Attentiveness interacts with the effect of transcranial direct current stimulation and white noise on cognitive performance

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Abstract

Scarce research has been conducted on the moderating role of attentiveness in the effect of tDCS on cognitive performance. On the other hand, research on the impact of auditory noise on attention has generally demonstrated the detrimental effect of task-irrelevant noise on performance of cognitive tasks, yet has also neglected to explore the role of attentiveness in this relationship. Accordingly, the current study examined whether attentiveness moderates the effect of white noise (WN) and transcranial direct current stimulation (tDCS) on cognitive performance. Twenty-four participants were split into a 'low attentiveness' group and a 'high attentiveness' group based on how they scored on the SNAP-IV attention subscale. Both groups completed the Cued Go/No-Go Task under three stimulation conditions: No-noise, WN, and tDCS. Reaction time and accuracy in the task were recorded. It was hypothesized that the 'low attentiveness' group would perform better in the WN and tDCS conditions, whereas the 'high attentiveness' group would perform worse in the WN and tDCS conditions, compared to the no-noise condition. These hypotheses were derived from the MBA model that suggests that external noise adds to the internal neural noise in the brain which increases the signal-to-noise ratio through stochastic resonance, and can either enhance or attenuate cognitive performance, depending on individuals' attentiveness level. Both hypotheses were partially supported, with the reaction times decreasing in the WN and tDCS conditions for the 'low attentiveness' group but increasing for the 'high attentiveness' group, relative to the no-noise condition. However, no difference was found in accuracy.

Keywords: attentiveness, white noise, transcranial direct current stimulation, the moderate brain arousal model, stochastic resonance

Introduction

Research on the impact of auditory noise on attention has generally demonstrated the detrimental effect of task-irrelevant environmental noise on performance of attention-demanding cognitive tasks (Dalton and Behm, 2007; Hygge, Boman, and Enmarker, 2003). The consensus on why noise impairs cognitive performance has been that attention is a limited resource for which the distracting and target stimuli compete. Numerous models of attention, most notably perceptual load theory (Lavie and Tsal, 1994), are based on this premise. However, recently a number of studies have found that moderate levels of auditory noise (i.e., 50 – 80 dB) can actually improve cognitive performance in individuals with low attentiveness (e.g., Helps, Bamford, Sonuga-Barke, and Söderlund, 2014; Sikström et al., 2016). This improvement has been attributed to a phenomenon called stochastic resonance (SR; Moss, Ward, and Sanita, 2004), where the addition of noise can amplify a signal normally below the firing threshold of neural cells, so the signal becomes strong enough to be detected. It has been postulated that this threshold is notably higher in individuals with low levels of attention (Sikström and Söderlund, 2007), and that noise helps boost the signal to become detectable, leading to improvements in the performance of cognitive tasks. Other types of stimulations such as electrical stimulation in the form of transcranial direct current stimulation (tDCS) have similarly been found to improve cognitive performance in general (Meideiros et al., 2012), although the mechanism, through which this is achieved, is believed to differ. Additionally, although several studies have examined the effect of tDCS on attention, past research in general has overlooked the role that attentiveness plays in the impact of tDCS on cognitive performance. Thus, examining the interaction between attentiveness and the effect these two types of stimulations have on cognitive performance, may expand and explain some of the disparate literature.

The Moderate Brain Arousal (MBA) Model

Sikström and Söderlund (2007) have developed a neurophysiological model, the moderate brain arousal (MBA) model that provides a two-fold explanation as to how attention interacts with noise and cognitive performance. First, it argues that noise can improve cognitive performance through SR. Second, it postulates that whether noise enhances or deteriorates cognitive performance is determined by individual differences in dopamine (DA) function.

Stochastic resonance. The brain constantly experiences unwanted electrical fluctuations (i.e. neural noise), even in the absence of external noise. When presented with input, it needs to be able to detect the signal from the noise. Efficient signal processing involves a high signal-to-noise ratio (SNR) so that the brain processes the signal, not the noise. An increase in input noise can increase the SNR, thereby enhancing signal detectability. This is exactly what SR achieves. SR is a phenomenon that helps improve signal detection in threshold-based systems by adding noise to a signal normally too weak to be detected, thus allowing the signal to pass the activation threshold and become detectable. This is believed to be possible because noise in the environment can be introduced into the neural system through the sensory system, adding to the internal noise and pushing it above the detection threshold. Thus, external noise could compensate for insufficient levels of internal noise. SR has been identified in a number of natural and artificial systems, such as in bistable optical systems (Gammaitoni, Hänggi, Jung, and Marchesoni, 1998), in the electroreceptors in paddlefish (Russell, Wilkens, and Moss, 1999), in the cuticular mechanoreceptors in crayfish (Douglass, Wilkens, Pantazelou, and Moss, 1993), and in the cercal mechanoreceptors in crickets (Levin and Miller, 1996). Most notably, SR is found in the all-or-none action potentials of neurons in the central nervous system (CNS) and the peripheral nervous system

