How Stimulation Timing Affects Game Performance: A Study of High-Definition Transcranial Direct Current Stimulation on Visuospatial Working Memory

Master Thesis by Nick Nau (s2277131)
Department of Psychology of Conflict, Risk and Safety, University of Twente
1st Supervisor: Dr. Maximilian A. Friehs
2nd Supervisor: Dr. Ir. Jan-Willem J.R. van t Klooster
August 19th, 2024

Abstract

The improvement of the cognitive functions in humans has become an increasingly important field of scientific research and a subject of broad interest in our society. In order to increase these cognitive functions, scientists are constantly trying to further develop techniques, such as the transcranial direct current stimulation (tDCS). This stimulation technique uses weak electrical currents to alter the action potential of neurons in the brain. One development in this area is the High-Definition tDCS (HD-tDCS) which allows for a higher focality that can lead to more concrete inferences about the specific area, explaining why it is frequently implemented nowadays. This is a convenient method since it does not require surgery and can therefore be used in different areas besides research, for example gaming. The stimulation can have different effects depending on the timing of administration, which can be designated as online or offline. Online stimulation describes administering the stimulation during a task while offline stimulation describes the stimulation administered before a task. In this study, the HD-tDCS method was used to stimulate participants' (N = 26) right lower dorsolateral prefrontal cortex (rlDLPFC) to influence their visuospatial working memory before playing the Super Hexagon game. This was conducted with both anodal (excitatory) and cathodal (inhibitory) stimulation and included a sham condition. A gradual improvement was seen in participants performing the task through different measurements. However, the conducted MANOVA showed no significant differences between the stimulation conditions on the high scores or average scores of the participants. Therefore, the results indicate no significant effects of offline HD-tDCS on visuospatial working memory.

Keywords: HD-tDCS, offline, visuospatial working memory, right lower dorsolateral prefrontal cortex (rlDLPFC), anodal, cathodal, Super Hexagon game

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Since the beginning of time, humanity strives to go faster, be stronger and raise higher. To achieve this, different methods from substances to improved training methods have been developed. One of these methods is brain stimulation, which can be used to alter physiological processes in the brain. A meta-analysis by Polanía et al. (2018) explains that non-invasive brain stimulation (NIBS) is one of the most commonly used methods. NIBS studies have made valuable contributions for clinical and practical applications by testing correlational inferences for causal relationships (Polanía et al., 2018). The NIBS technique alters physiological processes in the brain and allows for a broad range of studying causal brain function relationships like motor, language, attention, memory, reasoning, and decision making (Polanía et al., 2018). The use of NIBS makes it possible to research the brain function and combat illnesses that stem from the brain in order to reduce their symptoms. To research the alteration of brain functions with NIBS, performance in various task can be measured and compared. Besides tasks, the timing of the stimulation is shown to change the effects of NIBS (Pirulli et al., 2014). A stimulation can be offline (before a task is performed) or online (during the performance of a task), which can lead to different changes in the brain (Pirulli et al., 2014). Studies collected in a meta-analysis by Müller et al. (2022) already found significant results of influencing human cognition by stimulating the brain. As people have studied the effects of NIBS, the idea of not only using it for research or clinical settings but to enhance cognition was developed. The potential of enhancing cognitive capabilities of healthy people for work or for (e-)sports is getting more attention from the public. A study revealed that a well-trained working memory helps players perform better in different videogames (Hazarika & Dasgupta, 2018). Working memory describes the storage and retrieval of information (Hazarika & Dasgupta, 2018). However, research regarding the different effects of stimulation timing on working memory performance using NIBS are not yet conclusive. Therefore, the question is: What are the effects of stimulation timing on working memory performance in participants playing a video game?

Theoretical Framework

Visuospatial Working Memory

Working memory is a cognitive process that helps everyone with accomplishing daily tasks. According to Fanari et al. (2019), working memory is divided into two main components, being the phonological loop and the visuospatial sketchpad. The phonological loop is used for the holding and the usage of verbal information while the visuospatial sketchpad is used for the holding and the usage of visual and spatial information (Fanari et al., 2019). Another explanation from literature describes the task of the visuospatial working memory as the storage and retrieval of visual and spatial information in a short timespan (Hazarika & Dasgupta, 2018). A person remembers information that they observe over a short period of time and uses that information for decision making, reasoning and other cognitive functions (Hazarika & Dasgupta, 2018). While working memory can be used in many ways, visuospatial working memory has specifically been found to be an important skill in video games (Hazarika & Dasgupta, 2018). One method used in NIBS studies to assess visuospatial working memory is the Corsi-Block tapping task (e.g. Van Asselen et al., 2006; De Boer et al., 2021). This task is a common neuropsychological test designed to assess spatial working memory (Van Asselen et al., 2006). The goal of the game is to mimic a sequence of blocks that get pressed in a row. Another possibility is the n-back task, which is commonly used in neuroimaging literature to examine working memory (Jaeggi et al., 2010). The goal of this task is to monitor a sequence of stimuli and indicate when the current stimulus matches the preceding one. The difficulty can be increased by changing the goal to match a stimulus with one that appeared two or more steps earlier. An example related specifically to visuospatial working memory is the Super Hexagon task developed by Cavanagh (2012) (Jalife et al.,2012). This task is a game, with the goal of dodging obstacles which makes the task complex, engaging, and motivating for participants who have to perform it for longer time intervals (*Super Hexagon on Steam*, n.d.).

In prior research, different methods to study the visuospatial sketchpad and visuospatial working memory have been described. Llana et al. (2022) described studies that used 2-dimensional or 3-dimensional computer screens to display a task to assess visual and spatial working memory. While a 3-dimensional display of a task could make the game more appealing, the game like characteristics of the Super Hexagon game should not be overlooked. Jalife et al. (2021) suggest the 2-dimensional Super Hexagon game as a measurement to assess visuospatial working memory because of its simple nature. Furthermore, the continuous sound of the game helps to keep the mind focused on the visuospatial working memory task (Jalife et al., 2021). Ben-Sadoun and Alvarez (2022) state that playing games such as Super Hexagon requires a high information processing speed, sustained attention, and division of attention. Therefore, the authors conclude that the Super Hexagon game is cognitively demanding even though it is a simple game in which players can only rotate clockwise or counterclockwise (Ben-Sadoun & Alvarez, 2022). The authors describe working memory as a vital part in video games, like the Super Hexagon game (Ben-

Sadoun & Alvarez, 2022). While the Super Hexagon game is found to be connected to the visuospatial sketchpad and therefore visuospatial working memory (Jalife et al., 2021), when a brain stimulation study is being conducted, the correlated brain area must be exactly determined.

The Right Lower Dorsolateral Prefrontal Cortex

Even though literature about brain regions and their functions shows some overlap in what specific brain regions are used for (Bikson & Rahman, 2013), existing research gives a good indication on which brain areas are used for which purpose. For example, with the help of lesions, which are small cuts in the brain, the dorsolateral prefrontal cortex (DLPFC) was found to be related to the working memory (Postle et al., 2000), along with other transcranial magnetic stimulation (TMS) studies that further prove this connection (Balconi, 2013). Although Balconi (2013) describes two different branches of research, the DLPFC is generally identified as the main brain area for working memory.

The first branch suggests that the task of the left DLPFC (lDLPFC) is processing and recovering verbal information while the right DLPFC (rDLPFC) is responsible for processing and recovering spatial information. The second branch suggests that the lDLPFC is mostly used for processing information and the rDLPFC is mostly used for recovering information. Even though the two branches differ, they reach an agreement by identifying the rDLPFC's main task as the recovery of spatial information (Balconi, 2013). While the DLPFC is a large area, it can be distinguished not only between rDLPFC and lDLPFC but also between upper and lower DLPFC. A review by Wischnewski et al. (2021) states that the lower part of the DLPFC can be used to improve working memory in NIBS studies. The position of the visuospatial sketchpad was specified even more by Schneiders et al. (2011), who showed that oxygen levels in the blood decreased in the right lower middle frontal gyrus which indicates that this area was activated. Furthermore, for stimulation studies, the electrode positions F5 and F6 are mentioned to be the best for stimulating working memory (Wischnewski et al., 2021). This combined literature supports that the right lower DLPFC (rlDLPFC) and the right lower middle frontal gyrus are connected to visuospatial working memory and that F6 is a good electrode position to stimulate in NIBS research.

High-Definition Transcranial Direct Current Stimulation

The typical idea of brain stimulation involves surgery, which Hariz (2014) refers to as deep brain stimulation. However, with non-invasive brain stimulation (NIBS) techniques this is no longer necessary. NIBS techniques were created so that an external stimulation device can be easily put on and off a person's head (Antal et al., 2022). There are different NIBS techniques that can be used for research (Fregni et al., 2006; Antal et al., 2022; Bergmann & Hartwigsen, 2021). Some of the methods that stimulate brain activity use magnetic pulses (TMS) or electrical currents (transcranial electric stimulation, tES). One of the methods using electric currents is transcranial direct current stimulation (tDCS), which is increasingly and experimentally used in e-sports to enhance a player's learning curve and their performance (Toth et al., 2021). The tDCS technique works through a weak, continuous, electrical current which is either an anodal (excitatory) current or a cathodal (inhibitory) current (Antal et al., 2022; Schroeder & Plewnia, 2016). The current is applied to the brain by attaching electrodes to the participant's scalp. At least one of the electrodes is applying the current while at least one other different electrode will function as a return for that current (Antal et al., 2022). In the brain area that the electrical current flows through, the membrane potential of neurons is continuously altered toward depolarization (anodal) or hyperpolarization (cathodal) for the time of the stimulation in order to make neurons more or less likely to fire (Bergmann & Hartwigsen, 2021; Friehs & Frings, 2020; Saturnino et al., 2015). The electrical current enables neurons to fire more easily when stimulated with an anodal current while making it harder for neurons to fire when being stimulated with a cathodal current (Bikson & Rahman, 2013; Friehs & Frings, 2020). Even though there are studies challenging the effects of cathodal stimulation, the inhibitory effects of cathodal stimulation are still the most common (Schroeder & Plewnia, 2016). Pirulli et al. (2014) showed that for visual tasks, different parameters such as stimulation timing, strength of the stimulation and duration, can change these effects. Strength of the stimulation is specifically important in High-Definition tDCS (HD-tDCS) which uses smaller electrodes that can specifically target a region of the brain (Sharma & Chowdhury, 2019). A stronger stimulation in HD-tDCS can be used to achieve a higher depth of stimulated brain area (Alam et al., 2016). As prior research shows, tDCS and HD-tDCS is an adequate tool to study continuous cognitive processes since it allows for a continuous stimulation (Antal et al., 2022). Furthermore, the side effects are higher in TMS than tES which makes tES and tDCS better as a stimulation tool to decrease the risk of dropouts (Biagi, 2023). Besides the different stimulation types, stimulation timing can also vary and can have a different impact on a person's brain.

Online Stimulation vs Offline Stimulation

Brain stimulation can be applied at various times relative to a task, resulting in different effects. When brain stimulation is applied while a participant performs a task, it is referred to as online stimulation. When brain stimulation is applied before a task is performed, it is called offline stimulation. Pirulli et al. (2014) stated that brain stimulation can not only have a physiological effect, but a behavioural effect which can differ when a stimulation is administered online or offline. The effect of online stimulation is a change in membrane potential, altering how easy it is for a neuron to fire (Friehs & Frings, 2020). On the other hand, offline stimulation changes the synaptic and neurotransmitter activity in the specific brain area (Friehs & Frings, 2020). While online stimulation elicits effects immediately, offline stimulation elicits effects after five to seven minutes of a continuous stimulation, which is a possible explanation for an improved cognition five to ten minutes after the stimulation has ended (Nitsche et al., 2005). Bergmann and Hartwigsen (2021) support this, stating that an online stimulation can have immediate effects and an offline stimulation can have effects for hours after the stimulation has ended.

Many studies found successful cognitive enhancements through online stimulation (e.g. Friehs et al., 2021; Müller et al., 2022). Other studies, mention that offline stimulation has found positive effects on cognition, too (e.g. Friehs & Frings, 2020; Pirulli et al., 2014; Müller et al., 2022; Hill et al., 2016). Even though the polarity effects of a stimulation were studied a lot, Pirulli et al. (2014) showed that a cathodal stimulation prior to a task can improve the visual accuracy of participants. Additionally, Friehs and Frings (2020) showed that offline anodal stimulation can have positive effects on response inhibition, while offline cathodal stimulation had negative effects. Furthermore, Hill et al. (2016) stated in their meta-analysis that offline anodal stimulation of the DLPFC can increase reaction time and improve accuracy in healthy adults. Therefore, it has been shown that offline stimulation can affect performance after the stimulation stopped and that this effect can differ from the usually hypothesized outcomes.

Present Study

This study expands the research on NIBS of the rlDLPFC to enhance visuospatial working memory. This cognitive process is used for storage and retrieval of visual and spatial cues in a short period of time (Hazarika & Dasgupta, 2018). Next to other common tasks that assess the visuospatial sketchpad, the Super Hexagon game is described as a cognitive demanding task that can be used to evaluate visuospatial working memory (Jaeggi et al., 2010; Ben-Sadoun & Alvarez, 2022). Research about the working memory already showed that significant results are possible to achieve with brain stimulation (Balconi, 2013). Working memory has been shown to be related to the DLPFC (e.g. Seibt et al., 2015; Antal et al., 2022; Van Asselen et al., 2006; Wischnewski et al., 2021). The DLPFC is an important area for researchers, particularly in sport related cognitive enhancement (Seibt et al., 2015; Antal et al., 2022). Among other articles, a meta-analysis by Wischnewski et al. (2021) has shown that the rlDLPFC and more specifically the lower middle frontal gyrus with the corresponding electrode position F6 are the best area for stimulating visuospatial working memory (e.g. Van Asselen et al., 2006). Different electrode sizes can also be used in tDCS studies to stimulate this cognitive process. This research makes use of HD-tDCS to stimulate a more precise area, which will lead to fewer bridging effects between the specific brain area that this study is focused on and other brain areas. Next to the electrode size, another important factor that can influence the effect and outcome of the study is the timing of the stimulation. The above-mentioned literature has already shown that offline stimulation can have significant effects on performance (Friehs & Frings, 2020; Pirulli et al., 2014). While Friehs and Frings (2020) used anodal offline stimulation to improve verbal working memory, Pirulli et al. (2014) used cathodal offline stimulation to improve specifically visual performance. While prior research was performed using different stimulation devices or different tasks to measure performance, this study changes these parameters to find consistent results. By using a clone of the Super Hexagon game as the task to measure visuospatial working memory performance, this study will introduce a new option to study this cognitive process in tDCS research. Johnson et al. (2019) already successfully conducted a study with this game, which furthermore shows that it is a valid choice. Therefore, this study will aims to answer the research question: “How does offline HD-tDCS of the rlDLPFC using F6 as the stimulating electrode position affect visuospatial working memory performance measured by the Super Hexagon game?”

Previous research stressed the importance of visuospatial working memory while performing the Super Hexagon game (Ben-Sadoun & Alvarez, 2022). It was shown that this cognitive process can be stimulated at the rlDLPFC using F6 as the electrode position (Wischnewski et al., 2021; Van Asselen et al., 2006). Furthermore, it was suggested that anodal offline stimulation can have positive aftereffects (Friehs & Frings, 2020), which led to the first hypothesis for this research study H1: “The effects of the offline anodal HD-tDCS on the rlDLPFC using the electrode position F6 will improve the performance of participants playing the Super Hexagon game.”

Furthermore, literature does not give a clear indication of whether cathodal stimulation will inhibit cognitive performance or not (Friehs & Frings, 2020; Bikson & Rahman, 2013). However, cathodal stimulation has been shown to improve performance if it is applied before a task and if the study parameters such as strength of the stimulation and stimulation time are met (Pirulli et al., 2014). Therefore, it is secondly hypothesized that H2: “The effects of the offline cathodal HD-tDCS on the rlDLPFC using the electrode position F6 will improve the performance of participants playing the Super Hexagon game.”

