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Shocking advantage! Improving digital game performance using non-invasive brain stimulation

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A B S T R A C T

As digital gaming has grown from a leisure activity into a competitive endeavor with college scholarships, celebrity, and large prize pools at stake, players search for ways to enhance their performance, including through coaching, training, and employing tools that yield a performance advantage. Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that is presently being explored by esports athletes and competitive gamers. Although shown to modulate cognitive processing in standard laboratory tasks, there is little scientific evidence that tDCS improves performance in digital games, which are visually complex and attentionally demanding environments. We applied tDCS between two sessions of the Stop-Signal Game (SSG; Friehs, Dechant, Vedress, Frings, & Mandryk, 2020). The SSG is a custom-built infinite runner that is based on the Stop-Signal Task (SST; Verbruggen et al., 2019). Consequently, the SSG can be used to evaluate response inhibition as measured by Stop-Signal Reaction Time (SSRT), but in an enjoyable 3D game experience. We used anodal, offline tDCS to stimulate the right dorsolateral prefrontal cortex (rDLPFC); a 9 cm^2 anode was always positioned over the rDLPFC while the 35 cm^2 cathode was placed over the left deltoid. We hypothesized that anodal tDCS would enhance neural processing (as measured by a decrease in SSRT) and improve performance, while sham stimulation (i.e., the control condition with a faked stimulation) should lead to no significant change. In a sample of $N = 45$ healthy adults a significant session x tDCS-condition interaction emerged in the expected direction. Subsequent analysis confirmed that the statistically significant decrease in SSRT after anodal tDCS to the rDLPFC was not due to a general change in reaction times. These results provide initial evidence that tDCS can influence performance in digital games.

1. Introduction

In 2019, 55–67% of the global online population play digital games (Newzoo, 2018), with consumer spending on games exceeding $134 billion USD (Ibid). Playing games on computers, gaming consoles, or mobile devices is now a leading leisure activity of choice: there are approximately 200 million gamers in North America, 354 million in Europe, 330 million in the Middle East and Africa, 234 million in Latin America, and 1.2 billion in Asia (Ibid). Further fueling the popularity of digital game play is the rise of *esports*, which refers to: "*competitive gaming at a professional level and in an organized format (a tournament or league) with a specific goal (*i.e., *winning a champion title or prize money) and a clear distinction between players and teams that are competing against each other.*" (Newzoo, 2019). With the advent and rapid adoption of streaming services (e.g., Twitch.tv) that broadcast game play and game competitions, global esports revenues exceeded $1 billion USD last year (Newzoo, 2019). Over 495 million people are predicted to watch esports in 2020 (Ibid) and there is continued anticipated growth in viewership, driven largely by its popularity among young viewers.

As digital gaming has moved beyond a leisure activity into a competitive endeavor, there has been an accompanying rise in esports college scholarships (e.g., University of California, Irvine), professional esports teams, gaming celebrity culture, and prize money (Newzoo, 2019), with winners of large esports tournaments winning more money than winners of the Wimbledon tennis championship or the Masters golf championship (Jon Fingas 2019; Brian Lloyd 2019). With significant

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prize money, college scholarship funding, celebrity, and reputation on the line, players seeking to optimize their performance will spend significant time training, practicing gaming skills, and searching for tools that will yield competitive advantages.

One such performance-enhancing tool is transcranial direct current stimulation (tDCS), in which electrodes are applied to the scalp, and direct current flows from an active to a reference electrode, partly being deflected by the scalp and the rest being delivered to the brain tissue (Miranda et al., 2006), thereby inducing diminutions or enhancements of cortical excitability (Nitsche et al., 2008). Reports have emerged that regular and esports athletes are turning to tDCS to improve acute cognitive processing (e.g., Burstyner, Varter & Farrell, 2016; Cogiamanian et al., 2007; Okano et al., 2015; Vitor-Costa et al., 2015). Studies have shown that tDCS can modulate cognitive processes such as response inhibition in the Stop-Signal Task (Friehs and Frings, 2018, 2019a; Hsu et al., 2011; Kwon and Kwon, 2013; Stramaccia et al., 2017), interference control in the Stroop task (Frings et al., 2018; Jeon and Han, 2012; Loftus et al., 2015) and working memory (Friehs and Frings, 2019b; Oliveira et al., 2013), and although digital games are comprised of a range of perceptual, attentional, and cognitive skills that can be trained (Bediou et al., 2018), there has been no previous scientific application of tDCS to digital gaming. It is unclear if tDCS is effective only in controlled tasks, or if its efficacy in modifying and enhancing cognitive processes extends to tasks as complex and cognitively demanding as digital games. If tDCS modulation of performance in a digital game is successful, the present study makes two important contributions to literature. First, it demonstrates that cognitive performance results seen in controlled laboratory tasks can transfer into more ecologically-valid contexts with greater complexity and demand. Second, it suggests that tDCS has the potential to acutely improve performance in digital games, with implications for training and competition.

1.1. Measuring response inhibition

To measure response inhibition in the laboratory, the Stop-Signal Task (SST) was developed (Lappin and Eriksen, 1966; Logan et al., 1984). In the laboratory, the SST measures response inhibition capabilities in an ideal, distractor free setting, and has been used as a measure of response inhibition for over 50 years (Lappin and Eriksen, 1966; Logan et al., 1984; Logan et al., 1997; Verbruggen et al., 2019). Participants are usually seated inside a laboratory and presented with some simple choice reaction time task. Thus, a participant might be tasked to react as fast and as correct as possible to the direction on an arrow pointing either to the left or right. The arrow in this example acts as the go-stimulus that initiates the response. However, on a small subset of all trials a stop-signal is presented after the go-stimulus. Stop-signals usually are displayed either auditorily or visually and the stop-signal signifies that the participant should try to withhold the already initiated go-response. Generally speaking, when the delay between the go and stop signals (termed stop-signal delay; SSD) is increased, inhibition is more difficult, whereas when SSD is shorter, successful inhibition becomes more likely. Ordinarily, only task-relevant stimuli are presented during an SST. The resulting measurement of response inhibition, although precise, arguably does not generalize to stopping in digital games, which are complex visual environments with large amounts of information to be processed.

1.2. Selection and reaction in complex environments

Investigating and understanding response inhibition in visually complex environments provides an opportunity to look into attentional processes influencing the stopping of an already initiated action. For example, an e-sports athlete might have to stop advancing towards the enemy because a trap was spotted. Spotting the trap might be easier when no additional information has to be processed and the environment is free from distractors. In an everyday environment, a table-tennis player might have to decide to not return the serve if the ball goes wide or a person will stop their movement towards the stovetop once it is clear the heating element is still hot. In addition to response inhibition being important for daily human life, several psychiatric disorders such as such as substance abuse, binge-eating, problem gambling, attention-deficit-hyperactivity-disorder (ADHD) and obsessive compulsive disorder have been associated with decreased inhibition capabilities (Goudriaan et al., 2006; Lijffijt et al., 2005; Lipszyc and Schachar, 2010; Woolley et al., 2008). Thus, effective and efficient response inhibition is crucial for everyday behavior, especially in crowded environments. On the level of fundamental cognitive processes, there are two lines of research to be considered; research with a narrower focus on complex stopping tasks, and a more general approach detailing selection as well as reaction in complex environments. In general, research has demonstrated that with increasing perceptual demands, a participant's performance—as measured by error rates or reaction times—suffers.

First, Verbruggen and colleagues recently investigated the influence of visual distractors and peripheral stop-cues on stopping performance (Verbruggen et al., 2014), and results show that perceptually distracting stimuli impair stopping and general reaction speed. Similarly, Wessel & Aron utilized a more complex Go/No-Go task (Wessel and Aron, 2014) in which participants had to remember a specific combination of stimuli and only withhold their response whenever this feature-combination was displayed again. The authors showed that the go-reaction time (go-RT) increased as a function of feature matches (i.e., the higher the feature overlap between the presented and the stop display, the slower the RT). In a gaming environment, a player might encounter the enemy forces several times and only this time is this special unit hidden in the enemy army. After having fought the same enemy army multiple times, it can be hard to notice the singular change and modify behavior accordingly. These ideas are in line with the capacity sharing account (Verbruggen and Logan, 2015), which states that as cognitive demands increase (e.g., via selective and more complex stopping rules, low discriminability or intensity of the stop-signal), the processing rates for individual stimuli decrease and RTs are slowed. Additionally, Verbruggen, McLaren & Chambers proposed that stopping as a form of action control is also dependent on sensory processing; or put differently, detecting the stop-signal is the first step towards successful inhibition (Verbruggen et al., 2014).

