a difficult task when there are noises around.
2. When I need to concentrate and solve a problem, I have trouble focusing my attention.
3. When I am working hard on something, I still get distracted by events around me.
4. My concentration is good even if there is music in the room around me.
5. When concentrating, I can focus my attention so that I become unaware of what's going on in the room around me.
6. When I am reading or studying, I am easily distracted if there are people talking in the same room.
7. When trying to focus my attention on something, I have difficulty blocking out distracting thoughts.
8. I have a hard time concentrating when I'm excited about something.
9. When concentrating I ignore feelings of hunger or thirst.
10. I can quickly switch from one task to another.

11. It takes me a while to get really involved in a new task.
12. It is difficult for me to coordinate my attention between the listening and writing required when taking notes during lectures.
13. I can become interested in a new topic very quickly when I need to.
14. It is easy for me to read or write while I'm also talking on the phone.
15. I have trouble carrying on two conversations at once.
16. I have a hard time coming up with new ideas quickly.
17. After being interrupted or distracted, I can easily shift my attention back to what I was doing before.
18. When a distracting thought comes to mind, it is easy for me to shift my attention away from it.
19. It is easy for me to alternate between two different tasks.
20. It is hard for me to break from one way of thinking about something and look at it from another point of view.

Questionnaire: Repeated Questionnaire

Participant number: What is your participant number indicated by the researcher? (example: 1)
Session: What session is this?
Active Condition: Do you think you were actively stimulated today?
Sensation: What did you feel during the stimulation? (0 = nothing; 100 = very intense)
Itching
Tingling
Headache
Burning sensation
Uncomfortable
Other Sensations: Did you feel any other sensations? (0 = nothing; 100 = very intense)

____

____

____

Intensity: How strong were the sensations during the stimulation over the time? (0 = no sensation; 100 = very high sensation)
At the beginning (first 30 seconds "ramping up)
During the stimulation
At the end (last 30 seconds "ramping down")
Motivation (parts of the Intrinsic Motivation Inventory):
Indicate on a scale from 1 to 5 how much you agree with the following statements.

1 = Disagree	2 = Somewhat disagree	3 = Neither disagree nor agree	4 = Somewhat agree	5 = Agree

1. I had fun while playing the game.
2. I was motivated to do my best while playing the game.
3. I felt distracted during the game by the effects of the stimulation.
4. I could not perform to the best of my abilities during the game because of the effets of the stimulation.

Appendix D

Data Cleaning and Analysing Outliers

This is an overview of irrelevant excluded data.

Beginning Demographics Questionnaire: testing data, unnecessary columns removed: e.g. IP address, location, User language) and irrelevant rows (e.g. description of variable).

Summed Questionnaire: After the first analysis, the variables, valid obstacles and valid obstacles cleared, were deleted.

Table 12

List and Range of Extreme Values

Condition	Difference (High – Low)	Highest Extreme Value (Case No, ID)	Lowest Extreme Value (Case No, ID)
Average Duration			
OFA	13.67	11.84 (33, 7)	-1.83 (108, 22)
OFC	11.68	9.88 (121, 25)	-1.80 (63, 13)
ONA	16.02	15.76 (48, 10)	-0.26 (94, 19)
ONC	31.28	17.51 (124, 25)	-13.77 (3, 1)
SON	15.95	11.94 (35, 7)	-4.01 (64, 13)
Max Duration			
OFA	18.24	16.58 (16, 4)	-1.66 (108, 22)
OFC	21.18	17.64 (84, 17)	-3.54 (5, 1)
ONA	27.49	26.97 (2, 1)	-0.52 (119, 24)
ONC	32.89	24.86 (99, 20)	-8.03 (74, 15)
SON	33.73	22.15 (18, 4)	-11.58 (64, 13)
Obstacles Cleared			
OFA	131	76 (116, 24)	-55 (4, 1)

OFC	166	114 (21, 5)	-52 (5, 1)
ONA	171	142 (56, 12)	-29 (98, 20)
ONC	178	92 (57, 12)	-86 (3, 1)
SON	226	139 (76, 16)	-87 (60, 12)

Table 13

List of Outliers

Participant	Frequency of Extreme Values
1	6
4	2
5	1
7	2
10	1
12	3
13	3
15	1
16	1
17	1
19	1
20	2
22	2
24	2
25	2

Appendix E

Informed Consent

UNIVERSITY OF TWENTE.