Methods

Participants

In total, 26 participants were recruited for this study using the Sona system, the snowball sampling method, and flyers distributed at the University of Twente (UT). All participants were students at the UT. 17 male participants and nine female participants took part in the study. The age of the participants ranged from 18 to 29 (mean (*M*) = 23, standard deviation (*SD*) = 2.857). 19 participants indicated that their nationality was German, while four indicated that their nationality was Dutch. One participant indicated being from Romania, another one from Spain, and one participant did not indicate their nationality. 25 participants indicated that their right hand was dominant and only one participant indicated that their left hand was the dominant one. However, since all participants played with their right hand, the left-handed participant was not excluded. Every participant had the chance to receive five Sona credits for their participation in the study, which were distributed at the end of the study. The study required a repeated presence and took around five hours in total for each participant. Although the Sona credits were attributed, these were deemed not enough to compensate and motivate participants to engage in the study and finish the five sessions, since this is a study longer than most studies done at the UT. Therefore, the addition of five Bol.com vouchers for 20 euros each were used as a motivation tool, four of which were distributed among the participants in a raffle, and one was given to the person with the highest score in the game. This was done to motivate participants to perform to the best of their abilities while playing the game.

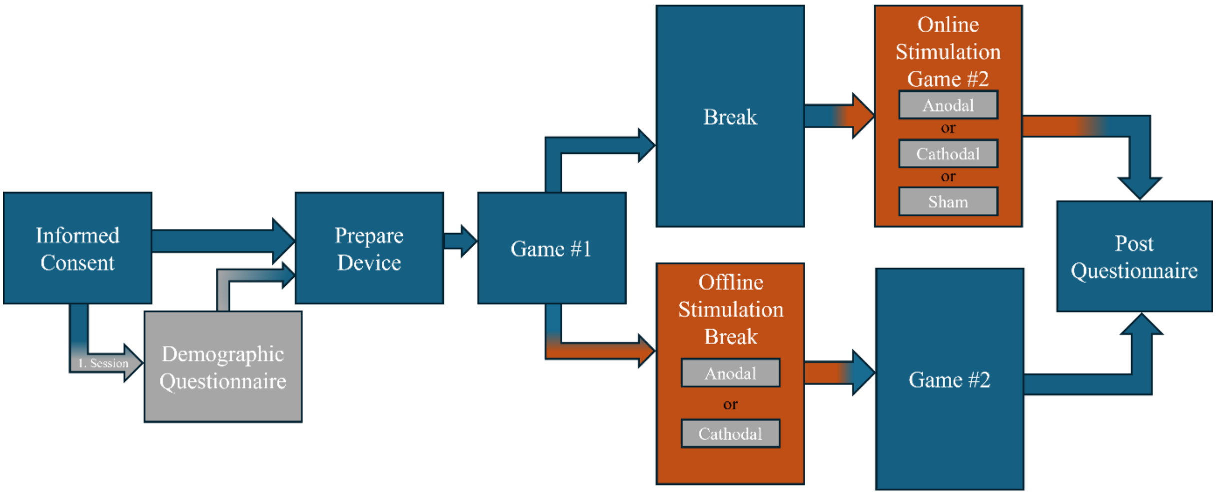
Different requirements had to be fulfilled to be eligible for participating in this study. The participants had to be 18 years or older; have sufficient English skills, because the study included questionnaires which were not available in a different language; and had to pass the exclusion criteria (Appendix 1). Some of the exclusion criteria were having a history of cardiovascular or psychiatric diseases, having brain implants or taking pharmaceuticals that could interfere with the stimulations (Appendix 1). This study was reviewed and approved by the ethics committee of the faculty of behavioural, management, and social sciences at the UT.

Procedure

The flowchart below shows the steps all participants had to follow throughout the study sessions (Figure 1). Participants had to read and sign the information about the study, fill in the exclusion criteria and give informed consent (Appendix 1). Before the first session, every participant was reminded that the study would take five sessions distributed over five weeks, each taking approximately one hour. This extra reminder was given to reduce the chance of dropouts. In every session, participants had to confirm that the informed consent they had given and the exclusion criteria they indicated in the first session were still accurate and valid by signing a respective form (Appendix 2).

Figure 1

Flowchart of the Procedure



Note. The blue colour indicates the steps all participants had to follow each session, while the grey colour shows steps that only had to be done once by each participant. Orange indicates the steps in which the stimulation was administered.

For the first session, every participant had to fill in a questionnaire about the demographics, whether they are right- or left-handed, and an attention questionnaire (ATTC) (Appendix 3). To assess participant's cap size, the head circumference was measured by using the distance from one finger above the eyebrows around the head over the occipital bun, also called inion, on the back of the head. The chosen cap size was then noted for further sessions.

After that, the researcher prepared the participant's head, by measuring the largest part around the head (circumference), marking the centre point of the head (CZ point), and putting on the cap. If necessary, the stimulation points were marked, the cap taken off, and any hair that could interfere with the stimulation was pushed aside and held in place by hair clips. Then, the researcher put the cap back on the participant's head, filled the stimulation points with electro gel, and placed the electrodes on the participant's head. Wires were connected to the electrodes without the battery to make participants feel as comfortable as possible while having a similar break time between the two playing times compared to other sessions. Moreover, the participants played the Super Hexagon game two times for five minutes with a one-minute break in between. Depending on the condition, the next steps differed as follows.

For the conditions sham online (SON), online anodal (ONA), and online cathodal (ONC), the first ten minutes of playing the Super Hexagon game were followed by a break of twelve minutes. Participants could read psychology magazines or talk to the researcher during the break which was meant to relax participants before the stimulation. Since there are a lot of variables which cannot be controlled, using the break period for an actual relaxing break was important to make sure participants were treated equally. For the second game, the battery of the tES device was connected to the wires and an impedance check was conducted to see if the resistance from the electrodes to the participant's head was adequate to start the stimulation. If the impedance check was sufficient, the stimulation was started. Participants had to wait between two to three minutes before restarting the game, to get used to the stimulation. Then, participants played again two times for five minutes with a one-minute break in between. Because of the 15 minutes of stimulation, participants and the researcher had to wait until the stimulation ended before taking off the cap, to make it comfortable for participants.

For the conditions offline anodal (OFA) and offline cathodal (OFC), the first ten minutes of playing the Super Hexagon game were followed by 15 minutes of stimulation. The battery was connected to the wires immediately after the participants finished their first game. An impedance check was done and when it was sufficient, the stimulation began. During the stimulation, participants could read psychology magazines or talk to the researcher. After the stimulation ended, participants immediately started playing the Super Hexagon game two times for five minutes with a one-minute break in between. The cap was removed from the participant's head after the game had ended.

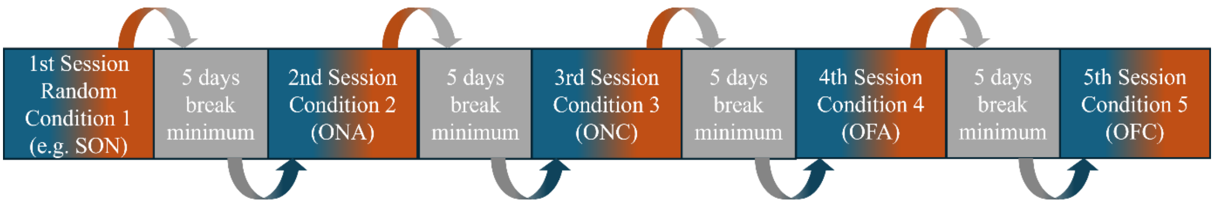
Then, the participants had to fill in a questionnaire about their sensations during the stimulation, their motivation while playing, and whether they had the impression that they were being actively stimulated. Lastly, the next appointment was set after at least 5 days of break in between sessions.

Design

For this study, an experimental within subject's design was chosen, implying that every participant will experience every condition (Figure 2). Participants had to make five appointments with at least five days in between each appointment. Per appointment, participants were assorted one out of the five different conditions in order to reduce the effects of session sequence on the data. Since people have different head shapes, different gaming experiences, and different learning speeds, this appeared to be the best way to make the different stimulation protocols comparable. The dependent variable in this study was performance, measured by maximum duration, average duration, and average duration uninterrupted. Maximum duration refers to the improvement a player made between the highest score they got in the first game and the highest score they got in the second game within one session. Average duration refers to the improvement a player made between the average score in the first game and the average score in the second game within one session, while counting all trials started by the participant. Average duration uninterrupted was calculated in the same way as the average duration variable with the exception that only the trials that were finished were included. Therefore, the trials cut off by the game were not included. Furthermore, switch frequency and rotation magnitude were chosen as additional indicators to get a more exact assessment of the performance. The independent variable was the changing stimulation protocol (condition), each of which every participant had to go through. The conditions were ONA, describing the anodal stimulation while a participant was playing the Super Hexagon game; ONC, describing the cathodal stimulation while a participant was playing the Super Hexagon game; OFA, describing anodal stimulation before a participant was playing the Super Hexagon game; OFC, describing the cathodal stimulation before a participant was playing the Super Hexagon game; and SON, describing a control group with a placebo stimulation, which was taken as a reference factor for the active conditions. Each of these conditions had to be completed by every participant. Since the experiment of this study was performed in cooperation with another student, there were five stimulation protocols in total. However, this article focuses on the timing of the stimulation and therefore only focuses on the offline conditions (OFA and OFC).

Figure 2

Study Design



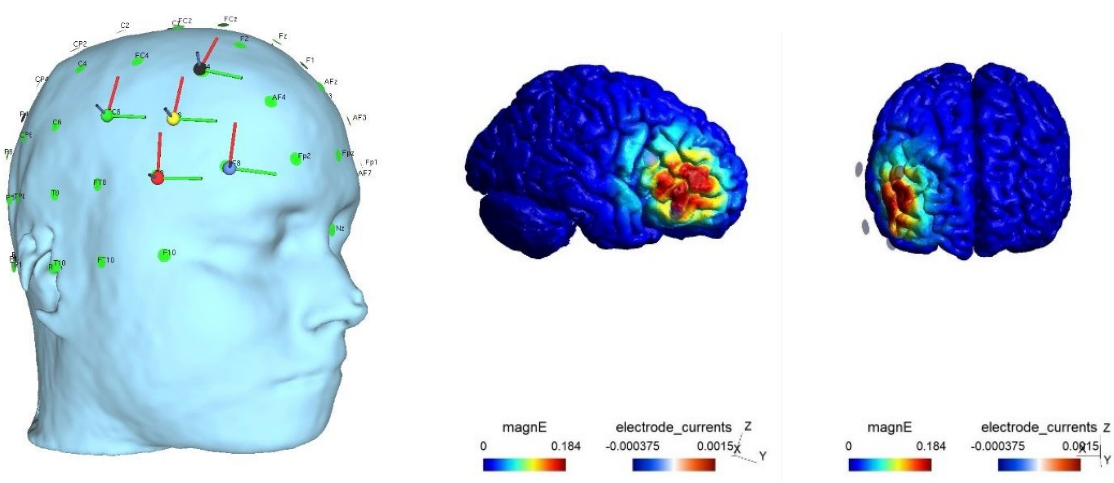
Note. Blue stands for the first part of a session in which no stimulation took place. Orange stands for part in one session where the stimulation took place. Grey stands for the time in which no session could happen.

There are different electrode sizes e.g. 5 cm x 7 cm electrodes (DaSilva et al., 2012), 5 cm x 5 cm which is most commonly used (Bikson & Rahman, 2013), but also π-electrodes which, as the name suggests, have the size of $\pi = 3.14159$ cm². This electrode size is designated by High-Definition tDCS (HD-tDCS) (Bikson & Rahman, 2013) and was chosen for this study. Because the electrodes are of a smaller size, a specific area of the brain can be stimulated more precisely, while other areas remain without stimulation effects (Sharma & Chowdhury, 2019). Lately, HD-tDCS studies have utilized the 4 x 1 HD-tDCS electrode configuration describing the assemblance of a box with return electrodes around the active electrode to keep the stimulation contained to a specific area (Sharma & Chowdhury, 2019). This 4 x 1 HD-tDCS electrode configuration allows researchers to draw specific conclusions about certain brain areas and their functions for human behaviour. To avoid the effects of return electrodes near the area of stimulation, these can be placed further away from the active electrode, which could lead to less focality of the stimulation but increase its depth (Alam et al., 2016).

The stimulation intensity was set at 1.5 milliampere (mA) which was tested before in a pilot study about different stimulation intensities and the level of discomfort participants would experience from them. The tested intensities 1, 1.5 and 2 mA revealed that 1.5 was the intensity that appeared to be acceptable for the participants. The combination of this pilot study with the literature (e.g. Friehs and Frings, 2019), which showed that 1.5 mA would be enough to evoke changes in the participant's brains in a significant way, led to the decision of using 1.5 mA as the stimulation intensity for this study. The impact of the stimulation on a participant's brain was visualized using SimNIBS (Figure 3).

Figure 3

Electrode Placement



Note. On the left the electrode placement on a participants scalp is shown. On the right the actively stimulated brain from the right hemisphere and from the front is shown.

Bergmann and Hartwigsen (2021) suggest that the 10-20 EEG electrode system can be used for an estimation of where brain regions are located. This system is used to divide the head into different areas and has since been improved to the 10-10 system, allowing for a higher specificity by adding more possibilities for electrode placements. Wischnewski et al. (2021) explained that the best way to achieve a stimulation of the visuospatial working memory is by using the electrode position of F5 or F6 for the active electrode. Since literature has shown the right side to be responsible for the visuospatial part of a person's working memory, F6 was chosen as the point where the stimulation was applied. The 4 x 1 electrode configuration was used for the electrode placements. The return electrodes were box shaped around the stimulating electrode in which AF8, F4, F8 and FC6 were the return electrodes in the outer positions, containing the area of the stimulating electrode, being F6 the active one (Figure 3). Furthermore, the stimulation should last for at least five to seven minutes to evoke aftereffects (Nitsche et al., 2005). The stimulation time was therefore set for 15 minutes for all conditions to ensure that participants could get accustomed to the stimulation before the game started in the online conditions, while still allowing for a buffer time between the end of the game and the ramp down of the stimulation.

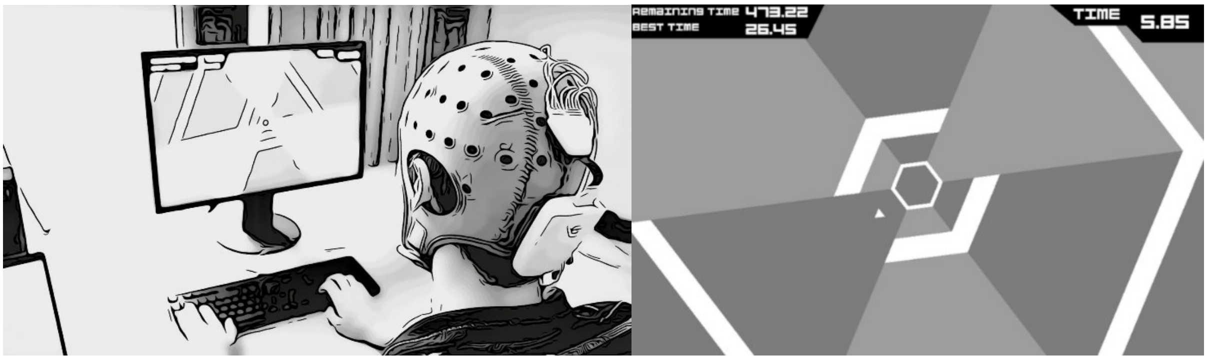
Materials

Game Materials

The study was performed on a 24-inch monitor screen with a 1920 x 1080 resolution to display the questionnaires and the Super Hexagon game. Participants were then provided with a keyboard and a mouse to fill in the questionnaires and play the Super Hexagon game (Figure 4). The game was displayed via a website, which also gathered exportable data from the user. To play the 2-dimensional Super Hexagon game, a player rotates a triangular shaped icon around the hexagon shaped centre to avoid obstacles (Ben-Sadoun & Alvarez, 2022). The core, the player icon, the obstacles, and the background rotate while playing (Ben-Sadoun & Alvarez, 2022). To succeed at the game, a player needs to avoid obstacles that enter from the edges of the screen while moving closer to the centre (Ben-Sadoun & Alvarez, 2022). The different changes made by Johanson et al. (2019) to the original game were the deletion of colour, keeping only white and grey; creating similarity in obstacle patterns; and deleting the pulsation of the centre and background to the rhythm of the beat. The obstacle patterns in the clone stayed the same, except for the direction they approach from. While the game's goal remained the same, bigger scenery changes, for example, switching from a hexagon shape into a square shape, were omitted. More changes were made to the original game's parameters, in which hitting an obstacle meant returning to the home screen. After a questionnaire was finished, the clone starts a game automatically. Per game, a fixed timer of 2 x 300 seconds playing time with a 60 second break in between was added. Hitting an obstacle stops a trial and starts a three second timer until a new trial starts automatically. Furthermore, after the first 300 seconds of playing time, the game stops on its own and begins the 60 second break time. After automatically starting the second playing time, a person can play for 300 seconds, until the game automatically ends completely.