Second, in complex visual search the prominent guided search model (Wolfe, 2010, 1989) as well as the multiple weighting system assumes that in order to perform a task correctly, a participant has to first search and select the target, second to discriminate and analyze the target, and third to plan and execute the response to the target (Nordfang et al., 2013; Rangelov et al., 2012; Zehetleitner et al., 2012, 2012). Generally models within the field similarly assume that visual attention and search is influenced by stimulus-driven factors (e.g., based on local contrast) and goal-directed guidance (e.g., based on task rules) (Gaspelin and Luck, 2018; Lamy and Kristjansson, 2013; Nordfang et al., 2013; Rangelov et al., 2012; Theeuwes, 2018; Travis et al., 2018). Thus, an object will be more likely to capture attention if it has a high local feature contrast (i.e., bottom-up saliency) and the object is significant for task-goal completion (i.e., top-down relevance) (Nordfang et al., 2013; Zehetleitner et al., 2012). In the case of a video-game, imagine a player in a real-time strategy game. At any given moment in a battle between the armies a lot of information is presented on screen. A player has to select the target (e.g., a vulnerable or high-value enemy unit), discriminate it against the background, and find it in the enemy army and afterwards execute a response (e.g., have friendly units attack). If the target is highly salient (e.g., the unit is brightly colored or has increased size) it is easy to identify. Importantly, a player will also be able to identify a less visible unit (e.g., a cloaked unit may appear as a shimmer on screen) because the player knows what to look for.

Importantly for the present paper, regardless of whether or not a focused, task-based or a wider, more general perspective is taken, prevailing theories assume top-down cognitive processes are able to

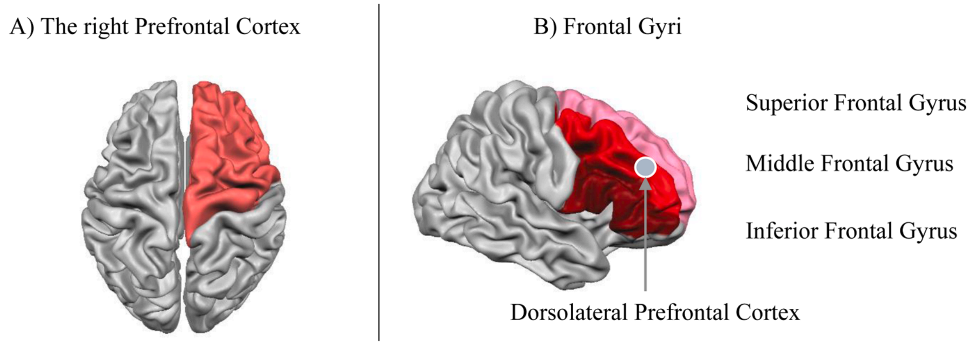

Fig. 1. A) The right prefrontal cortex. B) Superior (pink), middle (light red) and inferior frontal (dark red) gyrus. The approximate location of what is usually called the Dorsolateral Prefrontal Cortex is represented by a gray circle. Please note that these figures somewhat simplify the structure of the prefrontal cortex.

modulate the attentional focus during task performance and potentially mediate between perception and action. Thus, any means by which those cognitive processes can be influenced, will in turn modulate task performance.

1.3. *Underlying neural processes*

Results from patient studies with prefrontal cortex damage (Aron et al., 2003) or ADHD; (Lijffijt et al., 2005) demonstrate that the response inhibition process (i.e., the process of withholding an already initiated action) is affected by alterations in the prefrontal cortex. Importantly, it has been shown that the response inhibition process as measured by the SST is malleable on an individual level either, for example, by means of training (Kramer et al., 1999; Tsai, 2009; Wang et al., 2013) or by transcranial direct current brain stimulation (Friehs and Frings, 2018, 2019a; Hsu et al., 2011; Kwon and Kwon, 2013; Stramaccia et al., 2017). In short, several neuroimaging studies revealed a right-lateralized activation in the prefrontal cortex and several areas have been implicated consistently in the stopping process (See **Fig. 1A**) (Aron et al., 2004, 2014). The prefrontal cortex can be divided into three gyri according to their relative location: inferior, middle and superior frontal gyrus. Of special importance to the present study is a specific area within the MFG, the dorsolateral prefrontal cortex (DLPFC) (See **Fig. 1B**). An investigation into inhibitory regulation across domains revealed several important pathways involved in inhibition and their hierarchical structure (Depue et al., 2016). Results suggest that influence of the right middle frontal gyrus and with it the DLPFC influence other areas to initiate the inhibition of an action (see also Swann et al., 2012, 2013). The authors conclude that the right MFG sits atop the functional hierarchy and incorporates processes that enable information maintenance and goal-directed information updating. This is in line with other models that propose that parts of the prefrontal cortex are responsible for biasing information according to the task-goal and do not act themselves but rather exert control over other areas to carry out a desired response (Fuster, 2015; Miller and Cohen, 2001; Shulman et al., 2009). tDCS as a method of non-invasive brain stimulation can be categorized by polarity (anodal vs. cathodal stimulation of an area) and time (online stimulation during the task vs. offline stimulation before the task). Online tDCS effects (i.e., tDCS after-effects) revolve around subthreshold modulation of membrane potentials and the subsequent change in synaptic activity (Stagg and Nitsche, 2011). During anodal tDCS, online stimulation effects lead to a depolarization of the neurons under the electrode by increasing Na+ and Ca2+ ion flow into the cell (Gazzaniga et al., 2014; Liebetanz et al., 2002; Nitsche et al., 2003, 2005). Once the cell is sufficiently depolarized, voltage-gated ion-channels open. Additionally, small vesicles containing glutamate located in the presynaptic axonal terminal fuse with the presynaptic membrane at the synapse. Because the postsynaptic cell is already depolarized, the released glutamate binds to post-synaptic α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) and *N*-methyl-ᴅ-aspartate (NMDA) receptors and increases the expression of AMPA receptors (Blanke et al., 2009; Zhu et al., 2016). This increase in excitability (i.e., neuron depolarization), and the rise in glutamate concentrations accompanied by a decrease in gamma-aminobutyric acid (GABA) concentrations triggers positive backwards propagating potentials, which in turn increase synaptic strength and evoke plasticity similar to long-term potentiation (LTP) (Lisman, 2001; Lisman and Spruston, 2005; Stagg and Nitsche, 2011). The increase in neural activity and excitability due to anodal tDCS is typically associated with an increase in cognitive performance.

It has been shown that the DLPFC in general is sensitive to neuromodulation via tDCS, when combined with the SST (Ditye et al., 2012; Friehs and Frings, 2018, 2019a; Hayduk-Costa et al., 2013; Liang et al., 2014; Stramaccia et al., 2017), interference control tasks (Friehs et al., 2019; Frings et al., 2018; Loftus et al., 2015) and working memory (Dedoncker et al., 2016; Friehs and Frings, 2019b; Hoy et al., 2013; Jeon and Han, 2012).

Taken together these results provide substantial evidence that the cognitive stopping process is dependent on the right prefrontal cortex and that this area is sensitive to neuromodulation.