(PNS) where signaling is propagated and regulated by an influx and efflux of ions (sodium, potassium, calcium, and chloride) into the neurons that depolarize (i.e. excite) and hyperpolarize (i.e. inhibit) the cells. SR has been observed in several modalities, including vision (Simonotto et al., 1999), audition (Zeng, Fu, & Morse, 2000), and touch (Ward, Wells, Chua, & Timothy Inglis, 2005), and also operates across modalities, such as when auditory noise enhances visual signal detection (Manjarrez, Mendez, Martinez, Flores, and Mirasso, 2007). An example of SR in the detection of sensory signals is when the addition of white noise to a weak signal (e.g. tone) pushes the signal above the threshold, making the signal detectable (Moss, Ward, and Sannita, 2004). The SR effect is not restricted to sensory processing, however, as it has been found to improve performance of cognitive tasks such as auditory noise enhancing the speed of arithmetic computations (Usher and Feingold, 2000).

The strength of the SR effect largely depends on the amounts of internal as well as external noise. Studies have found that the SR effect follows a u-shaped curve, where too little external noise does not cause neurons to cross the threshold, whereas too much noise causes neurons to be unable to detect the target signal from the noise (Aihara, Kitajo, Nozaki, and Yamamoto, 2008). For some individuals, internal noise is naturally lower than optimal. In this case, noise can enhance cognitive performance through SR. For other individuals, internal noise is at an optimal arousal level, and for these individuals, external noise would only add too much to an already well-functioning system. Thus, the level of internal noise dictates whether external noise can enhance or impede the detectability of a weak signal.

Dopamine. According to Sikström and Söderlund, DA plays a major role in regulating background noise level within the neural system by modulating neural responsivity to the environment and determining the firing probability of neurons following exposure to a stimulus. Dopaminergic neurons fire action potentials through two modes: Tonically and phasically. Phasic DA release refers to the high concentration of DA being released and absorbed from axon terminals into the synaptic cleft in response to action potentials generated by environmental stimuli. In contrast, tonic DA refers to the low concentration of DA present in the extracellular fluid where it modulates the release of phasic DA through presynaptic inhibitory autoreceptors (Grace, 1995). It is tonic DA release that is conceived as the background neural noise. Low levels of tonic DA increase phasic DA release, whereas high levels of tonic DA suppress phasic release. Normal and excessive tonic firing is believed to be associated with cognitive rigidity. When there is an insufficient level of tonic DA present to down-regulate phasic DA release, the probability of neurons firing becomes so high that neurons will fire at random, rendering neurons excessively reactive to environmental stimulation (Bilder, Volavka, Lachman, and Grace, 2004; Castellanos and Tannock, 2002; Grace, Floresco, Goto, and Lodge, 2007). The excessive phasic DA transmission is believed to cause unstable neuronal activity, which emerges as cognitive impairments such as failure to sustain attention, a hallmark of ADHD (Volkow, Fowler, Wang, Ding, and Gatley, 2002). In fact, the most frequently prescribed drugs for ADHD, metylphenidate and amphetamine, work by increasing extracellular DA (Kuczenski, Melega, Cho, and Segal, 1997; Kuczenski and Segal, 1997). Low tonic levels are believed to be caused by altered DA transporter function, DA metabolism, and hetero- and auto-receptor function (Grace, 2000). Essentially, there is a need for a certain amount of noise (i.e., tonic DA) in the nervous system in order to function normally, and when this need is not met internally, noise must be introduced to the nervous system through external noise (Solanto, 2002). Thus, tonic DA levels determine the amount of external noise necessary for optimal cognitive performance.

The MBA model essentially suggests that inattentiveness stems from an overactive response to environmental stimuli caused by insufficient levels of extracellular dopamine. Accordingly, the effect that SR exerts on individuals differs depending on dopamine function in their brain in such a way that individuals with poor DA regulation (i.e., inattentive individuals) require more environmental stimulation (i.e. noise) for the facilitating effect of SR to be observed, whereas individuals with high internal noise require less external noise. Peak cognitive functioning is reached when arousal levels are optimal. Optimal levels of noise will vary from one individual to another due to these individual differences in dopamine function. The MBA model predicts that noise improves cognitive performance for inattentive individuals and attenuates cognitive performance for attentive individuals (Sikström and Söderlund, 2007).