Figure 4

Study Setup



Note. The study setup of how participants played (left) and a screenshot of the Super Hexagon game (right).

Stimulation Materials

A measuring tape and make up markers were used to measure the participants head and marking the CZ point. This was performed to put the neoprene cap with the 10-10 electrode placement system correctly on a participant's head. For the stimulation, the tES Starstim device made by Neuroelectrics was used with the electro-gel. The tES Startim device can deliver anodal and cathodal tDCS with 5 electrodes in the participant's head. The stimulation device can be activated via the NIC2 program which allows researchers to adjust strength, position, and polarity of the stimulation. With the NIC2 program, an impedance check with immediate feedback could be performed. Furthermore, the SimNIBS program was used for a visual representation of the stimulated area (Figure 4). The study information, exclusion criteria, and informed consent form (Appendix 1, 2) had to be signed by participants on paper. For the questionnaires, the Attention Control Scale (ATTC) (Appendix 3) and parts of the Intrinsic Motivation Inventory were used and reformulated to fit to this study (Appendix 4). The questionnaires were displayed using Qualtrics, an online tool to create and distribute questionnaires and to gather data. The study was conducted in the facilities provided by the BMS-Lab of the UT, located in the Cubicus building. To analyse the data, different statistical analysis programs like Microsoft Excel, R, R-Studios, and SPSS were used.

Data Preparation

After the Super Hexagon website had captured all data from the game and Qualtrics had captured all data from the questionnaires, the datasets were exported. The Super Hexagon website had captured different data in separate datafiles which led to two data files, performance dataset and rotation dataset, being exported. In addition, the two questionnaires designated the beginning questionnaire and the repeated questionnaire (Appendix 3, 4), led to two datasets being exported. A flowchart was created for an outline of the data preparation (Appendix 5). The cleaning of the four datasets was executed by deleting the rows that were filled with test runs and deleting the columns that were filled with redundant variables.

After all datasets were cleaned, certain variables had to be calculated before the analysis could begin. The performance dataset showed one row per five minutes of playing time instead of a full ten-minute game. Therefore, the data was adjusted by taking the higher number for the variable maximum game duration. Furthermore, the average duration a player played per trial for the variables average duration and average duration uninterrupted was calculated. This way, games that participants played before the stimulation could be compared to the games that participants played after or during the stimulation. Next, the stimulation protocols were manually added to the dataset under the variable condition, so that each stimulation protocol could be analysed. For the comparison of the conditions, the scores were calculated showing the difference between the first and second game played in the same session. This was repeated for the variables maximum duration, displaying how much the high scores improved; average duration, displaying how much the average trial time improved; average duration uninterrupted, displaying how much the average trial time, not interrupted by the game, improved. For the rotation dataset, the variable rotation input, displaying whether a participant turned clockwise or counterclockwise, was turned into a dummy variable, indicating with a zero that the player rotated counterclockwise and with a one that the player rotated clockwise. In the next step, the switch count variable was calculated per game by counting the times a player switched from one direction to the other, calculated from the dummy variable. Then the switch frequency was calculated, indicating the improvement of the variable switch count from the first to the second game in one session. The assumption was that the more often a participant switched between clockwise and counterclockwise, the more efficient they were. After that, the variable rotation magnitude was calculated using the variables trial time, event type, and rotation rate. Through the variables event type and trial time, the duration that one movement of a player took was calculated by subtracting the trial time value at the event type “move start” from the trial time value at the event type “move end”. The new variable movement time, which is displayed in seconds, was multiplied with the rotation rate (a player can make) which is displayed in degrees per second. Therefore, the new variable rotation movement magnitude displays the degree each player moved, for every move they made. This could then be used to calculate the average game rotation magnitude per game and the rotation magnitude which describes the improvement participants made from the first game to the second game in a single session. The assumption is that a participant using the shortest way possible to avoid an obstacle is more efficient and therefore uses less rotation distance. In the rotation dataset, participants five and 14 were each missing values from one game. They were kept in the dataset so that the other values from the four other sessions could be analysed. From the beginning questionnaire dataset, the ATTC average was calculated by first reversing the questions that needed to be reversed and then taking the average of all scores for all questions, which showed one as the least attentive and four as the most attentive. For the dataset of the repeated questionnaire, a calculation of the average motivation for each day the participants played was calculated. After that, the average stimulation intensity and the average discomfort were calculated. Because of a problem in the beginning of the study, some questions were not asked for the first four participants in their first session. The missing values for these four participants were added by calculating the mean of their scores in the other sessions. In the end, a dataset was created with the variables: ID, session, condition, gender, active perception, average duration, average duration uninterrupted, maximum duration, switch frequency, rotation magnitude, average discomfort, average motivation, average stimulation intensity, and average stimulation intensity grouped (Figure 5).

Figure 5

Example Dataset

ID	session	conditi	average	average	maximu	switch t	average	gender	ATTC sc	active p	average	total m	total in	average motivation	average
1	4	OFA	2.370833	2.004167	4.45	-42	1.352718	1	2	1	29	4	2	4.5	26.25
1	5	OFC	9.066167	4.407083	-3.54	-59	1.902819	1	2	2	3	4	1	5	38.33333
1	2	ONA	16.79556	8.900179	26.97	15	4.055912	1	2	1	19	4	2	3.25	20
1	3	ONC	-18.2392	-13.7656	-2.36	5	1.463579	1	2	1	5	3	1	4.75	38.33333
1	1	SON	18.11302	9.984919	11.77	54	6.332926	1	2	1	23.85	4	2	5	8.333333
2	3	OFA	4.815167	3.507091	3.15	-3	1.097923	1	2	1	22	4	2	5	43.41667
2	4	OFC	3.27452	1.059162	7.79	6	-2.29408	1	2	1	32.8	4	2	5	48.66667
2	1	ONA	12.81842	6.659221	9.67	-5	34.93505	1	2	1	13.4	4	2	5	43.33333
2	2	ONC	6.871038	4.122378	5.8	-3	-1.29229	1	2	1	27.2	4	2	5	36
2	5	SON	0.426972	-0.0916	-6.47	-8	-0.43748	1	2	1	1.6	4	2	5	45.66667
3	2	OFA	-0.41956	-0.26339	12.53	26	-6.39546	1	2	2	2.8	4	1	5	18.33333
3	3	OFC	1.32	2.065	17.48	16	-1.35334	1	2	1	22	4	2	5	13.66667
3	5	ONA	24.17962	9.706143	4.27	-1	8.147771	1	2	1	14.4	3	1	4.5	39
3	1	ONC	10.73848	5.899958	4.28	41	14.76517	1	2	1	2.1375	4	1	5	5.333333
3	4	SON	1.55125	-0.83036	-10.42	14	3.204	1	2	2	0.6	4	1	3.75	15.33333
4	1	OFA	13.21592	6.815218	16.58	43	10.01489	1	3	1	2.55	3	1	4	6.083333
4	2	OFC	8.83981	3.028571	8.03	22	-0.42813	1	3	2	1.4	3	1	2.75	5
4	4	ONA	30.96517	15.04133	2.41	3	-2.85969	1	3	1	4	3	1	3.5	13
4	5	ONC	18.614	8.966417	23.55	-42	-1.59674	1	3	1	2	4	1	3.25	4.333333
4	3	SON	17.715	7.831786	22.15	-3	-1.31607	1	3	1	2.8	3	1	4.25	2
5	5	OFA	12.29375	8.31975	4.57	-26	20.68302	1	3	1	9	4	1	4.75	17.33333
5	1	OFC	13.48187	6.952238	6			1	3	1	27.6	4	1	3.75	6.333333
5	3	ONA	11.68769	6.53389	12.23	32	2.016952	1	3	1	19	4	1	4.5	16
5	4	ONC	2.069667	1.657153	1.86	1	-5.4415	1	3	1	16	3	2	3	30
5	2	SON	10.81985	5.033468	2.36	13	0.082981	1	3	1	2.8	3	1	4.25	12.66667
6	4	OFA	-3.44478	-1.01992	2.21	21	-8.06107	2	2	1	67.4	3	3	4	33.66667

Note. Visualization of the data format for the final dataset.

Data Analysis

Analysing the final dataset started with a preliminary view of the data. The scores for the active perception variable were reviewed per condition, showing how many participants believed that they were actively stimulated. Then the maximum duration scores were reviewed and the decision to look for outliers was made. Bar charts were created to find potential outliers and to see if any outliers should be removed.

Next, the descriptives of the questionnaires were analysed. The mean and standard deviation for the variables average discomfort, average stimulation, and average motivation, was calculated for all participants across all sessions. After that, the mean and standard deviation of the ATTC scores was calculated. Bar charts were created to display the variables average discomfort, average motivation, and gender for each of the performance variables maximum duration, average duration, and average duration uninterrupted.

The first hypothesis, that offline anodal HD-tDCS of the rlDLPFC will improve the performance of participants playing the Super Hexagon game was analysed. The mean and standard deviation scores of the performance variables for all participants were calculated for the OFA, the ONA, and the SON condition. Then the Shapiro-Wilk test was chosen to analyse the assumption of normality for all performance variables and the conditions OFA, ONA, and SON. Histograms were created for a better visualization of the distribution. To test the first hypothesis, a MANOVA was chosen to analyse the impact of the variable condition on the three performance variables average duration, average duration uninterrupted and maximum duration. The Pillai's Trace test was chosen for its more robust values. Next, the Bonferroni correction was chosen to specifically analyse if the condition OFA had an impact on each of the three performance variables compared to the SON condition.

After that, the mean and standard deviation scores for the rotation variables rotation magnitude and switch frequency were calculated for all participants for the conditions OFA, ONA and SON. The Shapiro-Wilk test was run to test the assumption of normality of the data for the rotation variables for the conditions OFA, ONA, and SON. Histograms were then created for a better visualization of the data. After that, a MANOVA was run to analyse the two rotation variables for each of the three conditions, while the Pillai's Trace test was focused on. The Bonferroni correction was chosen to analyse the specific effect of the condition OFA on the rotation variables compared to the SON condition. The rotation data was further visualized by pie charts, showing movement degree categories and the frequency with which all participants used them.

Additionally, the analysis for the second hypothesis, that offline cathodal HD-tDCS of the rlDLPFC will improve the performance of participants playing the Super Hexagon game was performed. The mean and standard deviation scores of the performance variables for all participants were calculated for the OFC, the ONC, and the SON condition. Then, the Shapiro-Wilk test was chosen to test the normality for the distribution of data for all performance variables for the conditions OFC, ONC, and SON. Histograms were created for all performance variables for the conditions OFC, ONC and SON to visualize the distribution. The Bonferroni correction was chosen again to analyse the condition OFC and its impact on the performance variables in comparison to the SON condition.

After that, the mean and standard deviation for the rotation variables rotation magnitude and switch frequency were calculated for the conditions OFC, ONC and SON for all participants. To test the assumption of normality for the rotation variables across the conditions OFC, ONC, and SON the Shapiro-Wilk test was run. Histograms were created for each variable for the conditions OFC, ONC, and SON to better visualize the data. The Bonferroni correction was chosen again to analyse, if there was a significant difference between the condition OFC and SON regarding the outcome of the rotation variables. The rotation data was again visualized using pie charts with rotation degree categories for the conditions OFC, ONC, and SON.

After the two hypotheses were tested, additional analyses were run. Ceiling effects in the performance variables were further analysed, by taking the first three sessions separately.

The Shapiro-Wilk test was chosen to analyse the distribution of the data. Then a MANOVA was run with all three performance variables and the variable condition. The Pillai's Trace test was chosen for its robust values. This approach was chosen to potentially take out the sessions in which participants could not improve as much as they did before because of the increased difficulty of the game. Furthermore, ceiling effects could have also affected the data in the opposite way, in which increased learning effects would hide the effects of the conditions. That is why a Shapiro-Wilk test was run to analyse the distribution of the data while only using scores from session three, four and five. Then, a MANOVA was run for the last three sessions including all performance variables and the condition variable. The Pillai's Trace test was chosen for its robust values.

The correlation between the variables was analysed using Spearman's rank-order correlation to confirm that all the variables measured performance. Possible influences on the outcome of this study were checked by performing a MANOVA with the variable average ATTC on the three variables average duration, average duration uninterrupted, and maximum duration. The Pillai's Trace test was chosen for its robust values. Lastly, a MANOVA with the variable gender and the three performance variables was run. The Pillai's Trace test was used again for its robust values. After that, the Bonferroni correction was used to analyse the variable gender with each of the performance variables separately.

Results

Preliminary Results

A power analysis was conducted using G*Power 3.1.9.7. to determine the optimal sample size for a repeated ANOVA with five groups and five measurements. The analysis indicated that to detect a medium effect size $f = 0.333$ with an $\alpha = .05$ and power of .95, a minimum of 25 participants was needed.

Then, it was checked if the blinding of participants was successful. The descriptives of the active perception question revealed that the sham condition (SON) successfully blinded participants. The SON condition displays equal or lower amounts of participants, thinking that they were not actively stimulated, compared to the other conditions (Table 1).

Table 1

Descriptive Statistics of Active Perception per Condition

	OFA	OFC	ONA	ONC	SON	Total
Yes	24	20	25	24	22	115
No	2	6	1	2	4	15

Note. N = 26; Yes = participants believed that they were actively stimulated; No = participants did not believe that they were actively stimulated

At a first glance, the data showed the generally expected increase of high scores from the first to the last session. While a general improvement was expected, the magnitude of the improvement from session one to session five was higher than anticipated for some participants (Table 2). Since the magnitude of improvement and the differences between participants was high (Table 2), the decision was made to look at outliers.

Table 2

Examples of Maximum Duration Scores per Participant

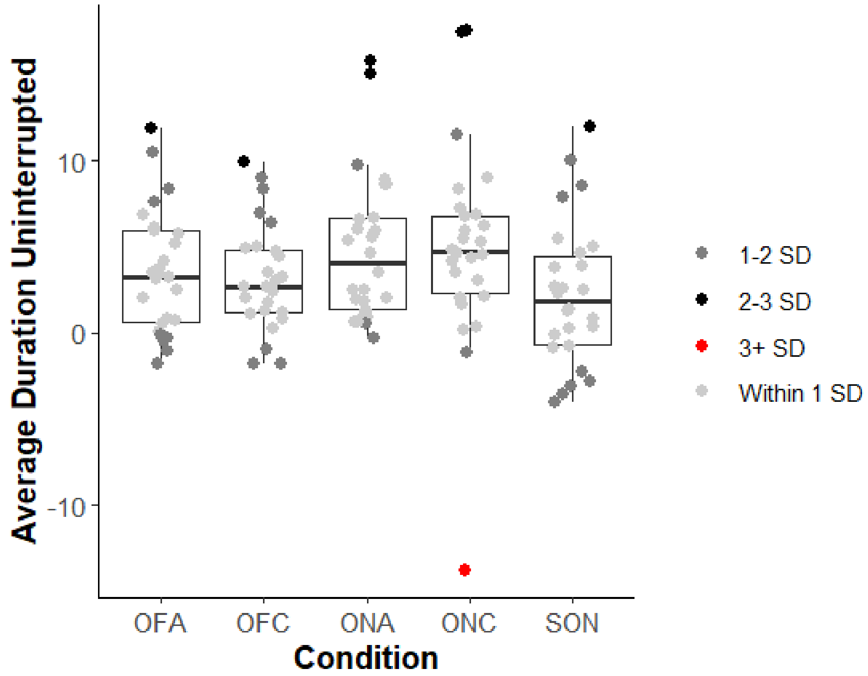
	P1	P2	P3	P4	P5	P6	P7	P8	P9
1st Session	26.11	18.27	37	24.65	23.67	17.25	37.02	17.27	17.25
5th Session	92.88	41.96	81.83	99.59	71.91	41.99	75.67	44.83	36.12

Note. The table shows participants one to nine as examples of the improvement through the variable maximum duration from the first game in session one to the last game in session five.

The criteria for exclusion were set at three standard deviations above or below the mean. Three Boxplots were created that showed the three performance variables per condition (Figure 6, Appendix 6). While the variables maximum duration and average duration showed no outliers more than three standard deviations away from the mean, the variable average duration uninterrupted showed one outlier in the ONC condition that met the exclusion criteria (Figure 6). However, this outlier was only one participant in one session and was in an online condition. Furthermore, the participant did not endure any observable distractions that would impact their performance. Since the participant actively tried to succeed at the game, the decision was made to not exclude him for performing worse. Therefore, no data was excluded from the analysis.

Figure 6

Outliers of Average Duration Uninterrupted per Condition



Note. The graph shows the improvement scores in seconds for each participant per condition.