1.4. *Digital gaming and response inhibition*

Although this large body of work demonstrates response inhibition in the laboratory and identifies the underlying neural mechanisms, this previous body of work has shortcomings with regards to its ecological validity and generalization to more complex, ‘realistic’ environments, such as digital games. Measuring response inhibition capabilities in a laboratory setting is valuable but fails to generate information about how humans cope with increasing situational complexity. Is response inhibition influenced by tDCS within the context of digital game play, in which there is greater visual complexity and attentional demand? The Stop-Signal Game (SSG; Friehs et al., 2020) is a 3D game in the infinite runner genre that is based on the SST (Verbruggen et al., 2019), and has been evaluated relative to the SST, satisfying all quality criteria while retaining measurement validity (Verbruggen et al., 2019) and being preferred by participants (Friehs et al., 2020). In detail, previous research has shown that the SSG leads to higher levels of intrinsic motivation and flow experience in participants compared to the SST (Friehs et al., 2020). An increased autotelic experience and a more unambiguous feedback led to an overall higher flow experience, as evidenced by the significant contribution of the aforementioned subscales. The increased motivation overall was mainly driven by a significantly higher evaluation of interest in and enjoyment of the SSG as compared to the SST. As such, the SSG can measure response inhibition in a digital game.

The SSG exhibits the same properties as the regular SST, apart from an increase in visual complexity and being generally more enjoyable for

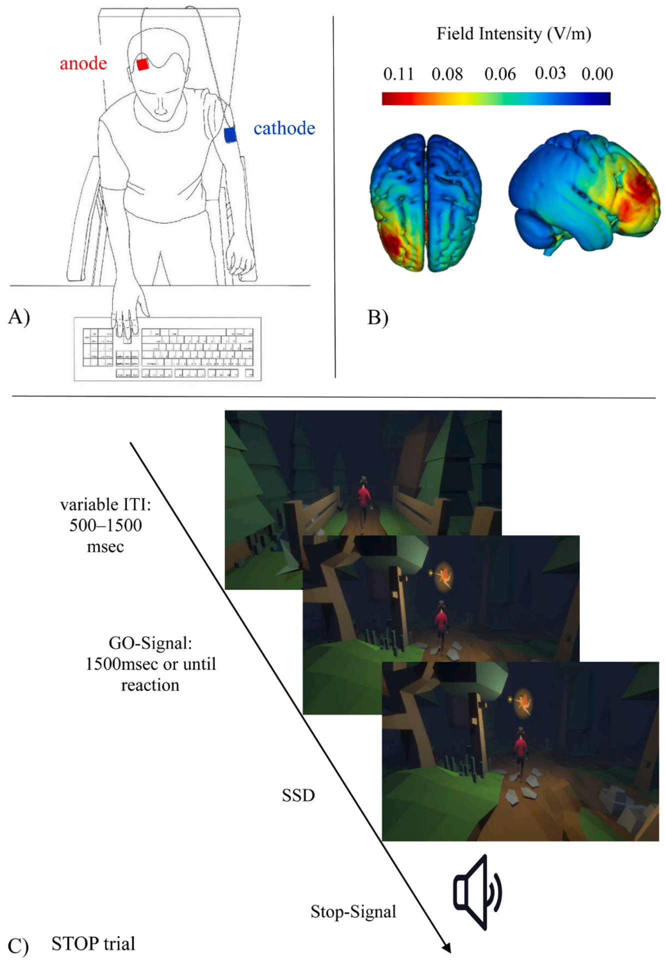

Fig. 2. **A**) Transcranial DC stimulation (tDCS) electrodes were positioned over F4 and left deltoid. **B**) DC flow during anodal stimulation using the HD-Explore software (Version 3.0, Soterix Medical Inc., New York, NY). The Montreal Neurological Institute and Hospital (MNI) 152 template was used for the magnetic resonance imaging (MRI) overlay. **C)** Exemplary, visual representation of a STOP trial in the context of the game.

participants. Mirroring the ordinary SST exactly, but enhancing ecological validity through visual complexity, the SSG required the participants to react to a visual stimulus (i.e., left or right pointing fairy sprite on the screen); on a random subset of trials an auditory stop-signal (i.e., beep-sound) was presented, which required subjects to withhold their already initiated response (see **Fig. 2C** for a static representation of a stop-trial). Importantly, Friehs and colleagues (Friehs et al., 2020) showed that the SSG produces a reliable inhibitory response comparable to the regular SST although participants responded somewhat slower. This slowing in overall reaction speed can be attributed to the increase in visual content that needs to be processed (Verbruggen et al., 2014). Overall, it can be assumed that the described SSG taps into the same cognitive processes and brain areas that are needed for response inhibition in the ordinary SST, but in a more ecologically valid game-like environment. Although the SSG can be considered more ecologically valid than the ordinary SST, it is not yet comparable to most commercial off-the-shelf digital games. Games can place a lot of demands on a player, which can involve the tracking of several different things in working memory and ignoring distractors in several modalities. Thus, the SSG can be considered as a clean, yet game-like context for measuring response inhibition, without any additional strain put on the player.

1.5. *The present study*

The present study set out to extend previous findings on tDCS modulation of SST performance in a visually complex task that is more similar to a digital game. In detail, we aim to provide evidence that non-invasive brain stimulation modulates performance in a digital game. To this end, we used anodal tDCS in combination with a visually complex Stop-Signal Game (SSG) (Friehs et al., 2020) to measure and modulate inhibitory capabilities in a pre-post design. Since the SSG was conceptually identical to a standard SST, we hypothesized that manipulation of rDLPFC activity by means of anodal offline tDCS would lead to an improvement in the cognitive processes involved. We expected a tDCS specific modulation of the purely cognitive performance measure while overall RTs should not be influenced by the stimulation. Nevertheless, because overall RTs and error rates are tied to visual selection or motor response speed we expected them to be higher in the SSG compared to the standard SST performance norms observed in the literature. However, a previous study comparing the SST and SSG did not find a significant performance difference between or within participants (Friehs et al., 2020). To reiterate, only the measure related to the cognitive inhibition process (i.e., SSRT) should interact with tDCS, while all other performance measures (i.e., RTs and error rates) should not be influenced by the stimulation but may be higher due to the situational complexity of the task. Based on previous tDCS studies modulating SSRT (Friehs and Frings, 2018, 2019a) the electrode was positioned over the rDLPFC (F4-position; right middle frontal gyrus) (Okamoto et al., 2004), while a larger electrode was placed over the left deltoid. The deltoid position for the reference electrode was chosen in order to avoid stimulation of other brain areas and to keep the stimulation as focal as possible. Similar setups have been used successfully before (Friehs and Frings, 2018, 2019b, 2019a, 2020; Friehs et al., 2019). Participants completed two SSG sessions separated by twenty minutes of tDCS in either the prefrontal anode or sham condition.

2. Experiment

2.1. *Method*

2.1.1. *Sample*

Forty-eight, right-handed students (thirty-seven female, eleven male) aged 18–29 (mean age 21.76 ± 2.29) participated in the study. Handedness was determined by self-report. We only recruited right-handed participants because the reference electrode was placed extracephalically over the left deltoid and the task required participants to react with their right hand. All participants had normal or corrected to normal vision and normal hearing. Participants were excluded from the study if information provided suggested prior neurological, psychiatric, or cardiovascular diseases. Furthermore, subjects were excluded if they recently consumed illegal drugs or alcohol the previous night. The study was approved by the local ethics committee of the University of Trier. All participants provided written informed consent.

From our previous studies on the modulation of SST performance (Friehs and Frings, 2018, 2019a) we expected an effect of $f = 0.33$ and a medium sized correlation between measures of $r = 0.4$. Together with an α-value of 0.05 and a power of $1 - \beta = 0.95$ a sample of at least 38 participants was planned to find a similar effect. Calculations were carried out using G.Power 3.1.3 (Faul et al., 2007).