Informed Consent

Consent to participate in a study at the University of Twente on:
Transcranial Direct Current Stimulation in Gaming Performance

I, ____ born on: ____________________

was adequately informed by ____

about the content, course and potential risks of the planned study. The verbal information on the subject was given to me. I understood the content. If further questions arise, I understand that I can ask the researcher at any time.
I agree to participate in the study. I was advised that my participation in the study is voluntary and that I can withdraw from the study at any time without giving any reason and without any disadvantage. I was also reminded that, even if I quit the study prematurely, I would be entitled to the corresponding remuneration of Sona credits.
I hereby assure that I will fill out all questionnaires truthfully and that I will answer all questions about my health and possible risk factors truthfully. In addition, I assure that as a participant in the study, I will follow the instructions of the researcher. The instructions can relate both to the handling of the technical equipment as well as to the experimental course and the conditions to be met.
Furthermore, I am aware that the researcher can cancel the experiment at any time if I disobey the instructions of the researcher and that the data collected becomes useless. Five Sona credits can be deducted if the participant actively sabotages the experiment.
I know that the data obtained from my research is to be further processed by computers and possibly used for scientific publications. I hereby agree that the processing and publication will take place in a form that excludes any association with my person. I can also withdraw this consent at any time without giving any reasons and without any disadvantages.
Furthermore, I note that the leadership of studies is with Gina L. Haccou and Nick Nau (M.Sc. Psychology, Department of Conflict, Risk & Safety). This project is supervised by Maximilian A. Friehs.

____________________________ ____________________________

Location, Date Signature (Participant)

Please answer all questions below truthfully:

	Yes	**No**
Do you have metal implants in the head?		
Do you have a history of seizure or epilepsy? (also in close family like siblings or parents)		
Do you have a skin condition? (Eczema, Psoriasis or open wounds on the head)		
Are you pregnant?		

Do you use medication? (psychopharmacy) (oral contraceptives or normal painkillers are fine) other, please specify:		
Do you have a brain lesion or a tumor?		
Do you have a significant brain injury or a head trauma?		
Do you have electronic devices in the body (e.g., hearing aids implanted)?		
Are you known to have allergic reactions to electrode materials or gels or latex?		
Do you have severe cognitive impairments?		
Are you currently participating in other neuromodulation therapies?		
Do you have any chronic cardiovascular or psychiatric disorders?		
Are you under the age of 18 years old?		

____________________________ ____________________________

Location, Date Signature (Participant)

Enschede,

____________________________ ____________________________

Date Signature (Researcher)

Declaration of confidentiality
I undertake, in the service of science and in order not to jeopardize the further conduct of the study, to remain silent about the objectives, content and course of the research until the end of the experimental conduct (end-2024).

Date, Signature (Participant) ______________________________

Appendix F

Order of Stimulation Protocols per Group

Table 11

Stimulation Protocols

Group	Session 1	Session 2	Session 3	Session 4	Session 5
1	SON	ONA	ONC	OFA	OFC
2	ONA	ONC	OFA	OFC	SON
3	ONC	OFA	OFC	SON	ONA
4	OFA	OFC	SON	ONA	ONC
5	OFC	SON	ONA	ONC	OFA