Effect of auditory noise on cognitive performance

The few studies that have examined the role of attentiveness in the impact of auditory noise on cognitive performance have consistently found that inattentive individuals experience an improvement in cognitive performance while listening to auditory white noise (WN), whereas attentive individuals do not. These studies corroborate the hypotheses laid out in the MBA model, likely because they have been conducted by some of the same researchers who devised the model. For instance, Söderlund, Sikström, and Smart (2007) investigated how exposure to WN would improve performance on a self-performed task (SPT) compared to a verbal task (VT) in 21 children with ADHD compared to 21 controls. For both cognitive tasks, participants were presented with verbal commands such as 'roll the ball' but in the SPT they were instructed to perform the action of the verbal command, whereas in the VT they were not. Immediately following both tasks, participants were asked to recall as many of the verbal commands presented as possible within two minutes. Because the use of gestures improves recall (i.e., the enactment effect), the SPT was considered a high recall performance, which was believed to be associated with low internal noise level, whereas the VT was considered a low recall performance associated with high internal noise. Each participant was exposed to WN and a control condition without noise while performing the SPT and VT. Söderlund and colleagues predicted that WN would improve SPT recall for the ADHD group but not for the control group, and that WN would not significantly affect VT recall for the ADHD group but it would attenuate VT recall for controls because of the SR curve being right shifted in the ADHD group. They found that WN improved SPT recall for the ADHD group but did not significantly impact SPT recall for the control group, compared to no noise. In contrast, WN did not significantly affect VT recall for the ADHD group but it did significantly lower VT recall for the control group, compared to no noise. This was consistent with their hypothesis that the SR curve is right shifted in ADHD individuals in such a way that they require more external noise to reach optimal brain arousal level, and is in line with the MBA model.

Similarly, Söderlund, Sikström, Loftesnes, and Sonuga-Barke (2010) explored whether 10 children rated as having low attentiveness according to teachers' reports would improve on a verbal episodic recall test (VERT) when exposed to WN compared to 41 children rated as having high attentiveness. Similar to Söderlund, Sikström, and Smart (2007), each participant was presented with 96 verbal commands once while listening to WN and once with no noise. Immediately following the presentation of the last item, participants were instructed to recall as many items as possible. The researchers predicted that the inattentive group would recall fewer items from the VERT in the no-noise condition than the attentive group, whereas the inattentive group would improve recall when exposed to WN, and recall would be attenuated for the attentive group. Their results were consistent with their hypotheses, with inattentive children recalling more items in the noisy environment rather than the silent environment, and the opposite being true for the attentive children. The study concluded that attentiveness is responsible for moderating the effect of WN on cognitive performance. These results are consistent with the notions proposed by the MBA model that the neural noise level in inattentive individuals is sub-optimal due to low tonic DA release, and that external noise may compensate for this and boost cognitive performance through SR.

Sikström et al. (2016) recently examined whether improvement on a Go/No-Go Task (GNGT) and 2-Back Task would be observed when individuals with high or low self-reported attentiveness were exposed to WN and transcranial direct current stimulation (tDCS). According to Sikström and colleagues, the mechanisms responsible for the improvement in cognitive performance following exposure to WN and tDCS differ, with WN influencing performance by introducing additional neuronal noise, and tDCS lowering the activation threshold, allowing for detection of target signals. Participants were exposed to 80 dB WN and 1mA tDCS, as well as a no-noise control condition while carrying out the GNGT and 2-Back Task. They found that performance of the Go/No-Go Task but not 2-Back Task improved for participants with low attentiveness when exposed to both WN and tDCS, compared to the no noise condition, but not for participants with high attentiveness. The researchers proposed that no interaction effect between attentiveness and 2-back task scores was found due to the higher cognitive demand placed by the 2-back task, resulting in a higher brain arousal level than for the GNAT and therefore more optimal performance for the low attentiveness group. The results for the GNAT were consistent with their hypothesis that cognitive performance would benefit from WN and tDCS for the low attentiveness group but not for the high attentiveness group. However, these findings cannot fully confirm whether tDCS and WN improves or attenuates cognitive performance because the researchers did not counterbalance the stimulation conditions, nor employ sham tDCS to control for placebo effects in the control and WN conditions.

Transcranial direct current stimulation (tDCS)

TDCS is a form of noninvasive neurostimulation that passes a low-intensity, direct electrical current between anodal and cathodal electrodes placed on the scalp in order to shift the polarity of neuronal resting membrane potential, heightening or diminishing neuronal excitability in particular brain areas of interest, depending on the current flow (Paulus, 2004; Priori, 2003). Anodal stimulation (A-tDCS) is commonly regarded as increasing cortical excitability through membrane depolarization, while cathodal stimulation decreases excitability through membrane hyperpolarization (C-tDCS; Nitsche and Paulus, 2000, 2001). The effect of tDCS depends on a number of factors, including the size, polarity and position of the electrodes, the current intensity, duration of stimulation, and the properties of the tissue in the stimulated area (Meideiros et al., 2012).