Questionnaires

To put the results into context, the surrounding factors and the results from the questionnaires were presented. The descriptive statistics of average discomfort and average stimulation intensity was checked. Participants reported low scores for both variables, which shows that the participants should not have been affected by uncomfortable feelings but should have been able to perform to their best abilities (Table 3). The standard deviation scores were very high, indicating that participants had very different perceptions about the stimulation intensity (Table 3). Average discomfort was also shown to decrease by session (Appendix 7). Furthermore, the motivation scores were, on average, very high in all conditions (above 4), giving a good indication that the motivation participants had while playing was high enough to assume that they did their best to succeed in the task (Table 3). To visualize the data, boxplots were created (Appendix 8).

Table 3

Descriptive Statistics of Discomfort, Stimulation Intensity, and Motivation

	Average Discomfort (Scale 0 – 100)	Average Stimulation Intensity (Scale 0 – 100)	Average Motivation (Scale 1 – 5)
	Mean (Standard Deviation)	Mean (Standard Deviation)	Mean (Standard Deviation)
SON	17.77 (22.722)	24.481 (20.622)	4.144 (1.044)
ONA	18.627 (15.865)	27.311 (18.2)	4.077 (1.12)
ONC	23.252 (19.97)	31.021 (21.717)	4.139 (1.188)
OFA	17.49 (16.872)	25.452 (16.754)	4.115 (1.098)
OFC	20.046 (17.033)	24.923 (16.293)	4.115 (.931)

Note. Values indicate the mean values for all participants and all sessions.

With all participants scoring in the middle range on the ATTC scale (1 - 4), an adequate attention of the participants can be assumed M = 2.308, SD = 0.471. Higher performance was found for participants who scored higher on the ATTC (Appendix 9). Additionally, the performance variables showed generally higher values for men (Appendix 10). All in all, possible disturbing variables did not show any signs of having interfered substantially with the performance of the participants playing the Super Hexagon game.

Hypothesis 1

The analysis of the first hypothesis, that offline anodal HD-tDCS of the rlDLPFC will improve the performance of participants playing the Super Hexagon game was performed. While the mean scores of the performance variables were higher in the OFA condition than in the SON condition, participants scored very differently, as shown by the standard deviation scores (Table 4). Furthermore, the average offline anodal scores were lower than the average online anodal scores.

Table 4

Descriptive of Performance Variables per Condition

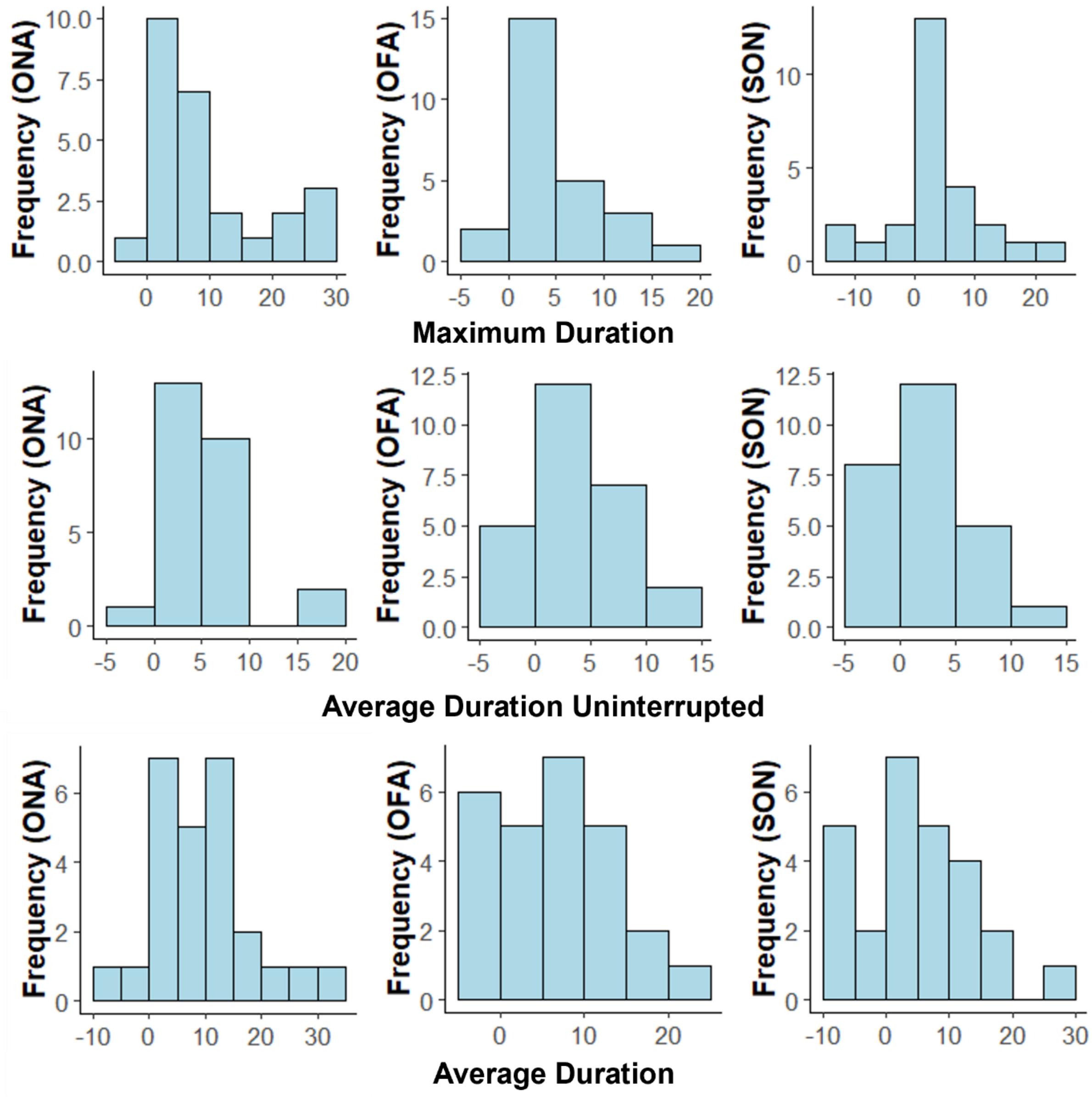
	Average Duration	Average Duration Uninterrupted	Maximum Duration
Conditions	Mean (Standard Deviation)	Mean (Standard Deviation)	Mean (Standard Deviation)
OFA	6.369 (6.9)	3.537 (3.583)	5.068 (4.444)
ONA	9.635 (8.773)	4.855 (4.299)	9.287 (8.765)
SON	4.475 (9.154)	2.223 (4.184)	3.548 (7.452)

Note. Values indicate the mean of improved performance scores within one session.

The Shapiro-Wilk test was run to see if the data from the three performance variables was normally distributed. The results showed that the OFA condition was normally distributed for the variables average duration and average duration uninterrupted but was not normally distributed for the variable maximum duration (Appendix 11). The SON condition was normally distributed across all three performance variables. The ONA condition was found to be normally distributed for the variable average duration but was not normally distributed for the variables average duration uninterrupted and maximum duration. Not all conditions were normally distributed for all variables which violates the assumption of normality. To make the distribution of the data easily comparable, histograms were created (Figure 7).

Figure 7

Distribution of Performance Variables per Condition



A MANOVA was chosen to analyse the overall impact of the condition variable (SON, ONA, ONC, OFA, OFC) on the performance variables average duration, average duration uninterrupted, and maximum duration. Because of the violation of assumptions, the Pillai's Trace test was chosen for the MANOVA analysis as its values are more robust. The results of the MANOVA indicated no significant effects of the conditions on the performance variables, Pillai's Trace $V = 0.13$, $F(12, 375)$ 1.38, $p = .17$, $\eta^2 = 0.004$. This shows that the conditions did not significantly impact the participant's performance.

Although the MANOVA did not reveal any significant overall effects, post hoc pairwise comparisons were conducted using Bonferroni correction to specifically assess the difference between the OFA condition and the SON condition for each performance variable. The Bonferroni-adjusted p-value for the variable maximum duration was p = 1.000, for the variable average duration was p = 1.000, and for the variable average duration uninterrupted was p = 1.000, indicating no significant difference between the OFA condition and the SON condition. The results indicate that the OFA condition did not have an impact on the performance of participants.

Rotation Data Hypothesis 1

As an additional analysis, the rotation data was explored. The improved switch frequency scores within a condition for all participants show high standard deviations, which indicates a high variation in scores across participants. The OFA condition is, like in the performance variables, higher than the SON condition but lower than the ONA condition (Table 5). The rotation magnitude variable showed no negative values, which is surprising, since the assumption was that less rotation magnitude would indicate a more efficient player (Table 5). However, the data revealed that the OFA condition did not have an impact on the rotation variables.

Table 5

Descriptives of Rotation Variables per Condition

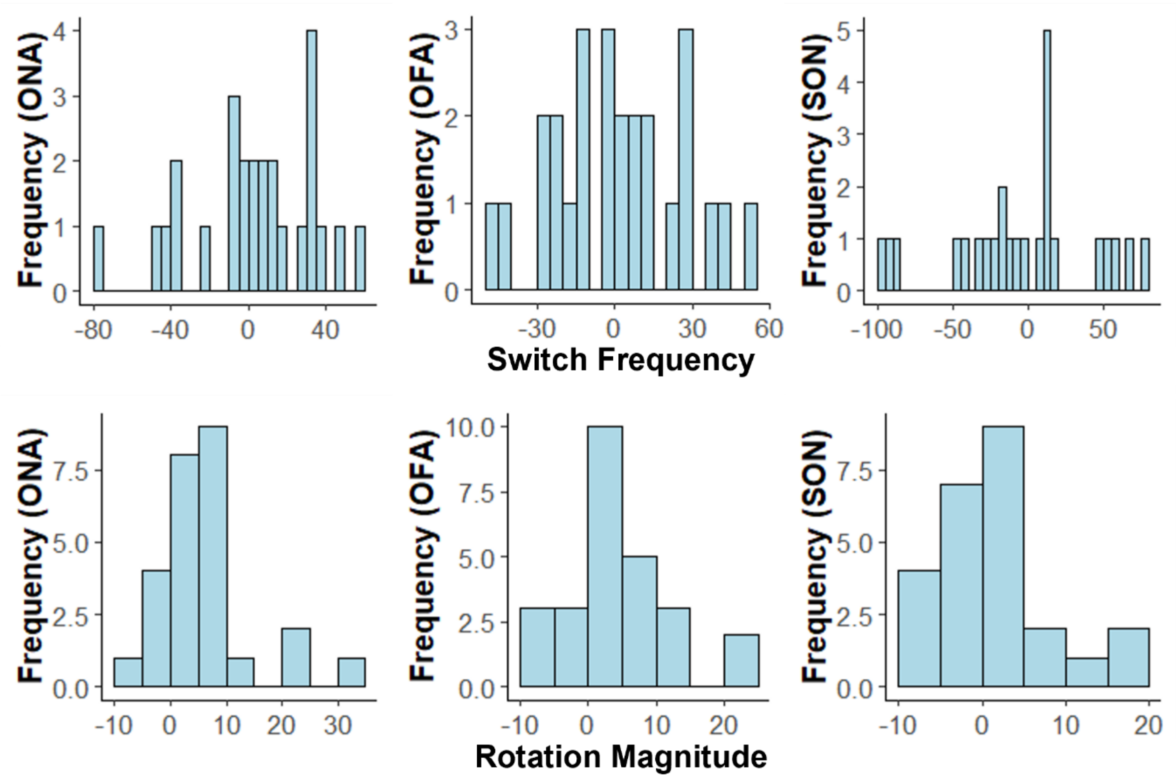
	Switch Frequency	Rotation Magnitude
Condition	Mean (Standard Deviation)	Mean (Standard Deviation)
OFA	1.62 (25.235)	3.867 (7.174)
ONA	3.19 (32.523)	5.929 (9.186)
SON	-4.2 (46.737)	1.489 (7.134)

Note. Positive values show an increase of values within one session while negative values show a decrease.

The Shapiro-Wilk test was chosen to check the distribution of the rotation data. The output revealed that the ONA condition was not normally distributed for the variable rotation magnitude but normally distributed for the variable switch frequency. Furthermore, the OFA condition and the SON condition were normally distributed for both rotation variable. Because not all conditions were normally distributed across all variables, the assumption of normality was violated (Appendix 12). Histograms were created for the rotation variables to visualize their distribution per Condition (Figure 8).

Figure 8

Distribution of Rotation Variables per Condition



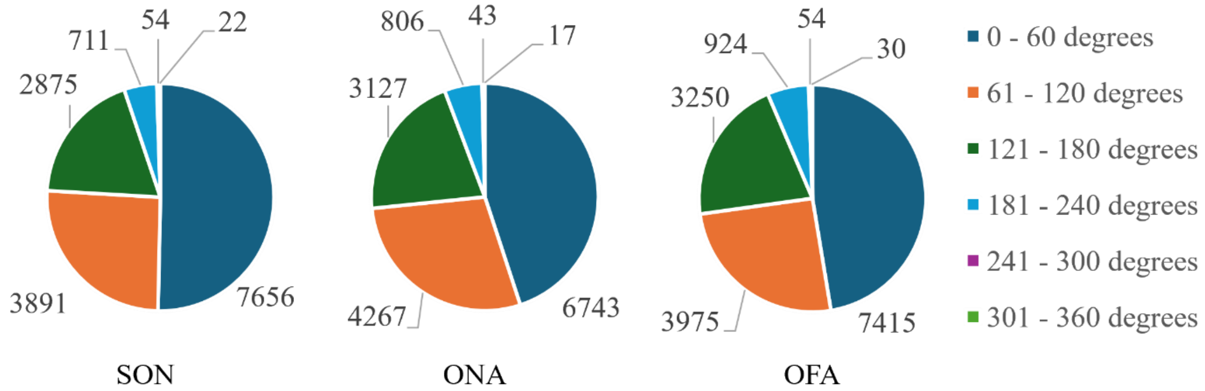
A MANOVA was chosen to see if the conditions (SON, ONA, ONC, OFA, OFC) had a significant impact on the rotation variables switch frequency and rotation magnitude. Because of the violation of the assumption of normality, the Pillai's Trace test was chosen for its more robust values. The results of the MANOVA showed no significant effects for the conditions on the rotation variables, Pillai's Trace $V = 0.103$, $F(8, 206)$ 1.405, $p = 0.196$, $\eta^2 = 0.052$. This shows that the conditions had no significant influence on the rotation variables.

Despite the MANOVA not finding significant results, a Bonferroni correction was chosen to specifically investigate whether the OFA condition differed significantly from the SON condition. The results showed that for the variable switch frequency the p-value was $p = 1.000$ and for the variable rotation magnitude the p-value was $p = 1.000$ indicating no significance. This shows that the condition OFA did not significantly affect the rotation variables.

The rotation data was also visualized in pie charts, which show the rotation degrees in 60-degree categories per condition. The pie charts reveal a slight difference between the sham condition and the active stimulation conditions. In active conditions, participants used larger movements, which is contrary to the belief that smaller movements are more efficient and will therefore be used more by participants who are being stimulated (Figure 9).

Figure 9

Magnitude of Movements Used per Condition



Note. The numbers display the counted times of rotations inside a certain degree category per condition. Because 360+ degree movements were even more rare than the 301 – 360 degree movements they were excluded from the graph.

Hypothesis 2

The analysis of the second hypothesis, that offline cathodal HD-tDCS of the rlDLPFC will improve the performance of participants playing the Super Hexagon game was performed. While there were differences between the mean scores of the performance variables, the standard deviation was very high. The OFC scores were higher than the SON scores for all three performance variables (Table 6). Interesting to mention is that for the variable maximum duration, unlike both other variables, OFC displays even higher scores than ONC.