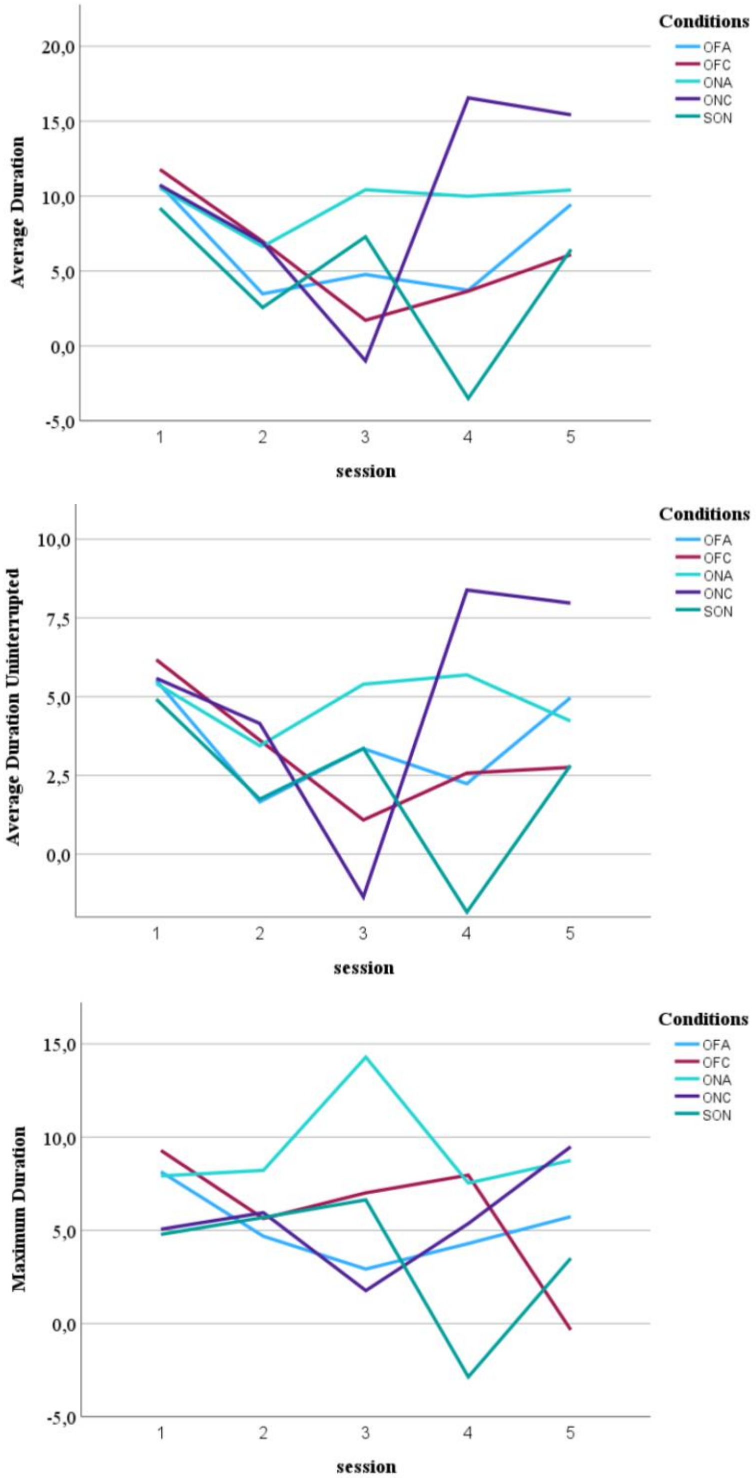
Note. Order of stimulation conditions per group. Sham online (SON), online anodal (ONA), online cathodal (ONC), offline anodal (OFA) and offline cathodal (OFC).