There is a rapidly growing body of literature using electrical stimulation to improve cognitive function, ranging from simple picture naming (Mottaghy, Sparing, and Töpper, 2006), phonological memory (Kirschen, Davis-Ratner, Jerde, Schraedley-Desmond, and Desmond, 2006), sustained attention (Nelson, McKinley, Golob, Warm, and Parasuraman, 2014), and working memory (Andrews, Hoy, Enticott, Daskalakis, and Fitzgerald, 2011) to more complex tasks such as implicit learning learning (Kincses, Antal, Nitsche, Bartfai, and Paulus, 2004) and analogical reasoning (Boroojerdi et al., 2001). While a slew of studies have demonstrated improvements in specific cognitive skills, some variability exists in the effect sizes of tDCS, with reports of individual differences in neuronal function leading to variability in response to tDCS (Li, Uehara, and Hanakawa, 2015). It is believed that passing an electrical current with adequate strength and duration causes a rapid increase in the electrical conductance of membrane, increasing permeability for ions and molecules. This notion is consistent with the hypo-dopaminergic state caused by low tonic DA levels, as proposed by the MBA model. One study found that exposure of 800 uA C-tDCS but not A-tDCS increased extracellular DA in rat striatum, suggesting that tDCS has a direct and/or indirect effect on the dopaminergic system in the rat basal ganglia (Tanaka et al., 2013). However, no human study to date has directly assessed the effect of tDCS on extracellular DA, so it remains unclear as to whether improvement in cognitive performance for individuals with low attentiveness following exposure to tDCS is due to increased tonic DA release or whether another mechanism is responsible for improvement such as lowering of activation threshold.

In spite of the explosion of research in the last decade suggesting that tDCS may enhance specific cognitive skills, Sikström et al. (2016) is the only study to date that has directly compared the effect that tDCS has on cognitive performance for individuals with high and low levels of attentiveness. Thus, which role attentiveness plays in the impact of tDCS and WN on cognitive performance is still largely an under-researched topic in cognition research, and therefore warrants further investigation. Nevertheless, several studies have examined the modulating effect of tDCS on various aspects of attention. For instance, Nelson, McKinley, Golob, Warm, and Parasuraman (2014) examined whether vigilance decrement (i.e. decline in performance of attention-demanding tasks over an extended period of time; Mackworth, 1948) would be reduced when participants received prefrontal tDCS. Nineteen adults were instructed to perform a signal detection task while receiving 1mA prefrontal tDCS at one of two different time points (early or late). Early tDCS was hypothesized to reduce the extent of the decrement, while late tDCS was hypothesized to restore performance to early task levels. The impact of tDCS was assessed using scores on the signal detection task, hemispheric blood flow velocity, and regional blood oxygenation, and was compared to a sham tDCS condition. They found that, compared to the sham tDCS condition, scores on the signal detection task improved, and both early and late tDCS groups experienced increased blood flow and oxygenation in the targeted brain areas after exposure to tDCS. In another study exploring the effect of tDCS on attention, Gladwin, den Uyl, Fregni, and Wiers (2012) predicted that tDCS compared to sham tDCS would improve selective attention during a Sternberg task. Fourteen college students received 1mA anodal tDCS placed above left dorsolateral prefrontal cortex for the first 10 minutes of completing the task. The effect of tDCS was expected to persist till completion of the test. Comparing scores on the Sternberg task in the active condition to those in the sham tDCS condition revealed that scores significantly improved when participants were exposed to tDCS compared to the sham tDCS condition, demonstrating the lasting effect of tDCS even after cessation. Though attentional networks are spread throughout the brain, research has generally implicated the frontal regions in performance of attentional tasks (Oken, Salinsky, and Elsas, 2006). Evidence for this comes from studies assessing regional cerebral blood flow changes when exposed to tDCS, such as that by Nelson et al. (2014), as well as PET and fMRI attentional studies demonstrating lateralized frontal lobe activation during the performance of attentional tasks, with the right prefrontal cortex generally exhibiting more activity than the left (e.g., Berman and Weinberger, 1990; Buchabaum et al., 1990; Cohen, Semple, Gross, and Holcomb, 1988; Cohen, Semple, Gross, King, and Nordahl, 1992; Deutsch, Papanicolaou, Bourbon, and Eisenberg, 1987; Pardo, Fox, and Raichle, 1991).

The present study

The current study is based on Sikström et al.'s study (2016), with the implementation of a few methodological changes to improve internal validity. Similarly, the purpose of this study is to examine whether the impact of WN and tDCS on cognitive performance depends on individuals' level of attentiveness. This was achieved by splitting participants into a 'high attentiveness' group and a 'low attentiveness' group, and exposing both groups to WN, tDCS and a sham tDCS no-noise condition during a Cued Go/No-Go task. Scores from the Cued

No/No-Go task were used to assess the effects of 1.5 mA tDCS and 80 dB WN, and were compared across groups and stimulation conditions. In the current study, 1.5 mA anodal tDCS was applied above the right inferior frontal gyrus (rIFG) and cathodal tDCS was applied above the inferior orbitofrontal cortex (IOFC) to determine whether modulation of these areas would affect performance, as these areas have been heavily implicated in response inhibition and attentional control (Hampshire, Chamberlain, Monti, Duncan, and Owen, 2010). Based on the MBA model, it was hypothesized that exposure to WN and tDCS would yield faster reaction times and greater accuracy on the Cued Go/No-Go task for the “low attentiveness” group, compared to the no-noise condition. In contrast, it was hypothesized that WN and tDCS would yield slower reaction times and poorer accuracy for the “high attentiveness” group, compared to the no-noise condition.