Table 6

Descriptives of Performance Variables per Condition

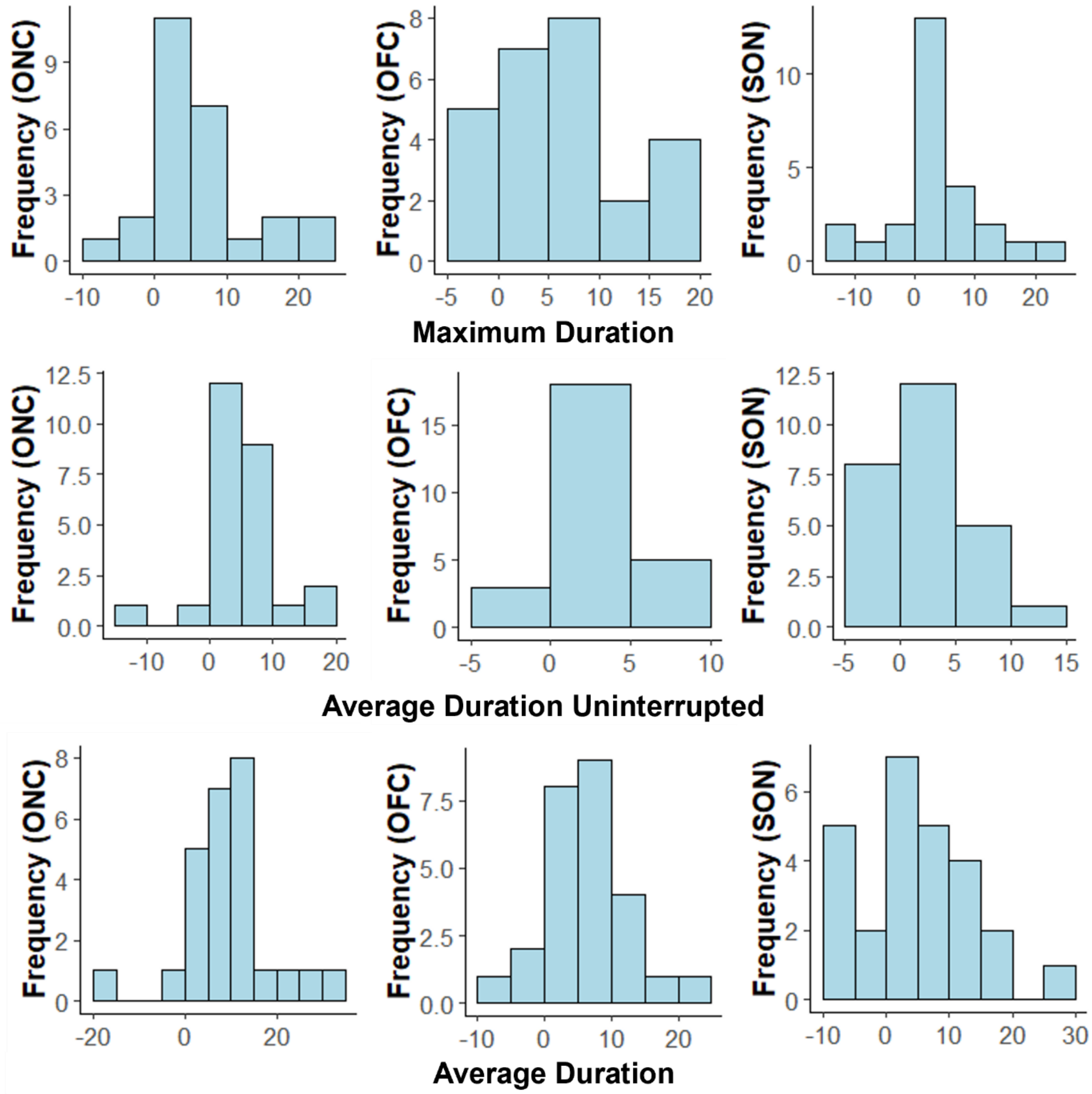
	Average Duration	Average Duration Uninterrupted	Maximum Duration
Conditions	Mean (Standard Deviation)	Mean (Standard Deviation)	Mean (Standard Deviation)
OFC	5.953 (6.516)	3.215 (3.081)	5.989 (6.627)
ONC	9.613 (10.291)	4.914 (5.881)	5.54 (7.587)
SON	4.475 (9.154)	2.223 (4.184)	3.548 (7.452)

Note. Values indicate improved performance scores within one session.

The Shapiro-Wilk test was run to check the assumption of normality for the performance variables in the conditions OFC, ONC, and SON (Appendix 11). While the ONC condition did not show a normal distribution for the variable's average duration and average duration uninterrupted, the OFC condition and the SON condition were found to be normally distributed for all three variables. Histograms were created to visualize the different conditions for each variable (Figure 10).

Figure 10

Distribution of Performance Variables per Condition



As stated above, the conducted MANOVA with all conditions (SON, ONA, ONC, OFA, OFC) and the performance variables average duration, average duration uninterrupted, and maximum duration indicated no significant effects of the conditions on the performance variables, Pillai's Trace $V = 0.153$, $F(12, 315)$ 1.41, $p = 0.160$, $\eta^2 = 0.051$.

Even though the MANOVA did not show a significant effect, a post hoc pairwise comparison was conducted using the Bonferroni correction. Specifically, the difference between the OFC condition and the SON condition was analysed. The Bonferroni-adjusted p-value for the variable maximum duration was $p = 1.000$, for the variable average duration the p-value was $p = 1.000$, and for the variable average duration uninterrupted the p-value was $p = 1.000$. This indicates no significant difference between the OFC condition and the SON condition and supports the results of the MANOVA, indicating no effects of the OFC condition on the performance of the participants.

Rotation Data Hypothesis 2

The rotation data was further explored by analysing the conditions OFC and ONC. The mean values were highest for the OFC condition, which was expected for the variable switch frequency but not for the variable rotation magnitude, as a negative value would indicate a higher efficiency for this variable (Table 7). The standard deviation scores were very high again (Table 7).

Table 7

Descriptives of Rotation Variables per Condition

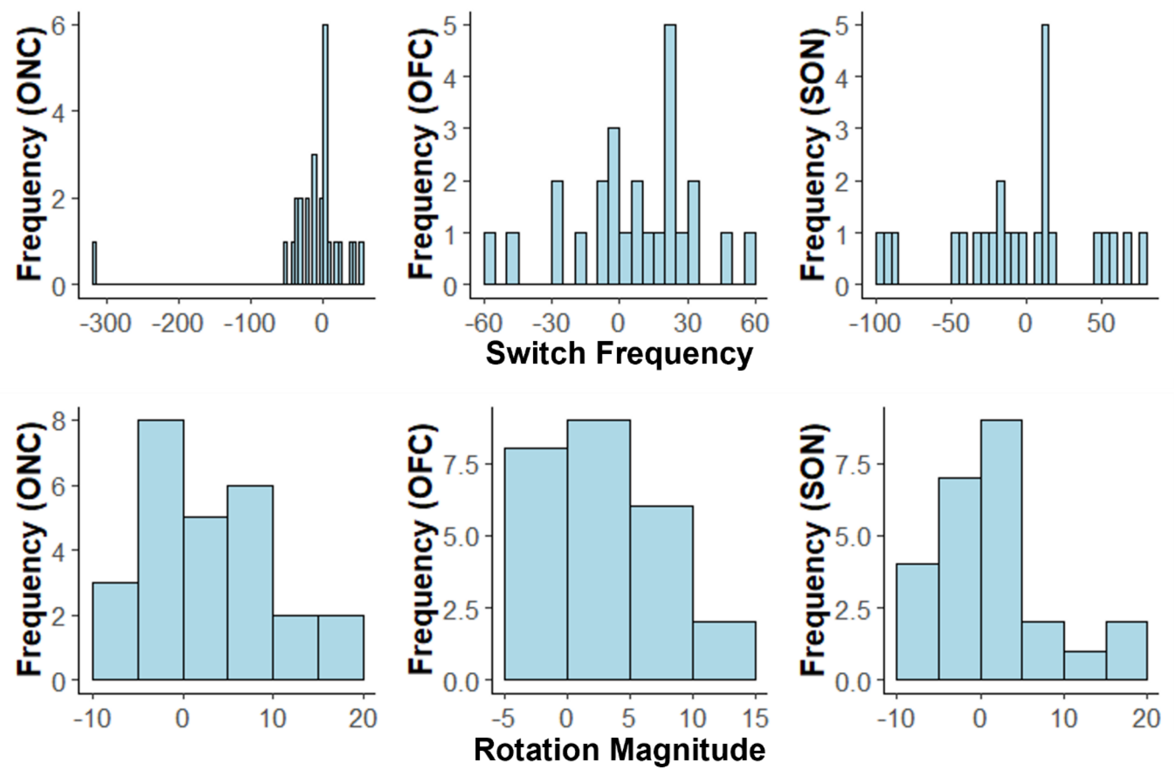
	Switch Frequency	Rotation Magnitude
Condition	Mean (Standard Deviation)	Mean (Standard Deviation)
OFC	6,48 (27.301)	3.404 (4.93)
ONC	-16.81 (67.07)	3.148 (6.87)
SON	-4.2 (46.737)	1.489 (7.134)

Note. Positive values show an increase of values within one session while negative values show a decrease.

To analyse the assumption of normality, the Shapiro-Wilk test was chosen. The output of this test revealed that for the variable switch frequency, the ONC condition was not normally distributed (Appendix 12). All other conditions were normally distributed for the switch frequency variable and the rotation magnitude variable. The histograms seen in Figure 11 show the distribution of both rotation variables for comparison.

Figure 11

Distribution of Rotation Variables per Condition



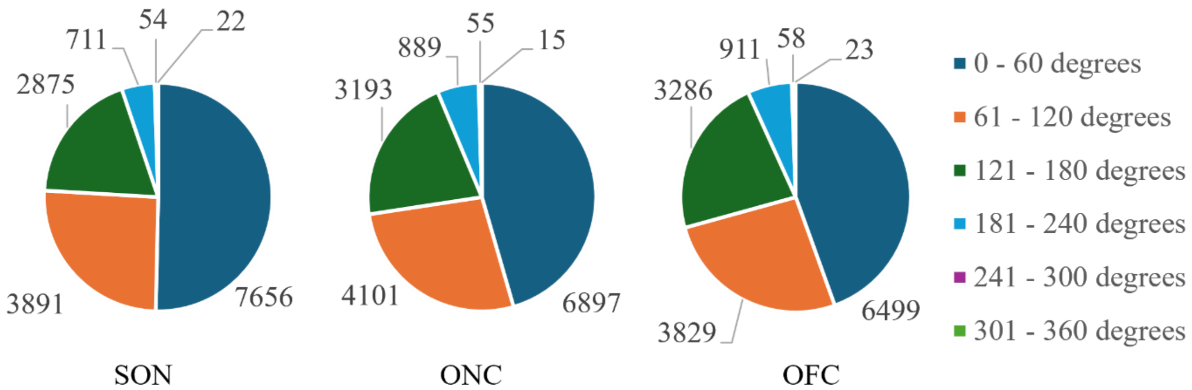
A MANOVA was chosen to see if the condition variable had a significant impact on the rotation variables switch frequency and rotation magnitude. Because not all conditions for all variables were normally distributed, the assumption of normality was violated. The Pillai's Trace test was therefore chosen for its more robust values. The results of the MANOVA showed no significant effects for conditions on rotation variables, Pillai's Trace $V = 0.103$, $F(8, 206)$ 1.405, $p = 0.196$, $\eta^2 = 0.052$. This shows that the conditions had no significant influence on the outcome of the rotation data.

The Bonferroni correction was chosen again for a post hoc analysis, even though the MANOVA results were not significant. The results of the analysis specifically about the differences between the OFC condition and the SON condition revealed that for the variable switch frequency the p-value was $p = 1.000$, and for the variable rotation magnitude the p-value was $p = 1.000$. This indicates no significant differences between participants rotation efficiency in the OFC condition compared to the SON condition.

The visualization of the rotation data was done with pie charts, which reveal a high tendency for smaller movements of participants across conditions (Figure 12). However, the movements in the active stimulation conditions increased, which is contrary to the belief that smaller movements suggest higher efficiency.

Figure 12

Magnitude of Movements Used per Condition



Note. The numbers display the counted times of rotations inside a certain degree category per condition. Because 360+ degree movements were even more rare than the 301 – 360 degree movements they were excluded from the graph.

Additional Analysis

Because of a possible ceiling effect that could be seen during a scan of the variable maximum duration of the data, the data was checked for the first three sessions. The Shapiro-Wilk test was chosen to see if the distribution of the data would improve. The results showed that the offline conditions OFA and OFC were normally distributed for all three performance variables while the online conditions ONA, ONC, and the SON condition were not always normally distributed (Appendix 13). This led to the decision of using the Pillai's Trace test again for a MANOVA analysis of all five conditions with all three performance variables. The results of the MANOVA was Pillai's Trace $V = 0.124$, $F(12, 219)$ 0.79, $p = 0.196$, $\eta^2 = 0.04$, indicating that there is no significant effect of the condition variable on the variables maximum duration, average duration and average duration uninterrupted. Taking out the last two sessions revealed no significant difference compared to the MANOVA analysis with all five sessions. The ceiling effect could also be interpreted to make the learning effect smaller and therefore reveal bigger changes of the influence of conditions. To make sure a ceiling effect did not have any influence on the data, the same analysis was performed with the last three sessions. The Shapiro-Wilk test was run for the last three sessions and revealed that the OFA, OFC, and SON condition were normally distributed among all three performance variables (Appendix 14). The conditions ONA and ONC on the other hand were not always normally distributed, which led to the decision of using the Pillai's Trace test for the MANOVA. The results of this test revealed that Pillai's Trace $V = 0.215$, $F(12, 219)$ 1.41, $p =$

0.164, $\eta^2 = 0.07$, which shows that the conditions did not have a significant effect on the performance variables.

To ensure that the chosen variables were measuring performance as intended, correlational analyses were run. The correlations between the performance variables and the rotation variables were checked using Spearman's rank-order correlation. This test was chosen because of the violation of normality in the data. Average duration and average duration uninterrupted were highly correlated $r_s = 0.97$, $p < 0.001$, $N = 130$ which means that the two variables are measuring almost the same concept. Average duration correlated moderately with maximum duration $r_s = 0.335$, $p < 0.001$, $N = 130$ which shows that the two variables measure a similar concept. The same can be said for average duration uninterrupted, which correlated similarly with maximum duration $r_s = 0.357$, $p < 0.001$, $N = 130$. Furthermore, average duration correlated with rotation magnitude only slightly $r_s = 0.224$, $p = 0.01$, $N = 130$, which means that the two variables have a small positive correlation to each other, however each variable measures mainly something different. Interestingly, rotation magnitude did not significantly correlate with maximum duration $r_s = 0.092$, $p = 0.3$, $N = 128$. No correlations were found between average duration and switch frequency $r_s = 0.031$, $p = 0.725$, $N = 128$, which means that there is no relationship between the variables. Overall, correlations between the variables were lower as expected, indicating that the variables did not measure the same construct to the degree that was anticipated.

A MANOVA was run to analyse the effects of the variables average ATTC and gender on the three performance variables maximum duration, average duration and average duration uninterrupted. The results of the MANOVA for the variable average ATTC showed, Pillai's Trace $V = 0.002$, $F(3, 124)$ 0.77, $p = .972$, $\eta^2 < 0.001$. This outcome describes no significant effect of ATTC scores on the variables average duration, average duration uninterrupted and maximum duration. The results of the MANOVA for the variable gender on the other hand seemed to have a significant effect, Pillai's Trace $V = 0.062$, $F(3, 124)$ 2,727, $p = .047$, $\eta^2 = 0.002$. Because of this effect, the decision was made to perform a Bonferroni correction to more specifically explore the relationship. The results revealed that the effect of gender on average duration $p = .098$, which shows no statistically significant difference. For the variable average duration uninterrupted the results showed $p = .015$, indicating that gender made a significant difference in the outcome of this variable. The analysis for the variable maximum duration revealed $p = .006$, which shows a significant difference on maximum duration that depends on the variable gender.

Discussion

This study aimed to find the effects of offline HD-tDCS of the rlDLPFC on visuospatial working memory performance, which was measured by playing the Super Hexagon game. The results of the MANOVA revealed no significant effects of the conditions on the three performance variables. The Bonferroni correction analysis confirmed the results of the MANOVA, showing that the OFA condition has no significant effect on the variables average duration, average duration uninterrupted and maximum duration. Therefore, the first hypothesis, being that offline anodal HD-tDCS of the rlDLPFC will improve a participant's performance while playing the Super Hexagon game, was rejected. The results are not in line with previous research findings. For example, Hill et al. (2016) stated that offline anodal tDCS can increase performance of working memory. Furthermore, Nitsche et al. (2005) stated that stimulations over five to seven minutes can create aftereffects, therefore these effects should have also been visible within this research. The stimulation in this study lasted for 15 minutes before participants started playing the game, which should have been enough to make aftereffects visible in the data. This was not the case, indicating that the condition variable did not have any effects on the performance variables.