Appendix G

Visualisation of Performance Data

Figure 13

Performance Data Over Sessions Across Conditions

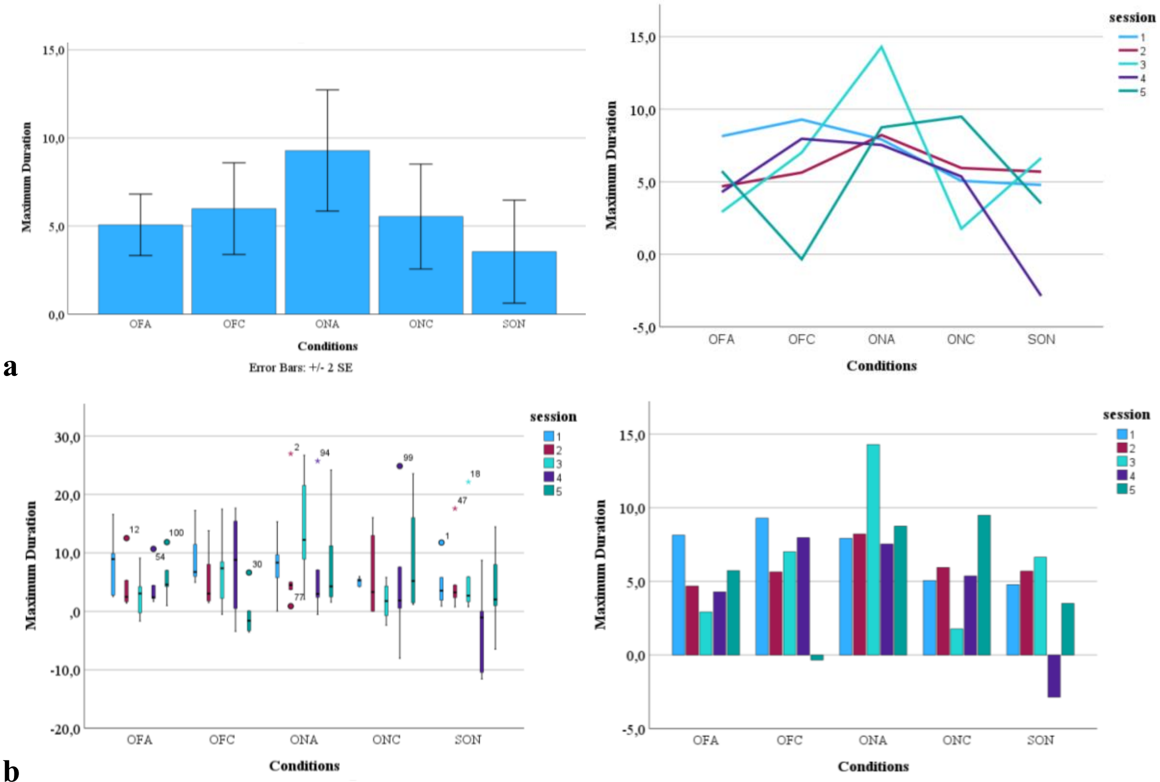


Appendix H

Visualisation of Maximum Performance

Figure 14

Maximum Performance Across Conditions and Across Sessions



a

b

Note. This shows that ONA scored the highest and Sham scored the lowest. Especially in session three, ONA appears significantly high, and ONC scores very low.