2.1.2. *tDCS*

Direct current was provided by a constant current stimulator (4-channel-DC-stimulator by NeuroConn, Ilmenau). In the anodal as well as the sham condition (i.e., the control condition with faked stimulation), one electrode of 9 cm^2 (3 × 3 cm) was positioned over the right DLPFC (F4 position according to the extended 10–20 electrode reference system; (Chatrian et al., 1988)), while the 35 cm^2 (5 × 7 cm) reference electrode was applied over the left deltoid muscle (**Fig. 2A**). The F4 position translates to a maximal stimulation of the right MFG (Okamoto et al., 2004). In the anodal stimulation condition, a constant current of 0.5 mA was applied for 19 min. There was a ramp up/ramp down period of 30 s at the start and end of the direct current stimulation. This resulted in a current density of 0.056 mA/cm^2 and 0.014 mA/cm^2 respectively. In the sham condition, a ramp up/ramp down phase of 30 s each was included at the start and right at the end of the supposed stimulation. This procedure provided participants with the sensation of being stimulated throughout the experiment without actually causing any neurological changes. This procedure has been used effectively in several studies before (Friehs and Frings, 2018, 2019v, 2019a, 2020; Friehs et al., 2019). **Fig. 2B** depicts the calculated current flow. The stimulation was controlled via a panel PC. Prior to the study current flow patterns over the stimulated brain regions were simulated using the HD-Explore software (Soterix Medical Inc., New York). This simulation of current flow given the tDCS procedure is important to verify the stimulation of the intended area. After the tDCS procedure at the end of the experimental session, we asked participants to fill out a questionnaire about the side-effects of the stimulation. Participants had to rate the following symptoms on a scale from 0 to 100: itching, tingling, heating up under the electrodes, induced headache and uneasiness. Additionally, participants were asked to rate the overall intensity of the side-effects during the ramp-up, plateau and ramp-down phase of the stimulation, corresponding to the beginning, middle and end of the stimulation. Participants were not told how long each phase of the stimulation lasted and participants were naïve to the stimulation condition they were assigned.

2.1.3. Stop-signal game

Participants were seated in front of a 19-inch color monitor with a viewing distance of 65 cm in a normally lit room. Participants responded only using their right hand by pressing one of two marked keys on a keyboard in front of the monitor. A visually complex Stop-Signal Task in the form on an infinite runner was implemented using the Unity engine (for technical details please refer to Friehs et al., 2020). Although visuals differed, the underlying SST architecture was based on SST used in the past and followed all recommendations for the use of the SST by Verbruggen and colleagues (Verbruggen et al., 2019; Verbruggen and Logan, 2008, 2009). Apart from the SSG mirroring the ordinary SST in task functionality, the SSG present the participants with a cover story that helps motivate their performance. Participants were told they were lost in a haunted forest and a fairy would help them escape it by pointing either to the left or right at every crossroads. However, an evil witch is able to take on the appearance of the fairy in order to trick the player into going deeper into the haunted woods but the witch can be detected by an audio-cue. **Fig. 2C** depicts the Stop-Signal Game. The pre-tDCS as well as the post-tDCS session consisted of a total of 300 trials, containing 75% Go- and 25% Stop-trials. The 300 trials were divided into 3 blocks with a 15 second break in between. Participants were instructed to react as fast and accurately as possible to the go-stimulus (i.e., a fairy pointing left or right) with the left or right arrow key and withhold their reaction when a stop-signal (i.e., a noise presented over headphones) occurs. The go-stimulus was presented for a maximum of 1500 msec or until reaction. The stop-signal was played over the headphones following a variable delay (the Stop-Signal Delay, SSD), which was initially set to 250 msec. The SSD was continuously adjusted with the staircase procedure in order to obtain a probability of responding of 50%. After the reaction was successfully stopped (i.e., button press was inhibited), the SSD was increased by 50 msec, whereas when the participants did not stop successfully, the SSD was decreased by 50msec. The inter-trial interval was set to a random value between 500 and 1500msec. **Fig. 2C** depicts the display sequence for the SST.

Several different performance measures were logged and calculated. This encompasses the aforementioned SSD and the probability of making a (wrong) response when a stop-signal is presented (*p(response|signal)*). The *SSD* represents the delay between the onset of the go- and the stop-signal. SSD adjusted in a staircase procedure during task performance as described above and thus, the SSD used for analysis constitutes the final SSD that results from in-game adaption of SSDs. Furthermore, two variables that are directly related to accuracy were logged: first, the amount of *omission errors* (reflecting the probability of missed response on no-signal trials) and second, the *choice errors* (reflecting the probability of a wrong response on no-signal trials). Additionally, two variables that are tied to RTs were logged; *no-signal RT* reflects the speed of a (correct) response on trials without a stop signal, and *signal RT*, which indicates the latency of the incorrectly-executed response on stop signal trials. Furthermore, the probability of a *correct inhibition* (i.e., the likelihood of inhibiting an already initiated action) was recorded for each participant. Most importantly, the stop-signal reaction time (SSRT) could be calculated based on a participant's performance. The estimation of the SSRT was based on the integration method with replacement of omissions (for a detailed description please refer to Verbruggen et al., 2019; Verbruggen et al., 2013). In short, in order to calculate the SSRT, all go-reactions are rank-ordered and go-omissions (i.e., go-trials in which the response was missed) are assigned the maximum RT in order to compensate for the lacking response. Afterwards, the most recent SSD is subtracted from the RT corresponding to the p(response|stop-signal)-percentile. The resulting value is termed SSRT. For example, if a participant performed 100 go-responses and p(response|signal) = 0.5, the corresponding RT is the 50th fastest go-RT. If we assumed this RT was 600 ms and the most recent SSD was 400 ms, the resulting SSRT would be equal to 200 ms. All participants performed the SST prior to and after 20-minutes of anodal or sham tDCS. Since it has been suggested that activation during stimulation can affect the stimulation outcome (Horvath et al., 2014), we provided participants with simple nature documentary magazines in order to reduce the mind from wandering and control for activation during the stimulation period. This procedure has been previously employed in tDCS studies (Friehs and Frings, 2018, 2019b; Friehs et al., 2019).

2.1.4. Procedure

Participants were randomly assigned to one of two tDCS conditions: (1) anodal or (2) sham stimulation of the right dorsolateral prefrontal cortex. Participants were naïve to their assigned condition. Each participant was subjected to a standardized procedure: (1) fill out a questionnaire concerning the exclusion criteria and demographic data, (2) pre-tDCS Stop-Signal Game, (3) tDCS-application, (4) post-tDCS Stop-Signal Game (identical to the pre-tDCS task), (5) side effects questionnaire and hair cleaning of electrode gel. The entire experimental procedure was approximately 90 min from entering to exiting the lab.

2.1.5. Design

The experiment was based on a 2 (session: pre-tDCS vs. post-tDCS) x 2 (tDCS condition: prefrontal anodal vs. sham) mixed design with only the tDCS condition independent variable (IV) being varied between participants. The main dependent variable (DV) was the Stop-Signal Reaction Time (SSRT) (i.e., the estimate of time needed to respond to the Stop signal and to cancel the movement), which is a measure of the covert inhibition process.

2.1.6. Data analysis

Data Analysis was done in three phases: First, in the data reduction stage, we excluded any participant that was uncooperative or produced faulty data. Specifically, participants were excluded if SSRT estimation was not possible, or performance data indicated strategic behavior not in line with the task demands. For details on data reduction please refer to the *Data Reduction* section. Second, SSRT was analysed in order to test our hypothesis that the response inhibition process can be modulated by anodal tDCS; specifically, we expected a reduction of SSRT after anodal offline tDCS. Third, all additionally gathered performance and side-effect measures were analysed in order to explore any additional

Table 1
Mean RTs in milliseconds (standard deviations in brackets below) dependent on time of testing and tDCS condition.

	Anodal				sham			
	signal RT	*no-signal RT*	*SSD*	*SSRT*	*signal RT*	*no-signal RT*	*SSD*	*SSRT*
Pre	892.90	960.06	476.67	460.39	905.64	967.66	496.45	445.21
	(96.88)	(113.97)	(139.36)	(52.92)	(102.88)	(119.44)	(141.38)	(42.68)
Post	912.11	964.82	503.82	439.81	928.16	995.12	524.13	453.82
	(103.93)	(124.99)	(136.94)	(33.73)	(115.51)	(136.95)	(141.47)	(33.19)

Table 2
Mean error rates and accuracy in their relative proportion to the total trial count (standard deviations in brackets below) dependent on time of testing and tDCS condition.

	anodal			sham		
	p (response| signal)	*omission error*	*choice error*	*p (response| signal)*	*omission error*	*choice error*
Pre	.47	.012	.0037	.46	.014	.0033
	(0.02)	(0.019)	(0.0062)	(0.03)	(0.022)	(0.0054)
Post	.46	.009	.0035	.46	.011	.0027
	(0.02)	(0.013)	(0.0036)	(0.02)	(0.016)	(0.0039)

effects tDCS might have had.