The Bonferroni correction was run for the condition OFC and supported the outcome of the MANOVA, showing no significant effect of OFC on the three performance variables. Therefore, the second hypothesis, being that offline cathodal HD-tDCS of the rlDLPFC improves the performance of a participant playing the Super Hexagon game, had to be rejected as well. While Bikson and Rahman (2013) stated that cathodal stimulation will inhibit cognition by increasing the threshold for neurons to fire, offline studies such as the one by Pirulli et al. (2014) showed the opposite effect for cathodal stimulation. Since this study focuses on offline conditions, an improved effect should have been found.

The outcome of the analysis for the first hypothesis could be explained by excitatory stimulation creating noise, which means the neurons will fire faster although they are not as effectively used as inhibited neurons (Schroeder & Plewnia, 2016). This would lead to no performance increase in participants and therefor would show no effect in the data. Compensatory effects could be a reason for the outcome of the second hypothesis, because they could have countered the effects of the stimulation to reach homeostasis of cortical activity (Friehs et al., 2021). Consequently, this could lead to cathodal stimulation triggering compensatory effects that enhance cognition and countering the aftereffects produced by the offline stimulation effects.

The nature of the HD-tDCS electrodes should have given more accurate effects than other tDCS methods since it specifies the stimulation area better than other electrode sizes (Sharma & Chowdhury, 2019). The current study rather matches other research that did not find significant results for offline tDCS conditions (Müller et al., 2022). Specifically for HD-tDCS, the lack of significant results could stem from the focus on sub-processes of working memory, which can create a bottleneck, describing a blockage of processing speed consequently increasing variability (Müller et al., 2022). Fanari et al. (2019) and D'Aurizio et al. (2023) explain that the visuospatial sketchpad is a part of the working memory, while also theorizing that the visual and spatial parts are divided. The bottleneck could be showing in the data when the HD-tDCS is targeting only visual working memory processes, but the spatial working memory process is not enhanced. That could lead to visual information being processed faster; however, the spatial part of the working memory cannot adjust to the amount of information, resulting in a bottleneck that prevents performance improvement. Balconi (2013) stated two different branches of theory regarding working memory. In the first one the rDLPFC is ones responsible for visuospatial working memory but in the other branch the rDLPFC is responsible for recovering information while the lDLPFC is used for processing information. According to the second branch described by Balconi (2013), the bottleneck could have occurred in this study because only the recovery of information was enhanced by the stimulation while the processing task of the lDLPFC was not, leading to not significant results. Literature showed that the Super Hexagon game is related to visuospatial working memory (Jalife et al., 2021) and that visuospatial working memory is located at the rlDLPFC, corresponding to the electrode position F6 (Wischnewski et al., 2021). Therefore, the stimulation should have increased performance.

A meta-analysis by Simonsmeier et al. (2018) revealed that tES is most effective during practice attempts, while the effectiveness declines when participants are examined on their performance. This could have had an impact on this study, since the participants were told that they will be assessed every time they are playing and that there are no practice attempts. In this study, all participants improved, not only while playing the game during one session but also from session to session. Learning effects like these were expected, however the degree to which some players improved from the first to the last session was higher than expected, which caused an impediment in the analysis. A possible explanation for different learning effects are the different backgrounds and learning styles of participants. While some participants had very high scores in their third session already, other participants were improving more slowly. Because the game is designed to become more difficult as players progress, a ceiling effect was anticipated.

A ceiling effect led to some participants stagnating on the performance from their third session, while others started improving only after the third session. However, even when considering a ceiling effect, the analysis could not find significant differences between conditions. Neither a consideration for conditions having a higher effect in the first three sessions, nor a consideration for conditions having a higher effect in the last three sessions revealed significant results.

Furthermore, analysis of the variables showed that apart from the very similar variables average duration and average duration uninterrupted, no variables correlated highly with average duration. This is a very surprising finding since the performance variables should all measure performance, they were expected to correlate more strongly. The rotation data was expected to be correlated too, since it was assumed that it measured efficiency. The analysis showed that smaller movements were more common, which supported the assumption that small movements might be more efficient, leading to higher performance. However, in all stimulation conditions, the bigger movements increased which was surprising. There was a weak positive correlation between the average duration and rotation magnitude which was not expected. This means that a higher rotation magnitude equals a better performance, which is contrary to the initial idea of the variable. Furthermore, switch frequency did not correlate with average duration, meaning that it is not related to the same construct, being performance. The indecisive correlations between the variables make it hard to draw conclusive statements about the outcome of this study.

Limitations

Due to the results of this study showing no significant effects, several explanations were developed. As a within-subjects design was chosen, participants had to come back five times to participate in the study, during the data collection phase. Participants could choose the dates of their sessions with the only limitation that the next session was not earlier than five days after the last session. This resulted in some participants taking breaks between sessions and completing all five sessions more slowly, while others finished the study much faster. The longer breaks between sessions could have affected the performance in a negative way, for example, it could have altered the effects of learning and therefore improvement scores. Participants who started the game after a longer break took longer to show improvement compared to those who had shorter breaks, resulting in a performance discrepancy. However, the goal of this study was not to increase the performance from one session to another, but within one session. Independently from how much the participants improved from one session to another, the relevant data regarding the effect of conditions was gathered within one session and should therefore have not been affected.

Another possible limitation could have been the determination of the rlDLPFC, which was not confirmed via a brain scan. The unique anatomy of human heads and brains dictates the precise locations of brain regions and where electrodes must be placed for brain stimulation research (Bergmann & Hartwigsen, 2021). Due to the scope of this study, and the lack of a brain scan for every participant, it is not possible to eliminate inaccuracies in the stimulation and consequently in the results entirely. However, literature states that a good estimate for finding the rlDLPFC is to use the F6 EEG electrode position (Wischnewski et al., 2021), which was implemented. Bergmann and Hartwigsen (2021) also stated that using the EEG electrode system is a good way to locate the stimulation points relative to the brain region if one has no access to a brain scan. This indicates that the usage of the EEG electrode system to determine the stimulation point of the rlDLPFC should have been adequate to achieve significant results.

Bone thickness, which can partially block the electrical current, differs between people (Bergmann & Hartwigsen, 2021). This problem could have impacted the results of the study. Bergmann and Hartwigsen (2021) stated further that this can be rectified by a higher intensity to ensure that the current reaches the brain area. These limitations were addressed in this study by conducting a pilot study to find the right stimulation intensity. Every researcher has to weigh between the making the stimulation more uncomfortable and stimulating with enough intensity to reach the brain area.

Furthermore, the Super Hexagon game could be a flawed measure to evaluate visuospatial working memory in a HD-tDCS setting, as could its cloned version created of that game. It should, therefore, be verified whether this game can be used as an adequate measurement for performance differences by stimulating the visuospatial working memory. However, studies of 2-dimensional games have proven them to be related to visuospatial working memory (Llana et al., 2022). Furthermore, a recent article explained that the Super Hexagon game is a good task to measure visuospatial working memory (Jalife et al., 2021). Even though this game was cloned for research purposes, the nature of the game did not change and therefore it was considered to be adequate for this research purpose.

Moreover, the choice of variables measuring performance could have influenced the outcome of this study. The maximum duration as a performance score might have been unstable and unreliable, as a participant could achieve a fortunate or exceptional performance within just ten minutes. A similar problem might occur with the variable average duration, because of the nature of the game, which automatically stops twice, although a player has not hit an obstacle yet, providing somewhat inaccurate data. Some participants even got high scores on their last trial, even though they were interrupted by the game. Average duration uninterrupted seemed to be the best measurement of performance out of the three, because it led to the most robust values. However, this variable is still not perfect because of the different trials it will delete. For one participant average duration uninterrupted could delete the best run of a participant while for others nothing was excluded, because they hit an obstacle shortly before the time of the game stopped. For another, average duration uninterrupted could have deleted a run which participants had barely started, increasing the average score of the participant. The trials that were cut off by the game got included in the variable average duration. This led to participants receiving worse scores even though they performed well. When participants knew about trails getting interrupted at the end of the game, their motivation might have decreased, since the players could no longer beat their high scores. This could also be attributed to the emphasis on high scores, as participants with the highest scores were offered a voucher. Losing motivation in the last seconds could lead to problems within the data by influencing the performance of the participants. However, the motivation scores were not designed to reveal changes in motivation but only showed the motivation during the whole session. Furthermore, the rotation data did not yield better measurements of performance, because the rotation magnitude showed a slight positive correlation, and the switch frequency did not correlate with any other performance data. Even though all three performance measures had their flaws, combining them and analysing them all should have given a good estimate of the performance of participants and therefore should have led to accurate results. Furthermore, high scores and average time variables are used regularly as performance variables and should therefore be considered an adequate measure of performance in this setting as well.

Future Research

While this study examined five different conditions, future research could expand by adding another condition in which the stimulation begins five to seven minutes before the task and continues while playing. This could give the participants more time to adjust to the stimulation and it could support the statement by Nitsche et al. (2005) who suggested that after five to seven minutes stimulation effects could be increased. Another option for future research is to study the exact position in the brain that is used while playing the Super Hexagon game. To achieve the highest accuracy, a brain scan should be performed for each participant while playing the Super Hexagon game in the first session and could be controlled in a later session to account for neural plasticity. Furthermore, since a ceiling effect was found, giving participants time to practice the game before stimulating them could lead to more reliable results. Another possibility to reduce ceiling effects is to do a between subjects' study in which participants only play the game once or twice on a single day, giving them less practice time and in turn increasing the stimulation effect. Since only the placement of the stimulating electrode was scientifically validated, future research could investigate the best position for the return electrodes, depending on where the stimulating electrode is placed. This could alter focality and depth of the stimulation and could lead to different results. Future research could also find different measurements of performance for the Super Hexagon game so that the representation of performance from a participant's gameplay would be more accurately displayed. This could also be done by altering the game slightly, for example, by changing the gameplay parameters. These parameters could introduce a set number of trials each participant has to perform instead of a timer that runs out, leaving a participant with unfinished trails. This could result in more accurate average scores since all trials would be completed until the player encounters an obstacle, without prematurely stopping any trials, leading to a possible exclusion. It would avoid excluding trials that were not finished, even though they might have had extremely high or low scores. Additionally, to include the learning effect, certain trials could be labelled as practice rounds while there could be exam rounds at the end, increasing the learning effect with the stimulation. Also, the rotation data could be analysed more closely to find out which variables really measure efficiency accurately. This could lead to more variables being included in an analysis and therefore a more accurate resemblance of performance for all participants.

Additionally, future research could focus on the theoretical aspects of why this study did not find significant results like the bottleneck. It would be interesting to see if HD-tDCS can trigger this phenomenon on a regular basis, since it is a technique that is specifically designed to increase focality. The bottleneck phenomenon could therefore not only be present for the visuospatial working memory but different parts of the working memory as well, leaving HD-tDCS studies more often without significant results. For example, future research could focus on finding tasks in which two different brain areas have to be used and stimulating both areas, one of the two areas, or no area and analysing the results. HD-tDCS could therefore help in specifying the brain areas that are needed for a specific task like the Super Hexagon task. Furthermore, the aftereffects of offline stimulation could be studied more. Questioning if aftereffects only appear when a cathodal stimulation is successfully inhibiting brain activity or if these effects are also present when compensatory effects are triggered could lead to interesting future research and a better understanding of offline tDCS studies results. Lastly, future research could evaluate the usefulness of a highly focal stimulation over multiple sessions or longer periods of time when neuronal plasticity is checked for. Does neuronal plasticity especially in parts of the working memory function happen so extreme that HD-tDCS must be used for shorter studies to see improved cognition could be one of the questions answered by future studies. Overall, future research could focus on different areas to help understand the effects of offline HD-tDCS and the visuospatial working memory.

Conclusion

In conclusion, this study expands upon previous research on tDCS effects on visuospatial working memory by introducing the Super Hexagon game as a new performance measure, contributing to the understanding of previously mixed results. Both the first hypothesis, being that anodal offline HD-tDCS of the rlDLPFC improves performance of participants playing the Super Hexagon game, and the second hypothesis, being that offline cathodal HD-tDCS of the rlDLPFC improves performance of participants playing the Super Hexagon game had to be rejected, since no significant effects were found. This leads to the question about the reasons behind these results.

The questionnaires showed that participants were motivated throughout the study and did not feel any discomfort that would alter the results, as seen in the analysis. Because this research was conducting thoroughly, the results of this study being not significant adds to the existing literature of offline stimulation and brings a valuable contribution to its understanding. Furthermore, HD-tDCS is not yet as widely used as regular tDCS, which makes this study valuable for future studies to be aware of the difficulties and the benefits of HD-tDCS. By adding the Super Hexagon game as a task to tDCS studies of the rlDLPFC, this study paves the way for future research to choose from different valuable tasks to measure visuospatial working memory. Overall, this research made a valuable contribution to future offline stimulation research and HD-tDCS research of the visuospatial working memory by providing a precisely documented study and a thorough analysis of the results. While there are tDCS studies that find significant effects, other studies, such as this one, do not. Reasons for the outcome of this study should be studied further.

It is to be noted that brain stimulation devices and its research does not come without risks. Some brain stimulation devices are available on the internet, so anyone can purchase them. This option leads some people to try and use upcoming techniques to improve their cognitive abilities for example while playing video games (Antal et al., 2022). However, these devices are not always officially certified, therefore not always approved for research, and may not be safe to use without proper technical knowledge (Antal et al., 2022). Extensive literature exists, for example Coffey (2009) or Antal et al. (2022), in which safe methods that could potentially increase cognitive performance with brain stimulation devices are described. However, the findings of this study contribute to the existing body of literature that presents mixed results, suggesting a need for further exploration and expansion in future research. Because this study could not find significant effects, future research should continue studying the effects of offline HD-tDCS on visuospatial working memory, in order to find proof for or against the improvement of people's visuospatial working memory.

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Appendices

Appendix 1

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 2

Session 2:

I hereby assure that the information on the consent form is still true and accurate.

____

Date, Signature

Session 3:

I hereby assure that the information on the consent form is still true and accurate.

____

Date, Signature

Session 4:

I hereby assure that the information on the consent form is still true and accurate.

____

Date, Signature

Session 5:

I hereby assure that the information on the consent form is still true and accurate.

____

Date, Signature

Appendix 3

Questions from the Beginning 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.

Appendix 4

Questions from the 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.

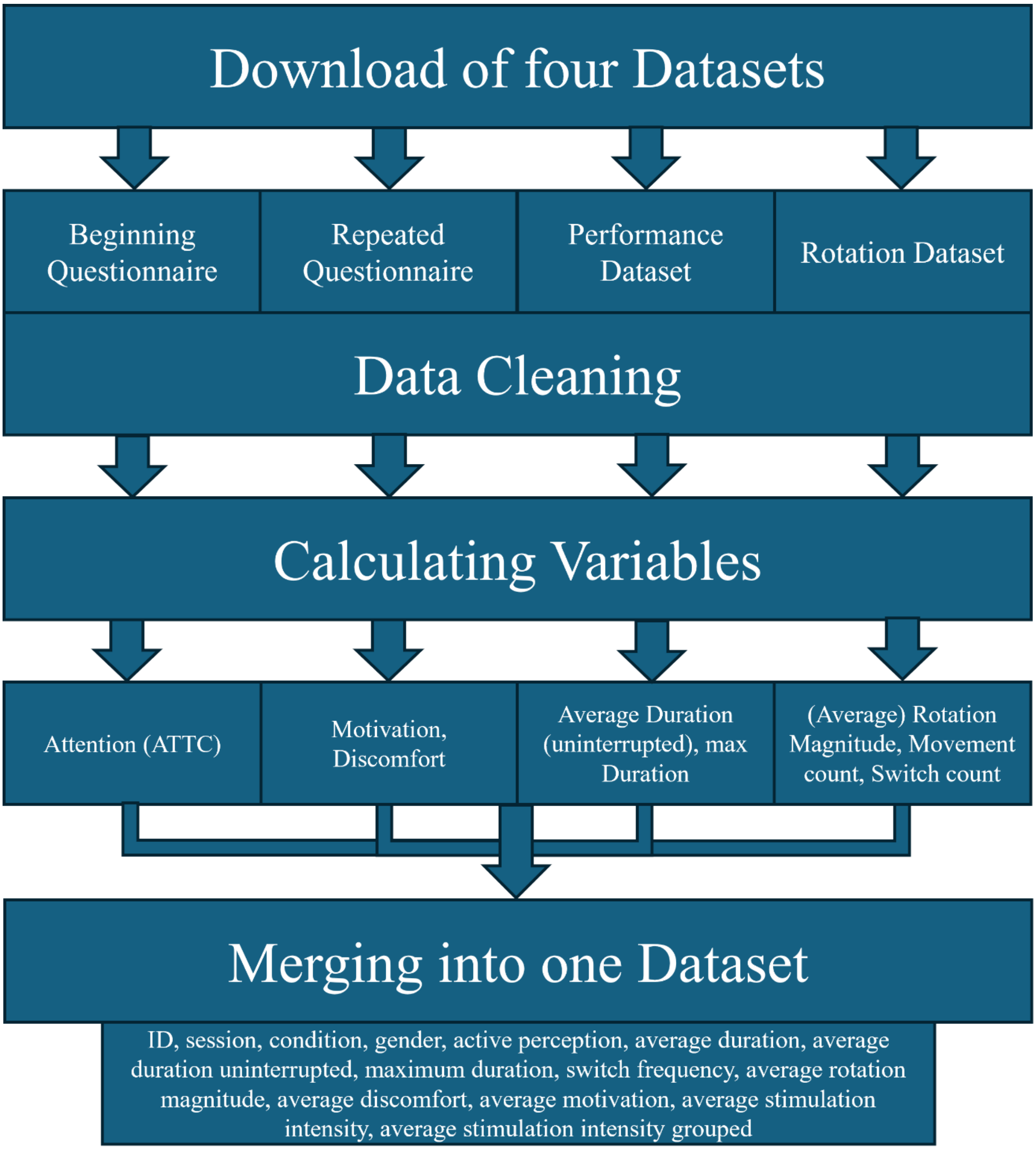
1 =	2 =	3 =	4 =	5 =
Disagree	Somewhat disagree	Neither disagree nor agree	Somewhat agree	Agree