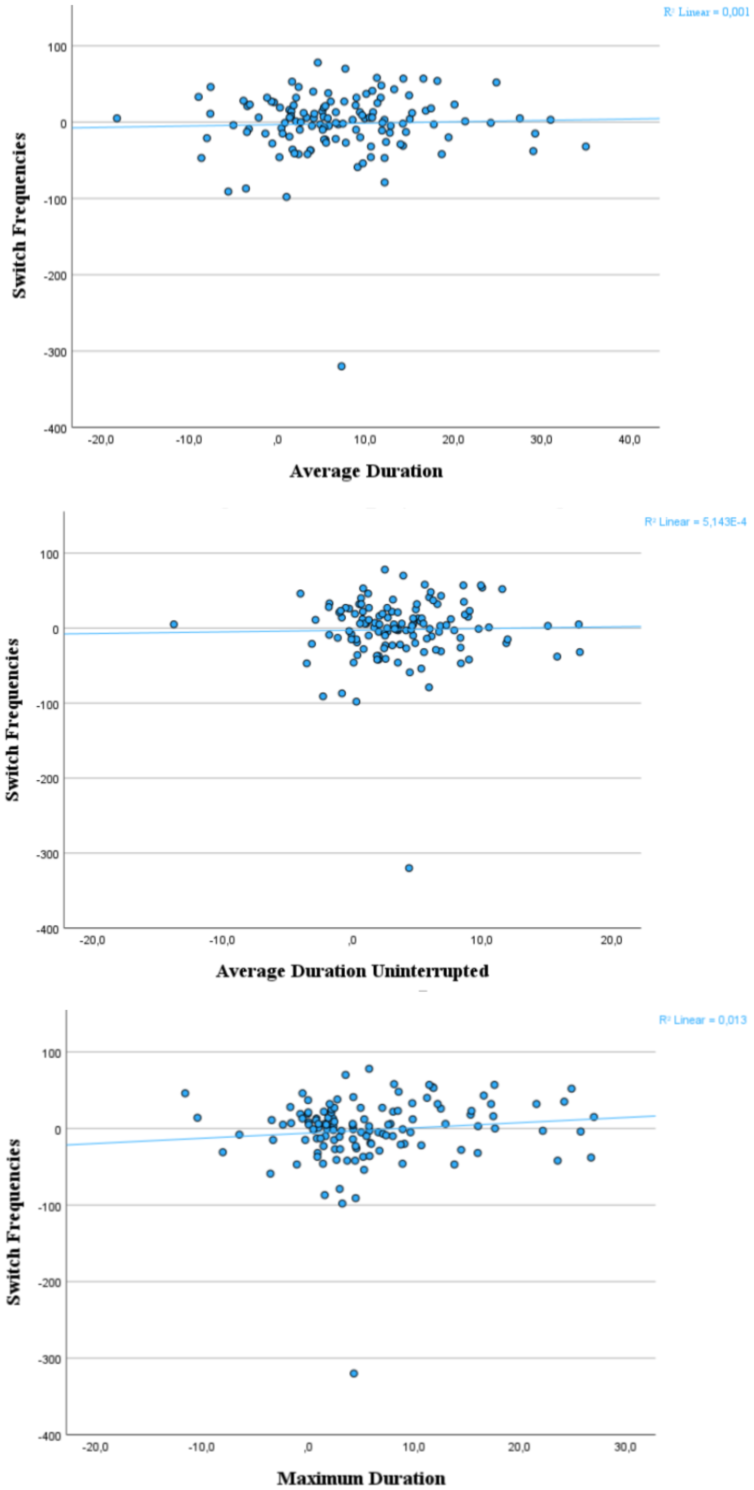
Appendix I

Correlations of Performance Data and Rotation Data

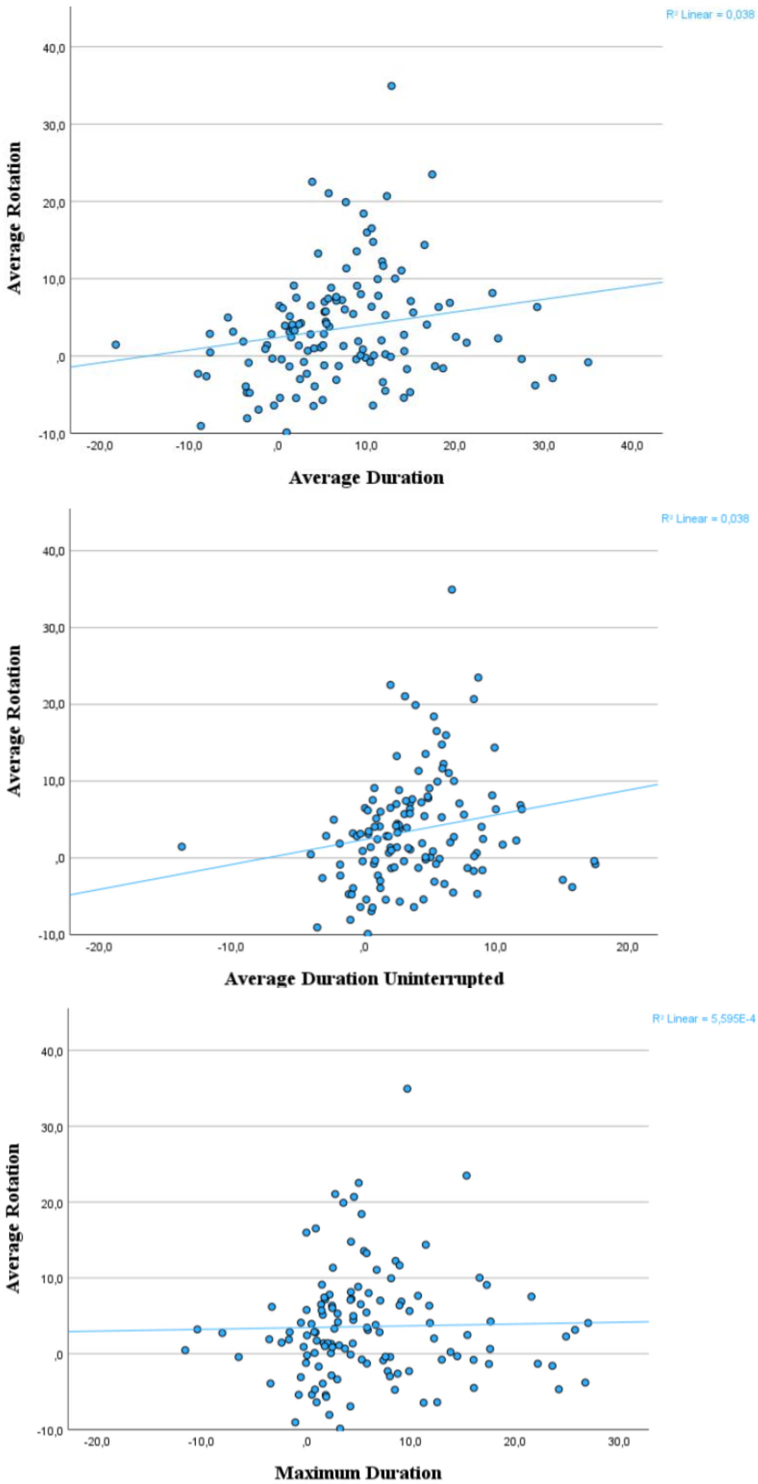
Figure 15

Visualising the Correlations of Performance Data and Rotation Data

a



b

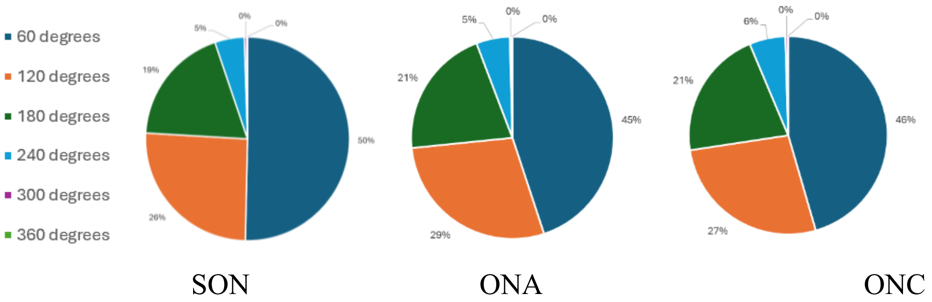

R² Linear = 0,038
40,0
30,0
20,0
10,0
,0
-10,0
Average Rotation
-20,0
-10,0
,0
10,0
20,0
30,0
40,0
Average Duration
R² Linear = 0,038
Average Rotation
Average Duration Uninterrupted
R² Linear = 5,595E-4
Average Rotation
Maximum Duration

Appendix J

Overview of Rotation Magnitude

Figure 16

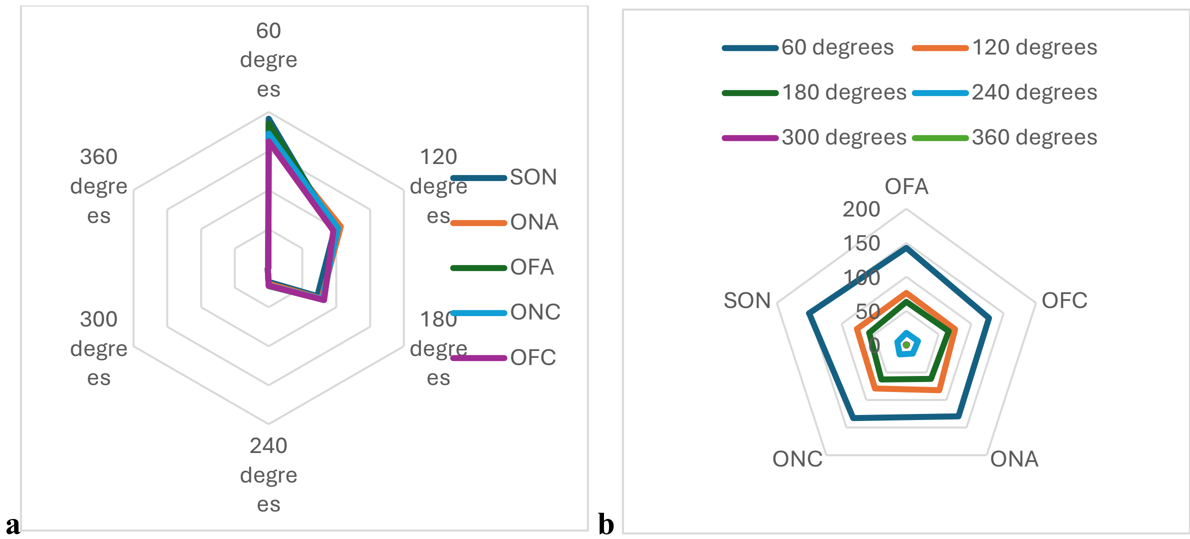
Rotation Magnitude in Degrees Travelled per Condition