Method

Participants

Participants were recruited through self-selection sampling. Recruitment for participants was conducted through posts published on Facebook using a web-based interest recruitment form. The only prerequisite for participating in the study was enrollment at Lund University, which was assessed with one item in the form. In order to ensure a spread in attentiveness, 100 participants were first screened for level of attentiveness with the SNAP-IV attentiveness subscale, with those scoring in the top 12% (M = 19.92, SD = 2.71) and bottom 12% (M = 2.42, SD = 1.62) being invited to participate in the study. Five participants dropped out of the study before completing all three testing sessions, so data from these cases were excluded from the final analyses. The final sample consisted of 19 university students (6 males, 13 females) from Lund University. Ages ranged from 19 - 30, with an average age of 23.74 (SD = 2.79). The majority (68.4%) of participants were undergraduates, while the remainder (31.6%) were postgraduates. The sample was mainly Swedish (63.1%), followed by Danish (10.5%), Polish (5.3%), German (5.3%), Chinese (5.3%), Hungarian (5.3%), and Slovenian (5.3%).

Design

The study employed a 2 (attentiveness level) x 3 (stimulation type) mixed-factorial design. The between-subjects variable (two levels) was the level of attentiveness (low attentiveness versus high attentiveness). The within-subjects variable (three levels) was the type of stimulation that participants were exposed to while completing the cognitive task (no noise, WN, and tDCS). The conditions were counterbalanced, totaling in six possible orders. The participants were randomly assigned to these orders. The dependent variable was scores from the Go/No-Go Task, measured as reaction time and accuracy. Accuracy was measured as percentage of correct responses.

Materials

Recruitment form. Participants' demographic and contact information was collected through the web-based interest recruitment form. The recruitment form also included the attentiveness assessement scale.

Attentiveness. Participants were screened for low and high attentiveness in the recruitment form using nine questions relating to attentiveness such as 'I make careless mistakes' and 'I can't pay attention' from the SNAP-IV rating scale (see Appendix A). This self-report inventory is commonly employed in clinical settings to screen for Attention Deficit Hyperactivity Disorder (ADHD) and Oppositional Defiant Disorder (ODD) symptoms in children and young adults but has demonstrated good reliability and validity across varying study samples (Bussing et al., 2008). The items were scored on a 0 – 3 rating scale. The sum of all items was calculated for each participant and used as an indicator for their level of attentiveness, where low scores reflected high attentiveness and high scores reflected low attentiveness.

Cognitive test. Cognitive performance was assessed through a Cued Go/No-Go Task, which measured sustained attention and response inhibition. The test was conducted through Inquisit 5 Lab. This task required participants to either respond as quickly as possible by pressing the spacebar or withhold a response by not pressing any key depending on whether a go or no-go stimulus was presented on the computer screen. The go stimulus was a green rectangle, and the no-go stimulus was a blue rectangle. The blue and green rectangles were either vertical or horizontal. The vertical rectangle had a higher probability of being green (a go stimulus), and the horizontal rectangle had a higher probability of being blue (a no-go stimulus). Participants were cued of the orientation of the rectangle with a outline of the rectangle shortly before the color of the rectangle was revealed. Each stimulus was presented for 1 second or until participant responded to it. The order of the trials was randomized. Two hundred and fifty trials were presented, which were expected to take approximately 10 minutes to complete based on previous studies. Performance was measured as error rates and reaction times. Participants were given practice tests prior to the testing sessions. Because the Go/No-Go Task is a relatively new instrument, concerns have been raised about its reliability being too low to be useful in research. Research suggests that Go/No-Go Task reliability largely depends on its content and block length, with reliabilities of 0.8 being obtained with as few as 60 trials per block (Williams and Kaufmann, 2012). A number of studies have attested to the validity of the Go/No-Go Task (Boldero, Rawlings, and Hasla, 2007; Gonsalkorale, von Hippel, Sherman, and Klauer, 2009; Teachman, 2007).

Auditory noise. Auditory noise was administered as white noise (WN) through headphones using the iPhone app ‘Smartnoise’ while the participants completed the cognitive task. The audio volume was kept at a moderate 80 dB, which was measured using the iPhone app ‘dB Volume Meter’.

TDCS. Electrical noise was administered with the Nuraleve SmartStim M1000 transcranial current stimulation device with an intensity of 1.5 mA (Sikström et al., 2016). The anodal electrode was positioned above the right inferior frontal gyrus (rIFG), and the cathodal electrode was positioned above the inferior orbitofrontal cortex (IOFC). The electrodes consisted of rubber enclosed in a pair of perforated sponge pockets soaked with a saline solution. A headband was used to secure the electrodes to the scalp and prevent them from sliding around.