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 5

Figure 13

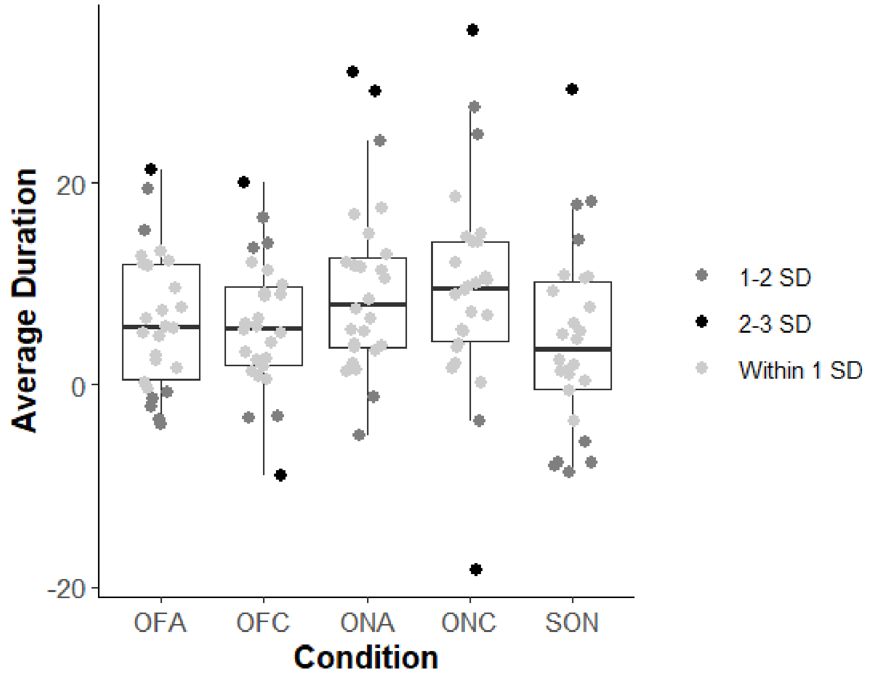
Flowchart of Data Cleaning



Appendix 6

Figure 14

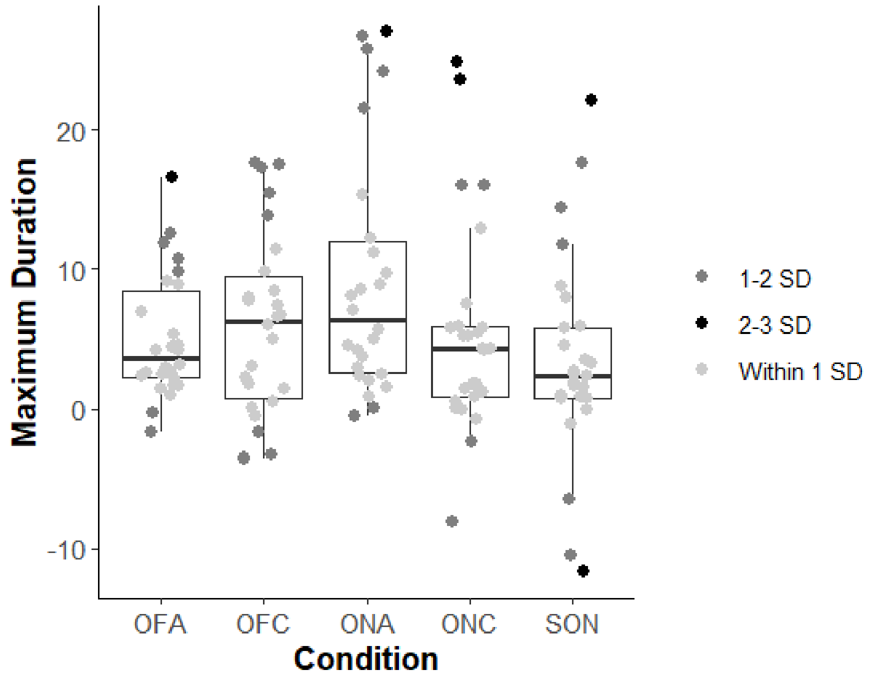
Outliers of Average Duration per Condition



Note. The graph shows the improvement scores in seconds for each participant per condition.

Figure 15

Outliers of Maximum Duration per Condition

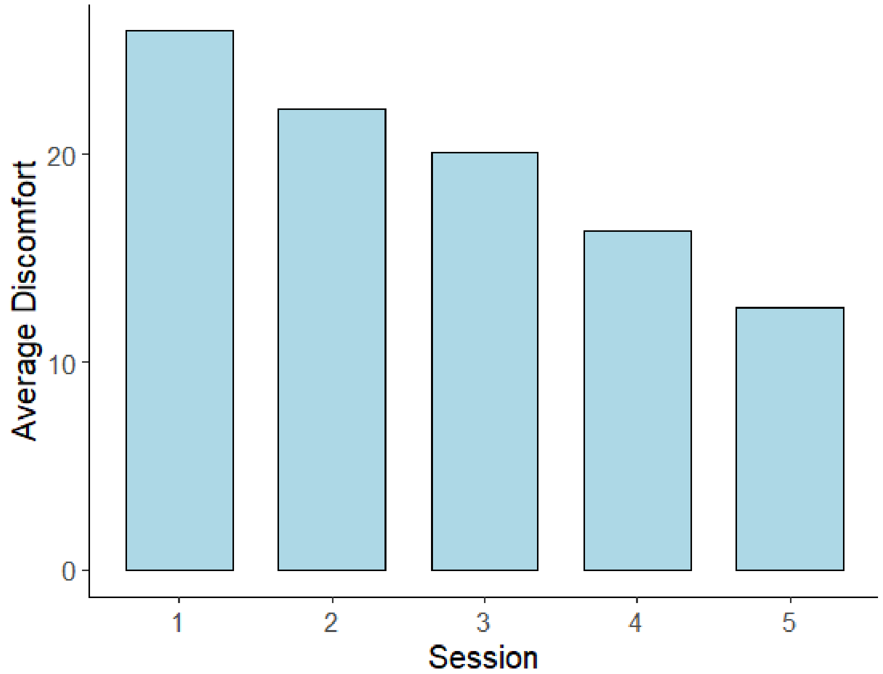


Note. The graph shows the improvement scores in seconds for each participant per condition.

Appendix 7

Figure 16

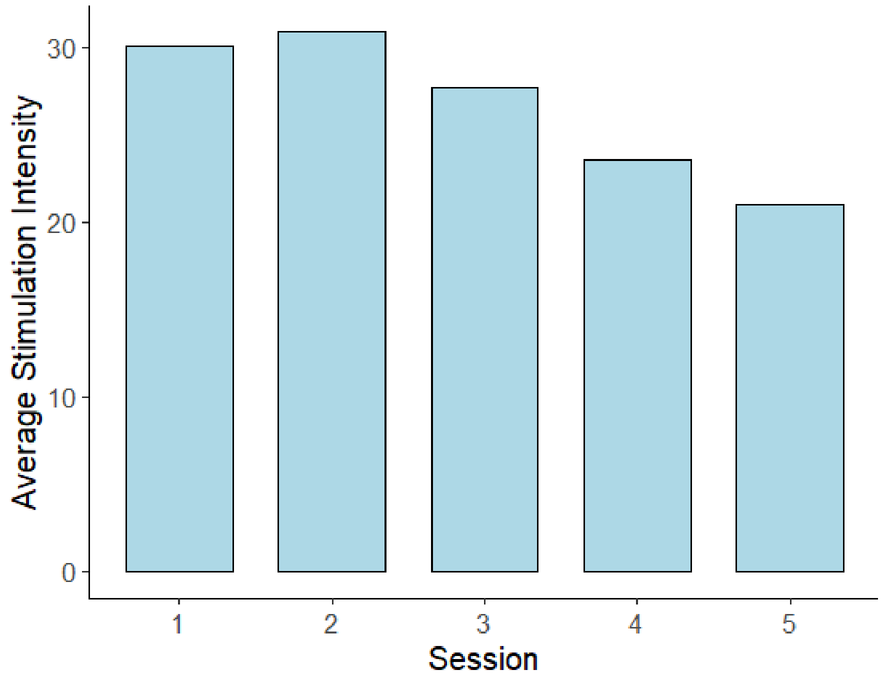
Average Discomfort Scores per Condition



Note. Discomfort scores are averaged for each participant and across participants.

Figure 17

Average Discomfort Scores per Session

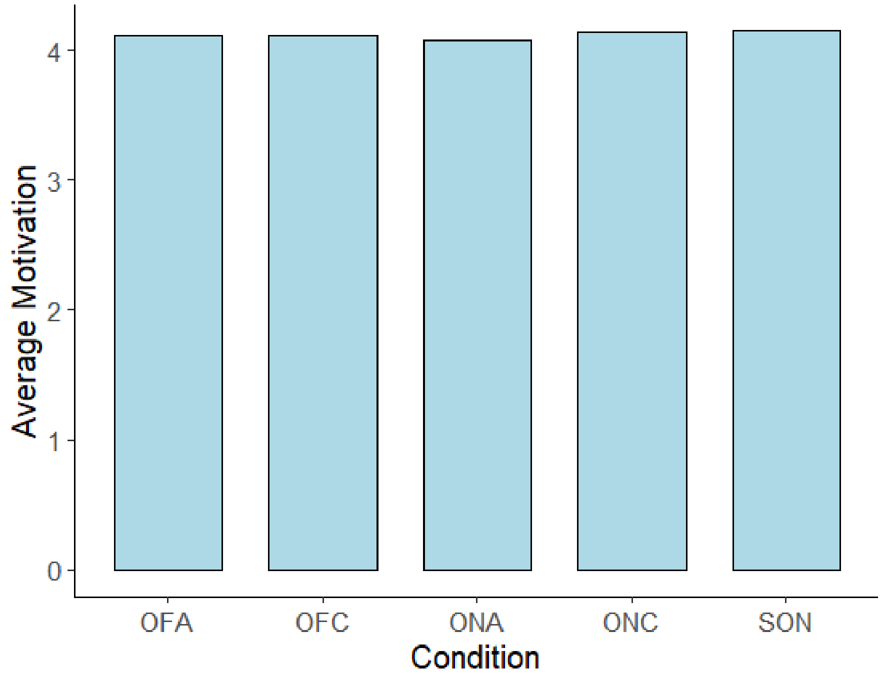


Note. Discomfort scores are averaged for each participant and across participants.

Appendix 8

Figure 18

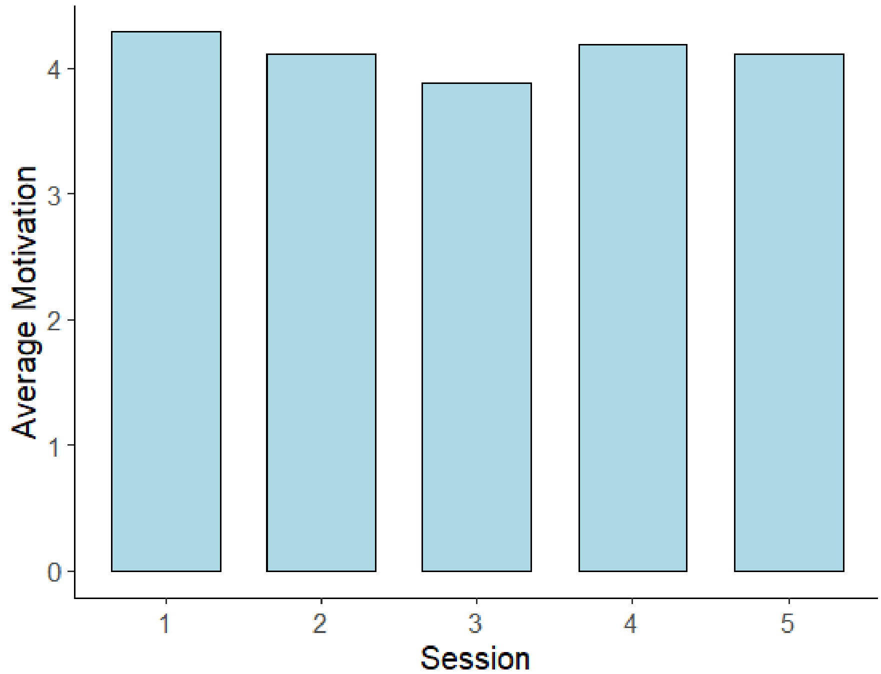
Average Motivation Scores per Condition



Note. Motivation scores are summed for each participant and averaged across participants.

Figure 19

Average Motivation Scores per Session

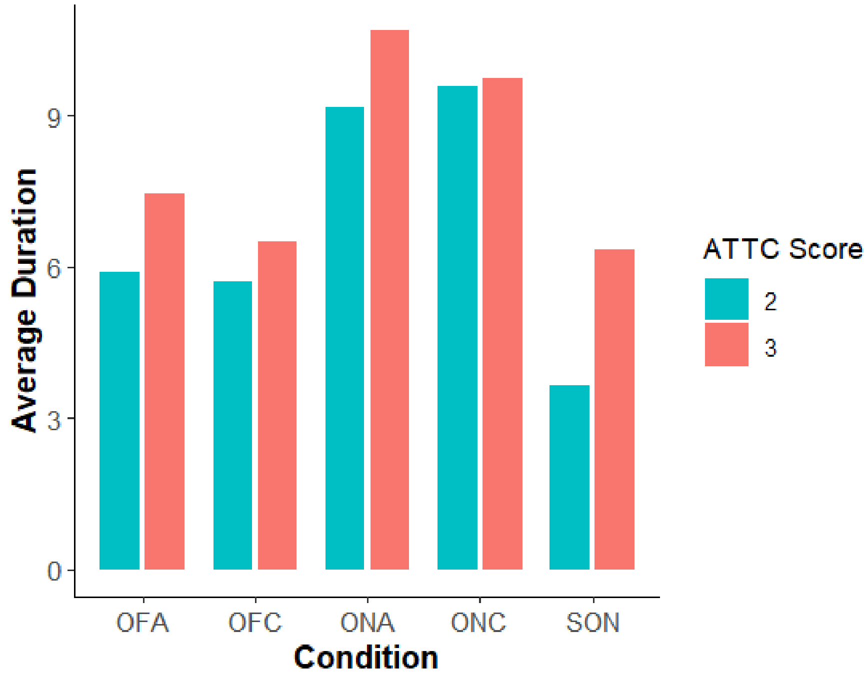


Note. Motivation scores are summed for each participant and averaged across participants.