2.1.7. *Data reduction*

For the exclusion of participants, we followed the recommendations by Verbruggen and colleagues (Verbruggen et al., 2019; Verbruggen and Logan, 2015). First, we tested the horse-race assumption for every participant by comparing signal-response RT and no-signal RT in the pre- and post-tDCS session. The horse-race assumption states that SSRT can only reliably be estimated if the RT on unsuccessful stop trials is smaller as the mean go-RT. Second, participants were excluded if their p (response|signal) was smaller than 0.4 or larger than 0.6 in either session. Third, outliers were determined based on the Tukey outlier criterion (Tukey, 1977), and removed along with participants who displayed strategic behavior. We characterized a strategic behavior as a high ratio between the overall no-signal RT and the SSRT. Based on these criteria, three participants had to be excluded, resulting in a final sample of forty-five subjects. The anodal tDCS group contained 23 participants (17 female, 6 male) aged 18–29 (mean age 21.87, SD = 2,65). The sham tDCS group contained 22 participants (17 female, 5 male) ages 19–25 (mean age 21.64, SD = 1.89).

3. Results

RT means, SSDs and SSRTs are depicted in **Table 1**. Errors and accuracy rates are depicted in **Table 2**.

In short, the results show that the inhibition process (as measured by SSRT) decreases after anodal tDCS (**Fig. 3B and C**). Signal and no-signal RTs were analyzed; change over time in those measures did not interact with tDCS (**Fig. 3A**). This pattern of results suggests that anodal offline tDCS over the rDLPFC improved the cognitive inhibition process and that this improvement was not due to a general speed-up or slowing-down of responses.

3.1. *Preliminary analysis*

To validate the gathered data, it is recommended to show that there is a statistical difference between the average signal-response time and the average no-signal RT for each experimental condition (Verbruggen et al., 2019; Verbruggen and Logan, 2015). 2 (trial-type: signal vs. no-signal) x 2 (tDCS stimulation: anodal vs. sham) MANOVAs revealed that signal-response time and no-signal RT are significantly different in the pre-tDCS ($F(1, 43) = 265.32$, $p < .001$, $\eta_p^2 = 0.86$) and post-tDCS ($F(1, 43) = 174.09$, $p < .001$ $\eta_p^2 = 0.80$) blocks as indicated by the main effects trial-type. No other effects reached statistical significance, validating our gathered data.

3.2. *SSRT*

SSRT was calculated using the integration method with replacement of omissions (Verbruggen et al., 2019). SSRTs were submitted to a 2 (session: pre-tDCS vs. post-tDCS) x 2 (tDCS condition: prefrontal anodal vs. sham) MANOVA. Both the main effect session ($F(1, 43) = 1.03$, $p = .32$) and tDCS condition ($F(1, 43) = 0.003$, $p = .96$) were not significant, suggesting that SSRT was on average comparable between pre-tDCS and post-tDCS testing as well as between the two stimulation conditions (anodal vs. sham). Importantly, the interaction between time of testing (pre-tDCS vs. post-tDCS) x tDCS stimulation (anodal vs. sham) was significant, $F(1, 43) = 6.09$, $p < .05$, $\eta_p^2 = 0.12$, which shows that changes in SSRT vary depending on the stimulation condition (see **Fig. 3B**). To further explore this interaction, two post-hoc t-tests against zero were carried out to evaluate the SSRT-change over time for each group separately. In detail, the SSRT was significantly shorter following anodal tDCS ($t(22) = 2.98$, $p = .007$) but remained equal after sham stimulation ($t(21) = -0.89$, $p = .39$). These results indicate that the inhibition process was significantly improved by anodal stimulation of the right DLPFC. Furthermore, we employed Bayesian analysis to confirm the significant difference in pre-post changes between the two stimulation groups. Therefore pre-post difference values for the anodal (Δ(anodal tDCS)) as well as the sham group (Δ(sham tDCS)) were calculated and submitted to a Bayesian independent sample *t*-test using JASP. We used a Cauchy prior distribution with $r = 0.707$ and specified the alternative hypothesis; Δ(anodal tDCS) > Δ(sham tDCS). With a Bayes factor of $BF_{10} = 6.25$ the tests provided strong moderate evidence for the alternative hypothesis (Wagenmakers et al., 2011, 2018a,b). Even when considering a more conservative alternative hypothesis in which the direction of the mean differences is not specified the Bayes factor showed moderate evidence for the alternative hypothesis; $BF_{10} = 3.17$. See **Fig. A1** in the appendix for details and the assessment of robustness depending on the width of the prior distribution. To rule out that significant baseline differences influenced the outcome, SSRTs in the pre-tDCS block (i.e., baseline performance) were tested against each other. There was no statistically significant difference between the two tDCS condition groups ($t(443) = -1.06$, $p = .30$) in their baseline performance (see **Table 1**).

3.3. *Error analysis*

Choice errors (i.e., pressing the wrong button after a go signal) and omission errors (i.e., missing a response on no-signal trials) were evaluated. Both types of errors were submitted separately to a 2 (session: pre-tDCS vs. post-tDCS) x 2 (tDCS condition: anodal vs. sham) repeated measures MANOVA. First, for choice errors, the aforementioned analysis did not result in a significant main effect of session, nor a main effect of tDCS condition or a significant interaction between the two (all $F < 1$). Second, for omission errors, both the main effects session ($F(1, 43) = 2.01$, $p = .16$) and tDCS condition ($F < 1$) were not significant, and neither was the two-way interaction ($F < 1$). See **Table 2**.