Procedure

The Cued Go/No-Go Task was completed under three conditions: WN, tDCS, and no-noise, which served as control. The participants were invited to the lab three times, with at least one day between each testing session. Spacing at least one day between the testing sessions was done to avoid order effects, as well as to prevent any possible tDCS effects from persisting into the following testing sessions. No maximum limit was imposed for the duration between the testing sessions, as it was not expected that participants would be able to come to the lab three consecutive days. To keep the conditions as similar as possible, participants wore both the headphones and the tDCS device throughout all three testing sessions. A tDCS current of 1.5 mA was administered for 10 seconds prior to the cognitive testing in all conditions but was gradually ramped down to zero when the cognitive testing started in the sham conditions (i.e. WN and no-noise). This was done to control for placebo effects, as well as to get participants accustomed to the sensation of tDCS. TDCS continued throughout the tDCS condition, and ceased as soon as participants had completed the task. The conditions looked like the following:

1. WN condition: Exposure to WN + exposure to sham tDCS
2. tDCS condition: No exposure to WN + exposure to tDCS
3. No-noise condition: No exposure to WN + exposure to sham tDCS

Following the completion of the final testing session, participants were presented with one item assessing deception awareness. Finally, they were debriefed.

Ethical considerations

Participants completed an informed consent form prior to participation in the study. This form assured participants that any data given would be kept anonymous and confidential, as well as inform participants that their participation was entirely voluntary, and that they could withdraw at any time or request to have their data destroyed. In the informed consent form, participants were informed that aspects of the study may not be made known to them until the experiment had concluded. During debriefing, however, participants were made aware of the minor deception. The deception involved participants being misled to believe that they would be exposed to tDCS in each testing session, when, in reality, they were only exposed to tDCS once. This was necessary to control for placebo effects, and to keep the conditions as similar as possible.

Although this study did involve physical intervention with tDCS, tDCS is generally considered safe mainly because: 1) the electric current applied is very low, and 2) there is no direct contact between the electrodes and the brain. Adverse effects of tDCS are also minor and short-lived, and commonly include headache, itching, tingling, discomfort, and redness on the skin where the electrodes are placed. Considering tDCS would only be applied for a few minutes at a time (approximately 10 minutes in each session), these adverse effects were not of great concern. TDCS is generally considered safe for periods up to 30 min (Bikson, Datta, and Elwassif, 2009).

Results

To evaluate whether attentiveness interacted with stimulation type, two 2 x 3 mixed ANOVA were conducted with the between-subjects variable as attentiveness level (low attentiveness versus high attentiveness) and the within-subjects variable as stimulation type (WN, tDCS, and no-noise).

Reaction time

Reaction time was examined in the first ANOVA. There was one outlier in the data, as assessed by inspection of a boxplot for values greater than 1.5 box-lengths from the edge of the box. This outlier was included in the analysis, as it did not substantially affect the results. Reaction time was normally distributed, as assessed by Shapiro-Wilk's test ($p > .050$). There was homogeneity of variances, as assessed by Levene's test of homogeneity of variance ($p > .050$), as well as homogeneity of covariances, as assessed by Box's test of equality of covariance matrices ($p = .205$). Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the two-way interaction, $\chi^2(2) = 23.008$, $p < .001$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .567$). No main effect of stimulation condition was found, $F(1.135, 19.290) = 1.549$, $p = .231$, partial $\eta^2 = .084$, but there was a statistically significant interaction between stimulation type and attentiveness level, $F(1.135, 19.290) = 22.922$, $p < .001$, partial $\eta^2 = .574$.

Simple main effects for attentiveness level were conducted to examine whether any differences in reaction times existed between the 'low attentiveness' group and 'high attentiveness' group at each stimulation condition. There was a significant difference in reaction times between the groups in the no-noise condition ($F(1, 17) = 23.136$, $p < .001$, partial $\eta^2 = .576$), but not in the WN condition ($F(1, 17) = 4.241$, $p = .055$, partial $\eta^2 = .200$), nor the tDCS condition ($F(1, 17) = 2.614$, $p = .124$, partial $\eta^2 = .133$).