Appendix 9

Figure 20

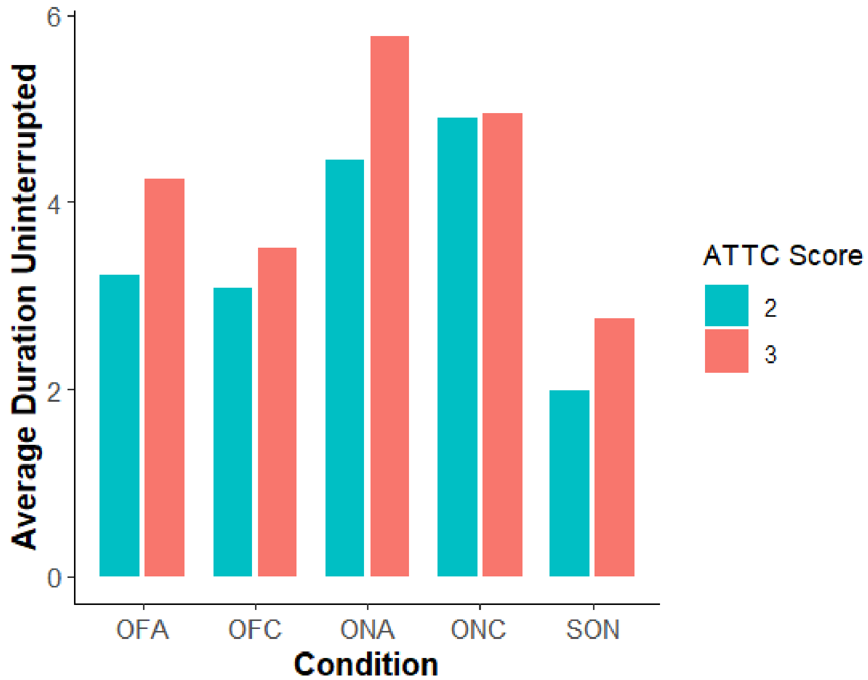
Average Duration Scores per Condition with ATTC score



Note. 2 = lower attention, 3 = higher attention

Figure 21

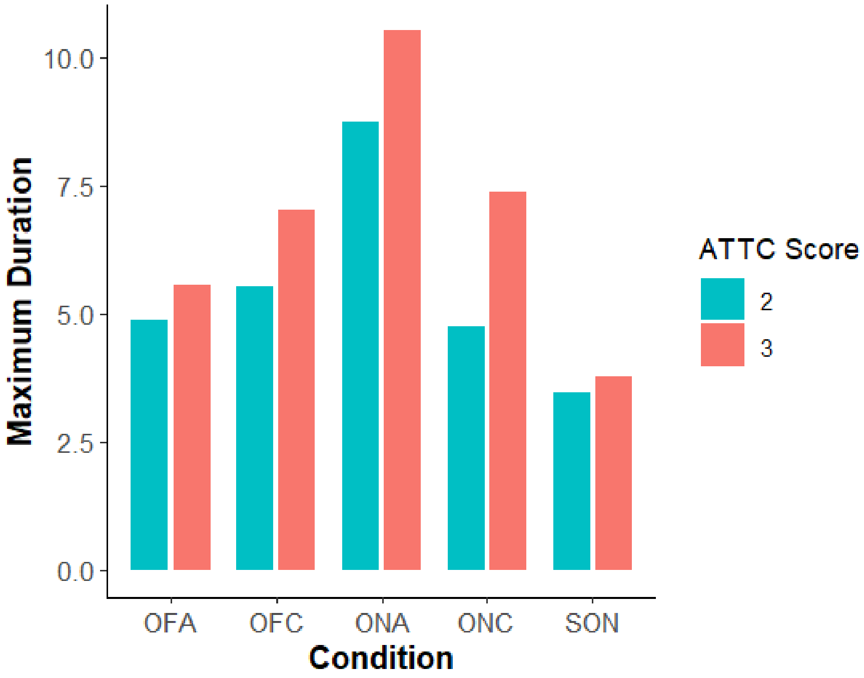
Average Duration Uninterrupted Scores per Condition with ATTC score



Note. 2 = lower attention, 3 = higher attention

Figure 22

Maximum Duration Scores per Condition with ATTC score



Note. 2 = lower attention, 3 = higher attention

Appendix 10

Figure 23

Average Duration Scores per Gender

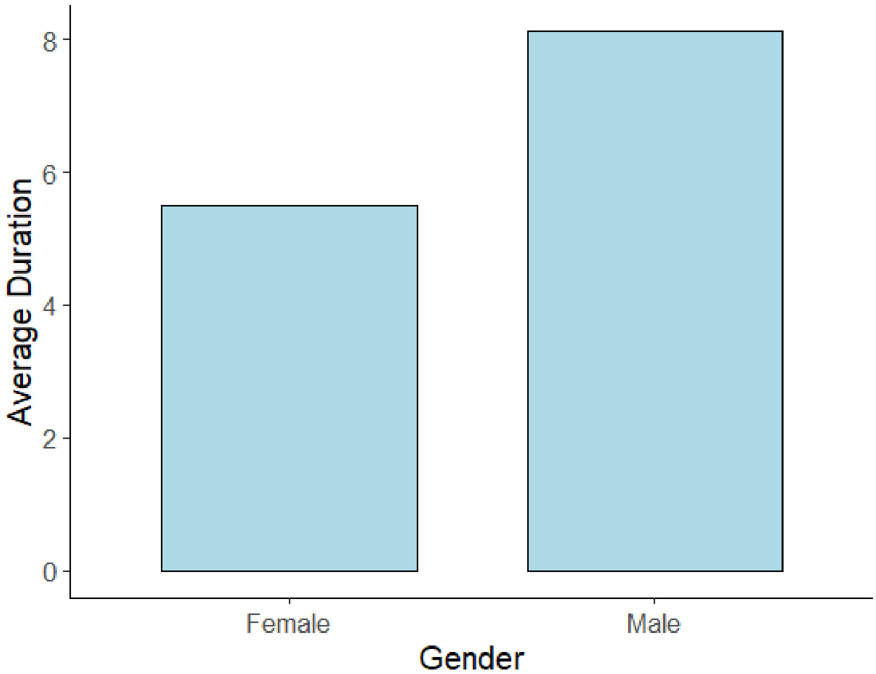


Figure 24

Average Duration Uninterrupted Scores per Gender

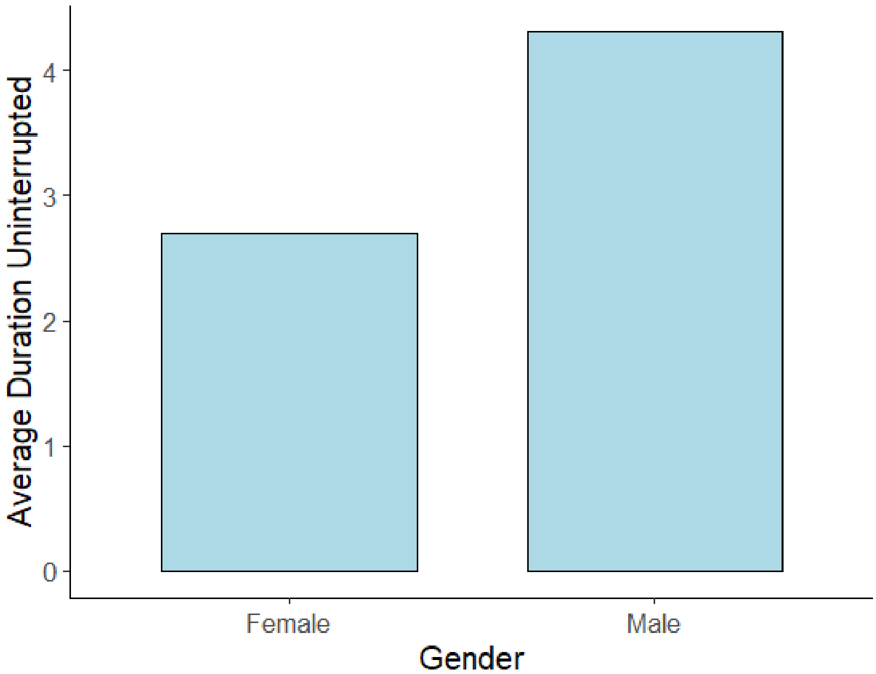


Figure 25

Maximum Duration Scores per Gender

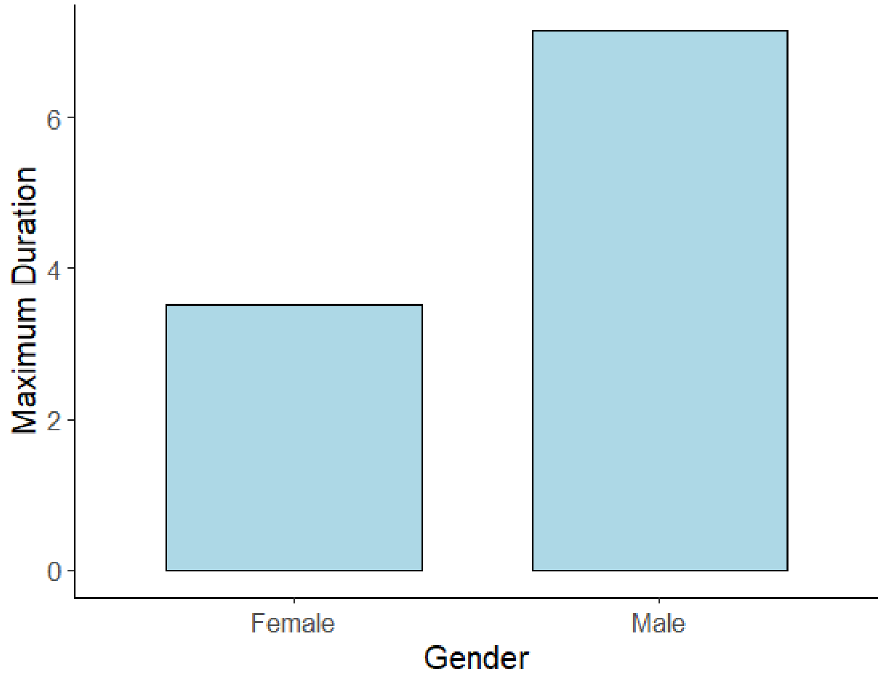


Figure 26

Average Stimulation Intensity Values per Gender

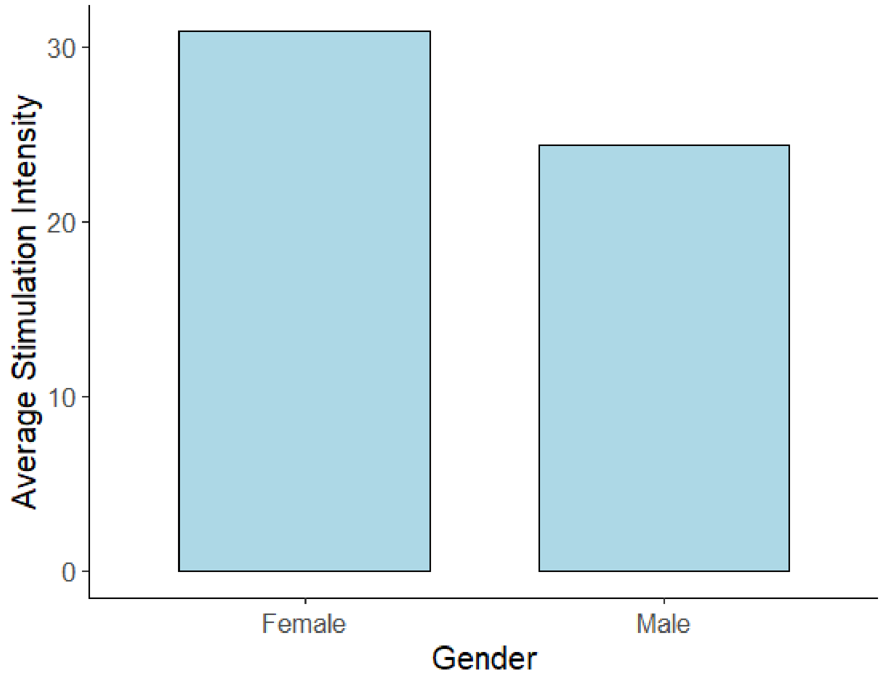
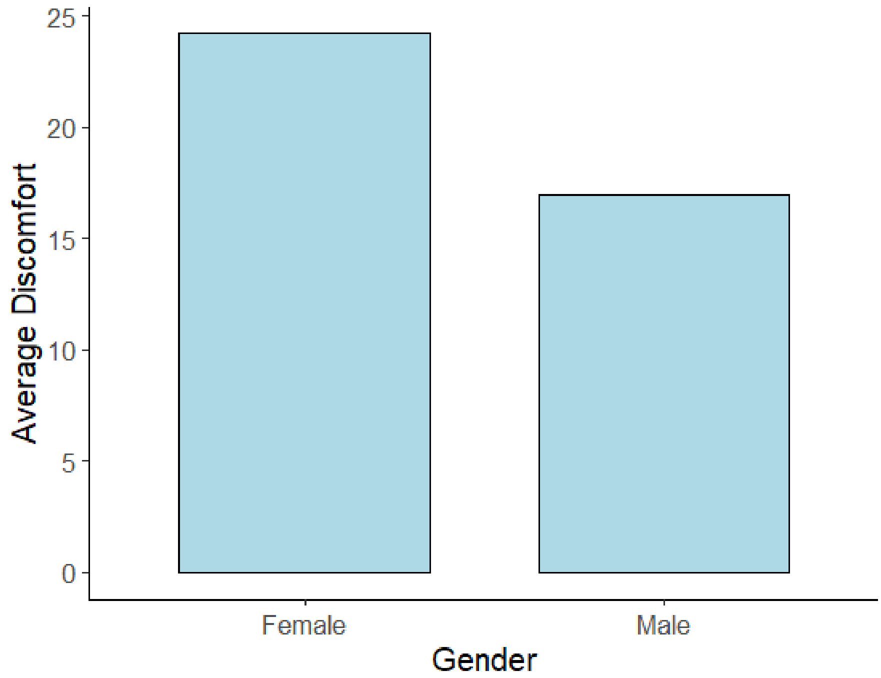


Figure 27

Average Discomfort Values per Gender



Appendix 11

Table 8

Shapiro-Wilk Test Results of Average Duration per Condition

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.962	26	.441*
OFC	0.991	26	.997*
ONA	0.934	26	.095*
ONC	0.947	26	.202*
SON	0.952	26	.263*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Table 9

Shapiro-Wilk Test Results of Average Duration Uninterrupted per Condition

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.957	26	.33*
OFC	0.962	26	.423*
ONA	0.886	26	.008
ONC	0.882	26	.006
SON	0.961	26	.403*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Table 10

Shapiro-Wilk Test Results of Maximum Duration per Condition

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.913	26	.03
OFC	0.943	26	.161*
ONA	0.847	26	.001
ONC	0.878	26	.005
SON	0.93	26	.077*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Appendix 12

Table 11

Shapiro-Wilk Test Results of Switch Frequency per Condition

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.987	26	.981*
OFC	0.966	25	.539*
ONA	0.962	26	.428*
ONC	0.567	26	.001
SON	0.961	25	.436*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Table 12

Shapiro-Wilk Test Results of Rotation Magnitude per Condition

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.933	26	.091*
OFC	0.975	25	.766*
ONA	0.85	26	.001
ONC	0.925	26	.059*
SON	0.926	25	.071*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Appendix 13

Table 13

Shapiro-Wilk Test Results of Average Duration per Condition for Sessions 1-3

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.965	16	.752*
OFC	0.96	15	.697*
ONA	0.921	16	.176*
ONC	0.816	16	.005
SON	0.969	15	.848*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Table 14

Shapiro-Wilk Test Results of Average Duration Uninterrupted per Condition for Sessions 1-3

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.954	16	.55*
OFC	0.98	15	.972*
ONA	0.875	16	.033
ONC	0.709	16	< .001
SON	0.976	15	.93*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Table 15

Shapiro-Wilk Test Results of Maximum Duration per Condition for Sessions 1-3

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.91	16	.116*
OFC	0.932	15	.296*
ONA	0.878	16	.036
ONC	0.891	16	.058*
SON	0.743	15	< .001

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Appendix 14

Table 16

Shapiro-Wilk Test Results of Average Duration per Condition for Sessions 3-5

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.933	16	.27*
OFC	0.964	16	.726*
ONA	0.926	15	.241*
ONC	0.959	15	.68*
SON	0.907	16	.102*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Table 17

Shapiro-Wilk Test Results of Average Duration Uninterrupted per Condition for Sessions 3-5

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.932	16	.266*
OFC	0.946	16	.432*
ONA	0.863	15	.026
ONC	0.916	15	.168*
SON	0.925	16	.205*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.

Table 18

Shapiro-Wilk Test Results of Maximum Duration per Condition for Sessions 3-5

Condition	Statistic	Degrees of Freedom	Significance
OFA	0.939	16	.331*
OFC	0.901	16	.084*
ONA	0.845	15	.015
ONC	0.866	15	.03
SON	0.945	16	. 415*

Note: Values marked with a * did not reach significance. Not statistically significant values indicate that the assumption of normality is met.