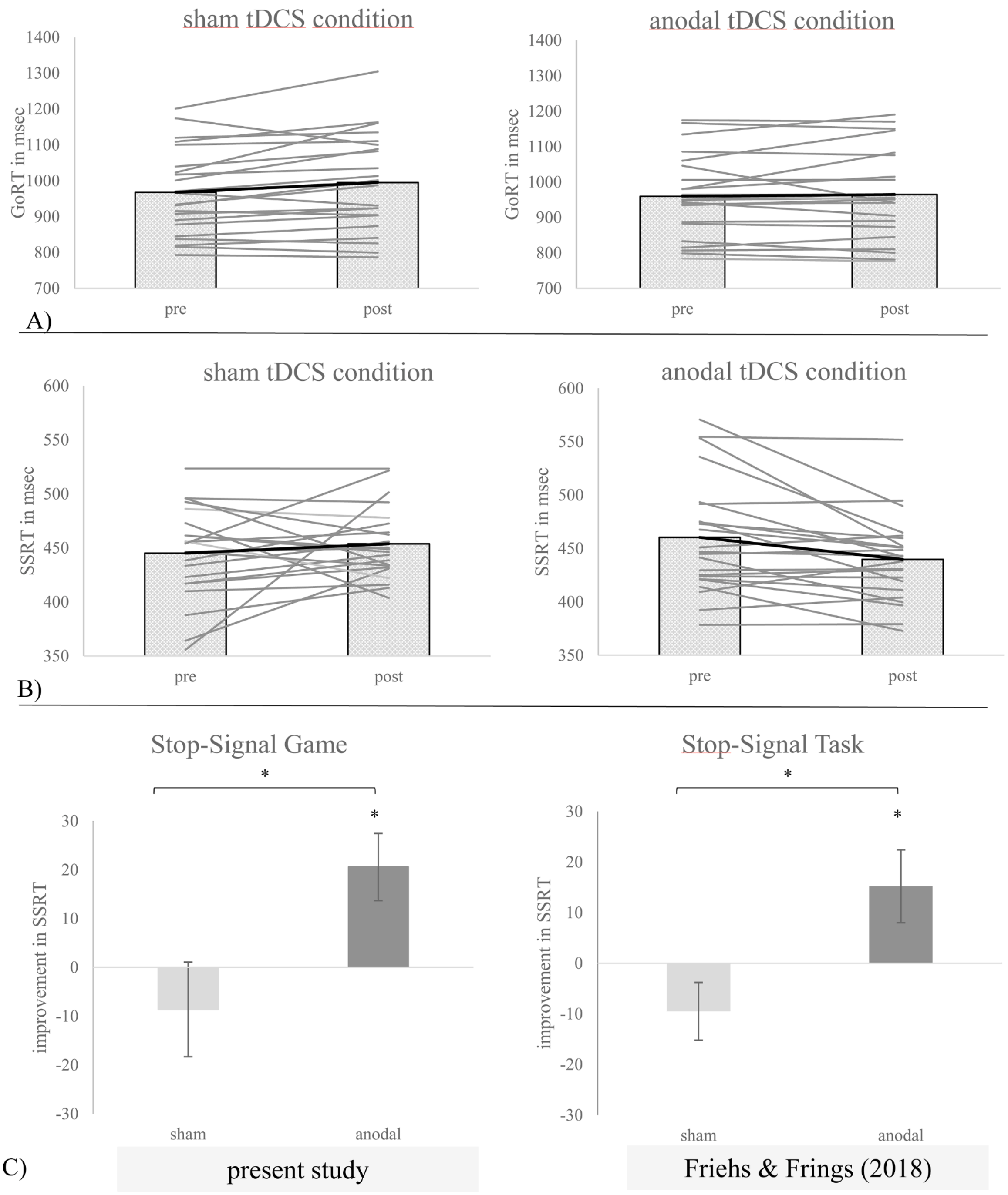

Fig. 3. **A)** Correct Go-RT depending on condition and time. Black line and bars depict the mean. **B)** SSRT depending on condition and time. Black line and bars depict the mean. **C)** Comparison between the results of the present study and Friehs & Frings (2018). * $p < .05$. Standard error of the mean is displayed for each group separately.

3.4. *SSD*

The stop-signal delay is the delay needed between the Go-signal and the onset of the Stop-signal to produce a 50% success rate. SSDs were submitted to a 2 (session: pre-tDCS vs. post-tDCS) x 2 (tDCS condition: anodal vs. sham) repeated measures MANOVA. The main effect session was statistically significant ($F(1,\ 43) = 10.55$, $p < .01$, $\eta_p^2 = 0.20$). Specifically, SSDs on average were larger in session 2 after tDCS ($M = 513.75$, SD = 137.96) compared to session 1 pre tDCS ($M = 486.34$, SD = 139.36), indicating that a larger delay between go and top signal was needed to produce the desired 50% inhibition-failure rate in the second play session. The main effect tDCS condition as well as the interaction of tDCS condition x session failed reached statistical significance (all $Fs < 0$). This indicates that the delay needed to evoke ~ 50% errors after a stop-signal did not vary depending on tDCS condition and did not interact with the factors (**Table 1**).

3.5. *No-Signal RT*

The correct no-signal RT was submitted to a 2 (session: pre-tDCS vs. post-tDCS) x 2 (tDCS stimulation: prefrontal anodal vs. sham) repeated-measures MANOVA. The main effect session ($F(1,\ 43) = 5.94$, $p < .05$, $\eta_p^2 = 0.12$) was significant, but the main effect tDCS condition ($F < 1$) and the two-way interaction ($F(1,\ 43) = 2.95$, $p = .10$) did not reach statistical significance. On average, participants reacted more slowly in session 2 ($M = 979.63$, SD = 130.37) compared to session 1 ($M = 963.78$, SD = 115.40), but importantly this general slowing did not interact with tDCS condition. See **Table 1** and **Fig. 3A**.

3.6. Signal RT

The incorrect signal RTs was submitted to a 2 (session: pre-tDCS vs. post-tDCS) x 2 (tDCS stimulation: prefrontal anodal vs. sham) repeated-measures MANOVA. While the main effect session ($F(1, 43) = 8.78$, $p < .05$, $\eta_p^2 = 0.17$) reached statistical significance, the main effect tDCS ($F < 1$) and the interaction of session x tDCS condition ($F < 1$) did not. In detail, participants had slower incorrect reactions in session 2 ($M = 919.95$, SD = 107.79) compared to session 1 ($M = 899.13$, SD = 98.93), but crucially this effect did not interact with tDCS condition. See **Table 1**.

3.7. Correct inhibition

The ratio of successfully-inhibited trials was submitted to a 2 (session: pre-tDCS vs. post-tDCS) x 2 (tDCS stimulation: prefrontal anodal vs. sham) MANOVA. The main effect session ($F < 1$) as well as the main effect tDCS stimulation ($F < 1$) did not reach significance. However, the interaction between session and tDCS condition was significant ($F(1, 43) = 6.07$, $p < .05$, $\eta_p^2 = 0.12$). Consequently, the pre- and post-tDCS values for p(response|signal) were compared for each group separately. While there was no significant change for the sham condition ($t(23) = -1.10$, $p = .28$), a significant change for the anodal tDCS condition was observed ($t(23) = 3.41$, $p < .05$). In detail, after anodal stimulation, the likelihood of a false response after a stop-signal occurred dropped by 0.006 (SD = 0.01); or, put differently, the likelihood of correctly responding to a stop-signal (i.e., not responding) increased by 0.06%. While the change was statistically significant, it does not seem practically relevant. Overall, these results show that the staircase procedure was successful in adjusting the SSD. See **Table 2**.

3.8. Side-effects

After the experiment, participants were asked to fill out a questionnaire and report the intensity of certain symptoms on a visual analogue scale from 0 to 100. Across anodal and sham stimulation, the most noticeable side effects were, in order of intensity, itching ($M = 26.60$, SD = 29.24), tingling ($M = 25.73$, SD = 18.10), heating up ($M = 11.11$, SD = 20.25), headache ($M = 8.00$, SD = 17.10), and unease ($M = 7.69$, SD = 12.77). Furthermore, after the experiment, the intensity of the stimulation was judged by the participants at the start (ramp-up period), in the middle (plateau-phase), and at the end (ramp-down period). The intensity of the reported stimulation side-effects seemed to decline over time, with side-effect intensity being rated largest during the ramp-up period ($M = 40.11$, SD = 30.03) compared to the plateau-phase ($M = 20.56$, SD = 18.87) and the ramp-down period ($M = 14.71$, SD = 20.00). Taken together this shows that the stimulation had little to no adverse effects on participants.

4. Discussion

This study set out to investigate whether single-session, anodal, offline tDCS over the rDLPFC can enhance the cognitive response inhibition process as measured in a visually complex Stop-Signal Game (SSG). The hypothesis that stimulation of the rDLPFC would result in an enhanced response inhibition process (i.e., a decrease in SSRT) was confirmed; in detail participants improved by 4.5% after anodal stimulation. Furthermore, we reported upon several other significant effects. First, signal and no-signal RTs were slower in session 2 compared to session 1. Similarly, SSDs were larger in session 2. Taken together these results either are a consequence of practice or indicate that participants slowed their responses down in the second session in order to perform better in the task due to the motivational pull of the game (Gee et al., 2012; Grund, 2015; Ryan et al., 2006). Crucially, however, no RT measure (apart from SSRT) interacted with the administered tDCS. Furthermore, the probability to respond given a stop-signal (i.e., p (response|signal)) interacted with tDCS. In detail, after anodal tDCS, the likelihood of correctly inhibiting the response increased by 0.6%. While this result was statistically significant, we are cautious in interpreting such a small effect. Nevertheless, this result is in line with the hypothesized improved response inhibition after anodal tDCS. In sum, our results suggest that anodal tDCS delivered to the rDLPFC can be used to improve the cognitive response inhibition process. These findings are in line and partially replicate previous studies from our lab (Friehs and Frings, 2018, 2019a). It has been suggested that “an important component of stopping is finding a balance between ignoring irrelevant information in the environment and monitoring for the occurrence of occasional stop signals” (Verbruggen et al., 2014) and we propose that our stimulation protocol optimized this balance, which lead to a more efficient monitoring and subsequent stopping processes.