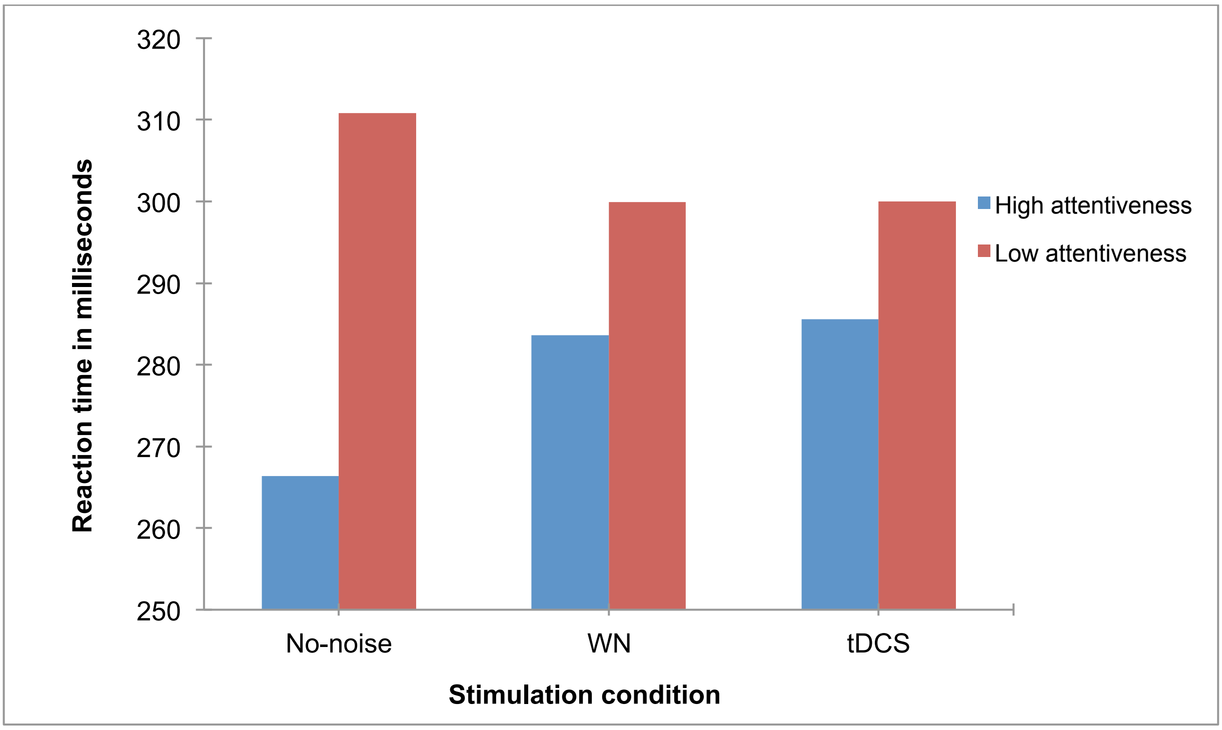
Low attentiveness group. In order to investigate whether reaction times in the stimulation conditions differed from each other, each group was analyzed separately with three separate one-way ANOVAs. Preliminary assumption checking for the data for the 'low attentiveness' group revealed no violations of normality, linearity or homoscedasticity. The results revealed a significant main effect of stimulation type on attentiveness level for the 'low attentiveness' group, ($F(2, 16) = 14.789$, $p < .001$, partial $\eta^2 = .649$). Reaction time was statistically significantly faster in the WN condition ($M = 299.94$, $SD = 17.85$, $p = .004$) and tDCS condition ($M = 299.98$, $SD = 20.35$, $p = .004$), compared to the no-noise condition ($M = 310.81$, $SD = 22.46$) but was not statistically significantly different between the WN and tDCS conditions ($p = .948$).

High attentiveness group. The data for the 'high attentiveness' group violated the assumption of sphericity as indicated by Mauchly's test of sphericity, $\chi^2(2) = 15.956$, $p < .001$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .537$). The results revealed a significant main effect of stimulation type on attentiveness level for the 'high attentiveness' group as well, $F(1.073, 9.657) = 12.539$, $p = .005$, partial $\eta^2 = .582$). Reaction time was statistically significantly slower in the WN condition ($M = 283.61$, $SD = 17.78$, $p = .003$) and tDCS condition ($M = 285.56$, $SD = 18.53$,

p = .008), compared to the no-noise condition (M = 266.36, SD = 17.78) but was not statistically significantly different between the WN and tDCS condition (p = .329).

Figure 1 graphs the mean values reaction times for the ‘high attentiveness’ group and ‘low attentiveness’ group.

Figure 1. Mean reaction times in milliseconds for the ‘high attentiveness’ group and ‘low attentiveness’ group in the no-noise, WN, and tDCS conditions.



Accuracy

Accuracy was examined with the second ANOVA. There was one outlier in the data, which was included in the analyses. The normality assumption was violated for the ‘low attentiveness’ group in the control condition, as assessed by Shapiro-Wilk’s test (p = .035). The data was transformed, and test comparisons were run between the transformed and non-transformed data to see if any meaningful differences emerged. However, as no meaningful differences were found, the original data was used in the analysis for the sake of clarity. There was homogeneity of variances, as assessed by Levene's test of homogeneity of variance ($p >$ .050), but no homogeneity of covariances, as assessed by Box's test of equality of covariance matrices ($p = .008$). Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the two-way interaction as well, $\chi^2(2) = 22.500$, $p < .001$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon =$ .570). No main effect of stimulation condition was found, $F(1.140, 19.374) = .450$, $p = .536$, partial $\eta^2 = .026$, and no statistically significant interaction between stimulation type and attentiveness level was found either, $F(1.140, 19.374) = .539$, $p = .494$, partial $\eta^2 = .031$. No further analyses were therefore conducted. It should also be noted that a ceiling effect occurred for some of the participants.