Note. The rotations were allocated into categories, including rotations from and up to specific ranges (60, 120, 180, 240, 300 and 360 degrees).

Figure 17

Rotation Magnitude: Comparing Conditions



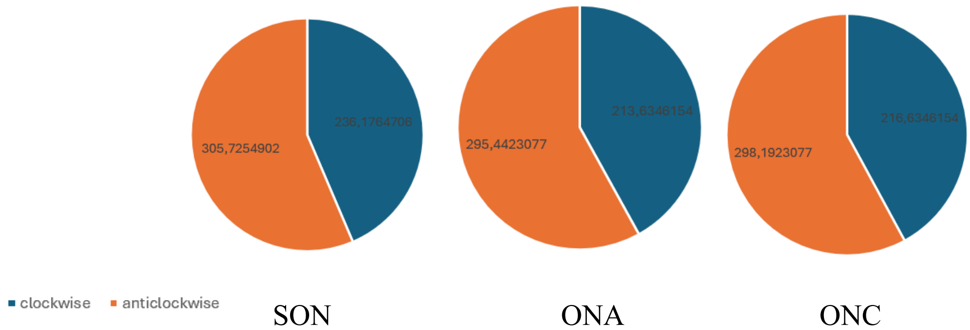
Note. **a** shows the degrees travelled with individual condition lines; when the lines move further outside, this rotation degree category was more present. **b** shows the distribution of the different average rotation degree categories per condition; the different colours show the degrees per rotation; the closer a colour approaches a specific condition, the more often this degree occurs within that condition.