4.1. Theoretical implications

In previous studies employing tDCS (Friehs and Frings, 2018, 2019a) it has been proposed that tDCS over the rDLPFC affects information biasing processes. In detail, the rDLPFC has been proposed to be critically involved in representing task-rules (here: stopping a response whenever a signal occurs) (Aron et al., 2014; Swann et al., 2013), preparing the required action (here: stopping the prepotent response) (Mostofsky and Simmonds, 2008; Pochon, 2001), and episodic retrieval of stimulus-response episodes (Manenti et al., 2012). This is possible due in part to the interconnected nature of the rDLPFC. Crucially, this brain area is connected to the premotor cortex as well as the inferior frontal cortex; both of which have been implicated in the action inhibition process (Aron et al., 2004, 2014; Bates and Goldman-Rakic, 1993; Fuster, 2017; Goldman and Nauta, 1976; Lu et al., 1994; Miller and Cohen, 2001; Schmahmann and Pandya, 1997). Furthermore it has been shown that the rMFG is active during inhibitory regulation of motor responses, memory retrieval and emotional reactivity (Depue et al., 2016). The authors interpret this as evidence for the right MFG playing a higher-order coordination role in inhibition in general across all domains.

Furthermore, patient and animal studies suggest that the DLPFC plays a key role in inhibitory and excitatory control over sensory processing (i.e., suppressing irrelevant and facilitating relevant information) (Bartus and Levere, 1977; Knight et al., 1999, 1989). The suppression of unnecessary, distracting information is of special importance in environments where the stop-signal is presented non-centrally or in a different modality, and the visual field is noisy. In the present study specifically, a failure to suppress the irrelevant visual information might have led to increased neural noise and the regulation of which was enhanced by anodal tDCS. This enhanced attention towards the relevant stopping information resulted in the participant being able to act faster on the stop-signal (as measured by a reduction of SSRT) (Verbruggen et al., 2014).

Taken together, the results of the present study provide another piece of evidence that prefrontal neurostimulation by means of tDCS can modulate human performance; even in visually distracting environments. More specifically, we argue that anodal offline tDCS over the rDLPFC enhances the cognitive response inhibition process by virtue of optimizing and monitoring the stopping process. Depending on the underlying model and focus, the present results could be viewed and explained more specifically from different perspectives. From a neuroscientific standpoint, an improvement in communication with other cortical areas and improved signal suppression of distracting information could be responsible for the observed effect (Cosman et al., 2018; Shulman et al., 2009).

From a purely cognitive psychological perspective, one might argue that an information biasing process has been modulated by modification of attention (i.e., better suppression of distractors and focus on task-relevant information) (Lamy and Kristjansson, 2013; Nordfang et al., 2013). This is supported by results showing that the SST performance is dependent on sensory processing demands (i.e., the implementation of action control is slower when distractors that draw cognitive resources are present) (Verbruggen et al., 2014, 2014). Extending this argument to more realistic environments and situations, it has been shown that cognitive load influences stopping in road traffic (Green, 2000; Summala, 2004). In complex visual search, researchers investigate perception and (re-)action in situations in which the amount of information exceeds the individual's processing capacity. Research shows that selection in complex environments is partially determined by top-down influences (Nordfang et al., 2013; Travis et al., 2018; Zehetleitner et al., 2012). With regards to the present study, one might argue that the enhancement of the processing stage (i.e., discrimination and response selection) was enhanced, which lies in the middle of visual perception and response execution (Liesefeld et al., 2018; Rangelov et al., 2012; Zehetleitner et al., 2012). This processing stage is responsible for analyzing the sensory input and selecting the appropriate response.

It is important to note that the cognitive and neuroscientific explanations are not mutually exclusive but rather just different, converging perspectives. Crucially, regardless of the explanation, based on the results we argue that an (attentional or neurological) information biasing process was modulated by tDCS, which in turn impacted the motor response. Furthermore, this study provides evidence that response inhibition functions similarly in simple and complex environments and it seems clear that the modification of the cognitive response inhibition process is not limited to an ideal environment without visual distractors but can also be transferred to more realistic, noisy settings, such as in digital game play.

4.2. Limitations

The present study has several important caveats. First, although we think it can be argued that the SSG used in the present study is conceptually and structurally identical to the ordinary SST, there are two dimensions on which the two differ: visual complexity and motivational pull. Thus, the underlying cognitive processes and neural correlates in both tasks may not be completely identical and may differ to some degree. This ties into the fact that the average RTs in the SSG were longer compared to the regular SST (Friehs and Frings, 2018, 2019a; Verbruggen and Logan, 2015; Verbruggen et al., 2014). But longer RTs are not surprising because of the amount of irrelevant background graphics and the missing standard fixation cross. Importantly, it has been reported that non-central stop-signals and visual distractors hamper the stopping process (i.e., higher SSRT) and increase overall reaction times (Verbruggen et al., 2014). These results highlight the importance of stimulus detection and attention in SST performance. Similarly, using a complex Go/No-Go Task, it was shown that RTs increase when the number of feature matches between go- and stop-trials increases (Wessel and Aron, 2014), and that higher cognitive demands can lead to higher RTs (Verbruggen and Logan, 2015). Literature shows that RTs increase when the number of (irrelevant) stimuli on screen increases and the saliency of targets decreases (Duncan and Humphreys, 1989; Estes, 1972; Estes and Taylor, 1966; Lavie, 1995; Lavie, 2005). With that being said, the present results on tDCS condition directly replicate those of Friehs & Frings (2018), which suggests a modulation of similar cognitive processes. Furthermore, one might even argue that the SSG is more representative of a real-life, natural environment, while the ordinary SST captures the inhibition process in its purest form and most optimal performance possible due to the low quantity of irrelevant information. It is likely that human inhibitory control in the lab does not necessarily reflect the speed of human inhibitory control in the field. As the Stop Signal Game is a more visually complex task than the standard SST, it represents human inhibitory control in a more realistic and ecologically-valid paradigm, and shows that response inhibition in this more complex environment that resembles a digital game follows the same pattern as in the purer basic SST. For a detailed discussion of the topic of task-similarity, see (Friehs et al., 2020).

Second, tDCS produces a somewhat broad stimulation. Although it was made sure that stimulation focality was maximal over the rDLPFC, it is possible that some current spread to adjacent areas such as the rIFC or the preSMA. If a significant portion of the electric current spread to those areas, the observed tDCS effect could not be fully attributed to the modulation of the rDLPFC.

Third, although the SSG is experienced as more enjoyable than a basic SST (Friehs et al., 2020), it is more representative of casual and mobile games played on a smartphone or tablet than the types of games played in competitive esports contexts. Performance in complex digital games such as multiplayer online battle arenas (MOBA), real-time strategy games (RTS), or first-person shooters (FPS) contain elements of many cognitive processes (Bediou et al., 2018) that are layered and integrated into a single play experience. Our results suggest that cognitive enhancements seen in basic laboratory tasks might extend to digital game contexts; however, more research needs to determine whether these benefits are seen in complex games used in esports and competitive gaming contexts.

Fourth, the SSG employs only basic gamification elements and thus is not necessarily comparable to complex commercial off-the-shelf games. Although our choice of game may make the present results less generalizable to complex commercial games, the use of additional game-like features could have obfuscated the effect of, or interacted with, the tDCS effect. Apart from increased graphical fidelity, the SSG utilizes only narrative elements, and the implied consequence of a player's choice during the game as game elements. Narrative elements and choice were shown to increase motivation and player experience in digital games (e.g., Bowey & Mandryk 2017; Bowey, Friehs & Mandryk 2019) and previous results confirm that the SSG indeed produces a higher intrinsic motivation and flow experience compared to a regular SST (Friehs et al., 2020).

It should be noted that although a player's performance and choice (i.e., go straight, turn left/right) had an implied consequence due to the cover story of being lost in a haunted forest, no actual game-like consequence (e.g., a change in score) was implemented, due to reasons outlined above (see also Friehs et al., 2020). However, player performance had a consequence on the task in two ways; a) the SSD was adjusted in accordance to player performance on stop-trials and b) the players received feedback at the end of each block about their performance.