Appendix K

Proportions of Direction Travelled

Figure 18

Distribution of Direction Changes: Switch Frequencies per Condition



SON ONA ONC

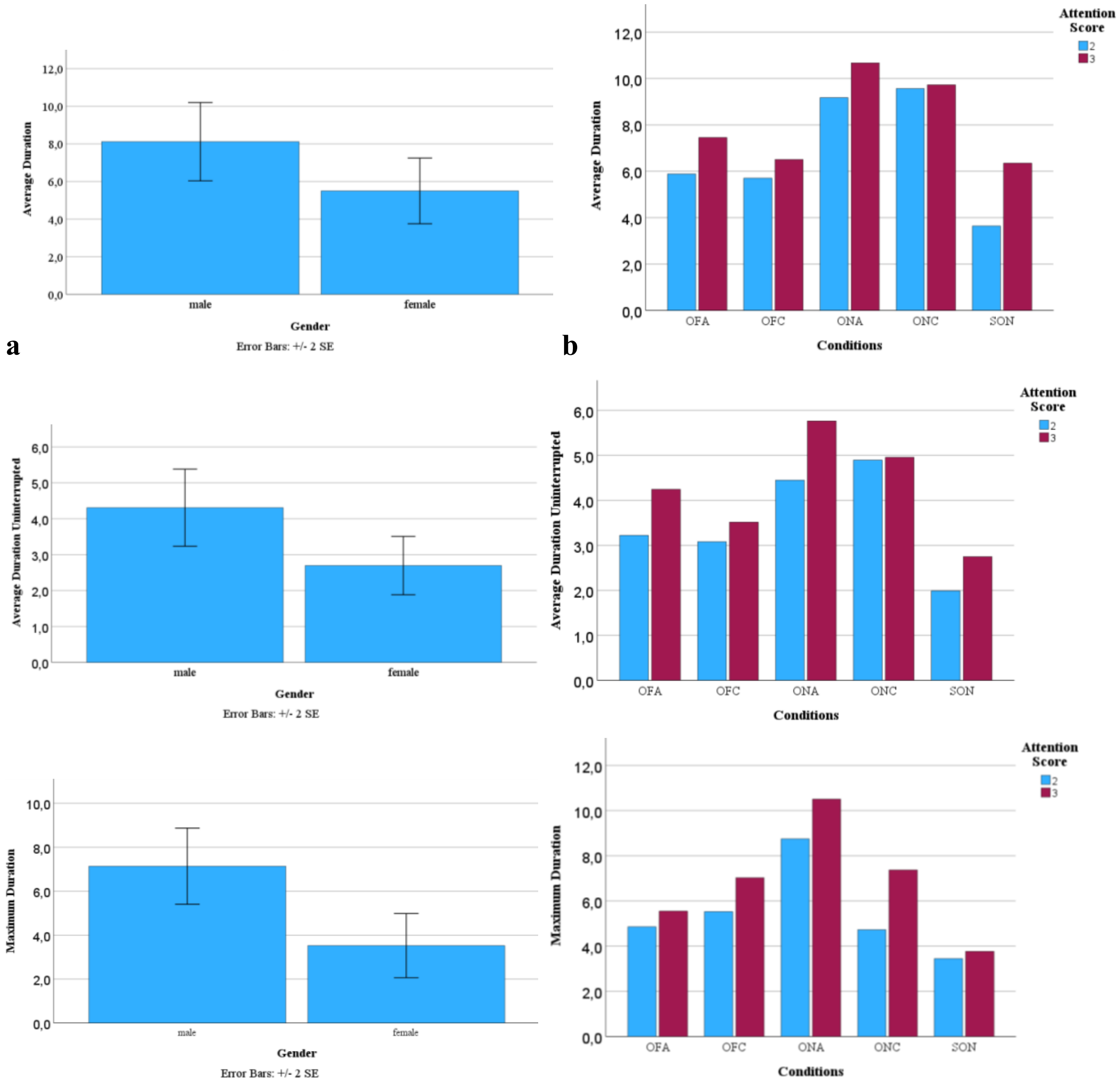
Note. The figure shows the overall distribution and amount of rotations per direction. For example, the orange proportion reflects the directions travelled anticlockwise, whilst the blue proportion shows the directions travelled clockwise.