Nevertheless, future work will have to investigate the influence of tDCS in complex commercial off-the-shelf games or games with mechanics that rely on different cognitive mechanism.

Fifth, in the present study the gaming experience of participants is unknown. However, because of the random group assignment and the sufficient power of the study, it is likely that the groups had on average equal gaming experience. Nevertheless, future studies should focus on comparing and contrasting tDCS in novices and experts.

4.3. Application

The evidence generated in the present study has implications for the sports and gaming industries. The video game industry has already surpassed all other forms of entertainment in revenue; according to the Entertainment Software Association, video games (hardware and software combined) have produced 43.3$ billion in revenue in the USA. Furthermore, 65% of American adults report they play video games, and about 46% of all gamers are female (ESA, 2019). The present result is especially important for the fast growing esports scene (Keiper et al., 2017; Sylvester and Rennie, 2017), in which skilled players perform for spectators in a competitive sporting contexts, and players are looking for

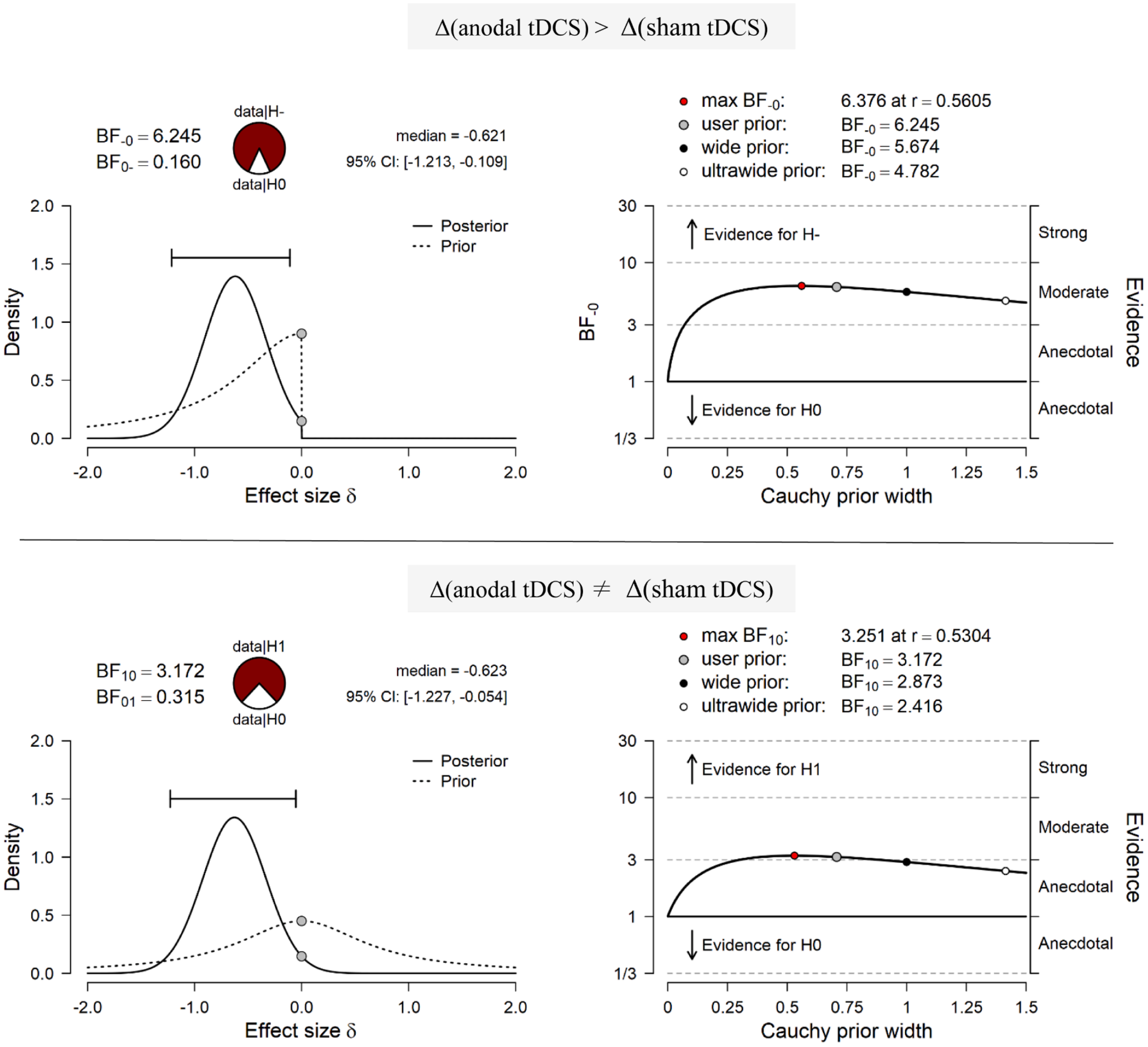

Fig. A1. Details on Bayes factor calculation and robustness depending on the alternative hypothesis used.

ways to gain a competitive advantage. It is already possible to purchase commercially consumer-oriented tDCS devices online for a little over $100 or build one yourself (Jwa, 2016). While self-stimulation using those unregulated devices is not recommended, the promise of enhancing your gaming performance is tremendously attractive for some people. We think that tDCS will most likely be used as a form of acute doping or to enhance training results, as there has been evidence to suggest that tDCS can enhance the training effect (Katz et al., 2017; Martin et al., 2014). However, as our results demonstrate, it should be noted that inter- and intra- individual tDCS effects vary drastically and that there are many factors that influence it (e.g., Coffman et al. 2014; Hsu et al., 2016; Chew et al. 2015; Kim et al. 2014). tDCS as a performance enhancer has already been used in cycling (Okano et al., 2015; Vitor-Costa et al., 2015), ski-jumping (Reardon, 2016), and recently in a basketball setting (Friehs et al., 2019). If this form of "brain doping" were to become reliable on an individual level with widespread usage, esports organizations would need to regulate the use of tDCS, and further, major ethical and social issues would need to be addressed (Friehs et al., 2019; Lavazza, 2019; Pascual-Leone et al., 2002; Simonsmeier et al., 2018). Although detection of the use of neuroenhancers such as tDCS is possible, it might not be feasible as the cost and time requirements associated with detecting its use are too high and there are already reports of transcranial electric stimulation being useful in athletic settings (Cogiamanian et al., 2007; Reardon, 2016; Vitor-Costa et al., 2015). Furthermore, fairness and social justice need to be discussed. Looking at socioeconomic status, the world presently is drastically unequal and inequality is rising (de Haan and Sturm, 2017; Kenworthy et al., 2018; Schwendicke et al., 2015; Wilkinson and Pickett, 2006). The benefits of cognitive enhancement would likely reach advantaged individuals first, increasing inequality further and splitting society into those who have access to enhancement and those who do not. In the context of professional esports, this could lead to a dangerous snowball effect, in which the winners have to keep on winning in order to afford the newest form of enhancement.

4.4. Conclusion

The results of the present study show that tDCS over the rDLPFC can reliably affect cognitive inhibition processes and that this effect is not limited to clean environments without visual distractors but also extends to more naturalistic settings, such as in a digital game. Additionally, the present study generates evidence that the underlying neural correlates overlap for the stop signal task and a game that embed these same cognitive processes into its mechanics. Important for the rising esports context, our results imply that performance improvements in digital game play though non-invasive brain stimulation may be possible. Further work is needed to determine whether the results seen in our infinite runner game extend to more complex game environments with higher attentional demand, which are typical of esports and competitive gaming.

Open practices statement

If the article is accepted for publication all data will be uploaded to PsychArchives and can be accessed free of charge.

CRediT authorship contribution statement

Maximilian A. Friehs: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **Martin Dechant:** Data curation, Formal analysis, Software, Writing - review & editing. **Sarah Vedress:** Data curation, Formal analysis, Software, Writing - review & editing. **Christian Frings:** Supervision, Methodology, Writing - review & editing. **Regan L. Mandryk:** Supervision, Resources, Funding acquisition, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

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Appendix

Fig. A1.

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