Appendix L

Additional Variables and Player Performance: Gender and Attention Scores

Figure 19

Performance by Gender and Performance by Attention Scores (ATTC)



Note. **a** shows the performance plotted by gender, reflecting the difference in performance. **b** shows the performance across the different attention categories, category three indicates more ease in focusing and shifting attention.

Appendix M

Descriptive Statistics: Sensations & Attention

Table 9

Descriptive Statistics of Discomfort, Motivation and Attention

	Mean (SD)	Minimum	Maximum
Average discomfort	19.67 (18.493)	0	77.2
Stimulation intensity	24.754 (18.593)	0	73.333
Stimulation intensity grouped	1.531	1	3
Average Motivation	4.254 (0.735)	2.5	5
Average Attention (ATTC Scores)	2.308	2	3

Figure 20

Average Discomfort Across Conditions

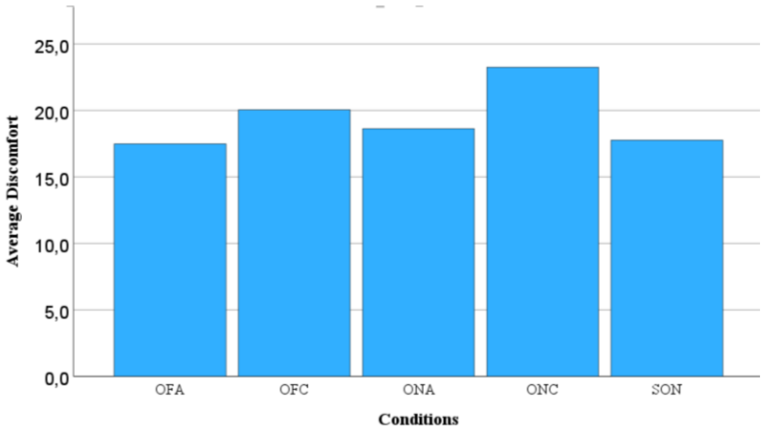


Table 10

Attention Control Scale

Participant	Total Attention Control	Focus Attention Control	Shifting Attention Control
1	2.15	1.89	2.36
2	2.1	2.22	2
3	2.4	2.11	2.64
4	2.75	2.67	2.82
5	2.65	2.89	2.27
6	2.45	2.67	2.27
7	2.25	2.44	2.09
8	2.2	2	2.36
9	2.55	2.89	2.27
10	2.25	2.22	2.27
11	2	1.67	2.27
12	2.35	2.11	2.55
13	2.5	2.67	2.36
14	2.5	2.67	2.36
15	2.4	2.11	2.64
16	2.6	2.89	2.36
17	2.6	2.67	2.55
18	2.3	2.44	2.18
19	2.6	2.22	2.91
20	2.35	2.44	2.27
21	2.2	2.22	2.18
22	2.45	2.44	2.45
23	2.35	2.11	2.55
24	2.45	2.56	2.36
25	2.3	2.56	2.09
26	2.05	2.11	2

Notes. Based on 20 items of one total scale (attention control) and two subscales (attention shifting and attention focusing). The items are measured on a four-point likert scale from 1 (almost never) to 4 (always). High values indicate ease in concentration in concentrating or shifting attention.

Appendix N

Normality Tests

Table 12

Assumption of Normality per Condition

Average Duration

Conditions	Statistic/Value	Degrees of Freedom	Significance
OFA	0.962	26	0.441
OFC	0.991	26	0.997
ONA	0.934	26	0.095
ONC	0.947	26	0.202
SON	0.952	26	0.263

Average Duration Uninterrupted

Conditions	Statistic	Degrees of Freedom	Significance
OFA	0.957	26	0.330
OFC	0.962	26	0.423
ONA	0.886	26	0.008*
ONC	0.882	26	0.006*
SON	0.961	26	0.403

Maximum Duration

Conditions	Statistic	Degrees of Freedom	Significance
OFA	0.913	26	0.030*
OFC	0.943	26	0.161
ONA	0.847	26	0.001*
ONC	0.878	26	0.005*
SON	0.930	26	0.077

Switch Frequency

Conditions	Statistic	Degrees of Freedom	Significance
OFA	0.987	26	0.981
OFC	0.966	26	0.539

ONA	0.962	26	0.428
ONC	0.567	26	<0.001*
SON	0.961	26	0.436

Average Rotation

Conditions	Statistic	Degrees of Freedom	Significance
OFA	0.933	26	0.091
OFC	0.975	26	0.766
ONA	0.850	26	0.001*
ONC	0.925	26	0.059
SON	0.926	26	0.071

Note: Shapiro-Wilk test for normality. * indicates significant values at $p < .05$.