Table 1. Means and standard deviations for accuracy in percentages.

Level of attentiveness	*N*	Accuracy in each condition					
		WN		tDCS		No noise	
		M	*SD*	*M*	*SD*	*M*	*SD*
High attentiveness	10	99.6	1.39	97.72	1.47	97.80	1.70
Low attentiveness	9	98.4	1.54	98.09	1.45	97.42	2.65

Discussion

The results of the current study partially support the first hypothesis that exposure to WN and tDCS improves cognitive performance in inattentive individuals, relative to no-noise. This study found that individuals with self-reported low attentiveness improved their reaction time on a Cued Go/No-Go Task when exposed to WN and tDCS, compared to no-noise. However, no interaction between accuracy and stimulation type was found. Similarly, the results also partially support the second hypothesis that exposure to WN and tDCS attenuates cognitive performance in inattentive individuals, compared to no-noise. Again, accuracy was not affected. The finding that reaction time for the ‘low attentiveness’ group decreased but increased for the ‘high attentiveness’ group when exposed to WN and tDCS, compared to no-noise, is consistent with a number of recent studies showing that individuals’ level of attentiveness moderates the effect that WN and tDCS have on cognitive performance. This is in line with the suggestion that individuals’ level of neural noise, which is modulated by DA function, determines whether the introduction of external noise through the perceptual system has a positive or negative effect on cognitive performance. For individuals with low neural noise who are subsequently classified as having low attentiveness, the addition of external noise in the form of WN and tDCS helps push target signals above threshold through the phenomenon of SR, making them detectable and thus enhancing cognitive performance. In contrast, for individuals with high neural noise who are subsequently classified as having high attentiveness, adding noise to an already optimal neural noise level makes it difficult for the brain to detect any target signals from the noise, thus attenuating cognitive performance.

The study was based on the MBA model that posits that attentiveness moderates the effect that WN and tDCS has on cognitive performance. According to the model, the mechanism responsible for the improvement in cognitive performance differs. While WN is believed to add to the internal noise in the brain and pushing target signals above the threshold by increasing the SNR ratio through SR, tDCS is believed to enhance signal detection by lowering the activation threshold of neural cells, although research has yet to confirm this. Although the current study was not able to show that tDCS works in this way, it did demonstrate that WN and tDCS are both effective techniques that can be used to enhance attentiveness and consequently cognitive performance for individuals with low attentiveness. No significant differences were found between the effectiveness of WN and tDCS in improving/deteriorating cognitive performance either, suggesting that both are comparatively effective techniques in this regard. How these two techniques can be practically applied, however, may depend on whether individuals are seeking short- or long-lasting changes, with WN being a short-term solution, and tDCS being a relatively long-term solution.

One point to consider when interpreting these findings is that although SR is posited to follow a u-shaped curve, where cognitive performance peaks at a moderate noise level, no absolute optimal noise level exists. Because of individual differences in DA function, what is an optimal noise level for one individual could be too much or too little for another individual. Declaring 80 dB WN and 1mA tDCS, the same loudness and intensity used in this study, to be the optimal noise level for individuals with low attentiveness to reach peak cognitive functioning would therefore be deceptive. There is also the possibility that individuals vary in their activation thresholds, with some having a higher thresholds requiring more noise to become sufficiently aroused, and others having lower thresholds requiring less noise. The interaction between cognitive performance and noise intensity may account for some of the conflicting findings in the literature. Future research should explore the differential effects of varying noise intensities on cognitive performance.

Limitations

One limitation of the current study is the use of only one test of cognitive function that assessed sustained attention and response control. Although these are two fundamental components of attention, they are only two of many aspects of cognition that could be affected by external noise. The focus of this study was not on how noise specifically affected sustained attention and response inhibition but rather cognitive performance in general. Thus, any test assessing cognitive performance could have been employed. The reason the Cued Go/No-Go task was selected was to stay as similar to Sikström et al.'s (2016) study to see whether their findings could be replicated when the order of conditions was counterbalanced and when sham tDCS was added to the WN and no-noise conditions. Whether the Cued Go/No-Go task measured what it was supposed to measure was not important but rather the fact that any aspect of cognitive performance improved. Nevertheless, future research should explore whether the findings in this study generalize to other cognitive tasks such those assessing executive and motor functions, as well as confirm whether the effects vary depending on task difficulty, as was demonstrated by Sikström et al. (2016).

Because of the large number of trials in the Cued Go/No-Go task, it is conceivable that participants experienced vigilance decrements, which would be reflected in increased error rates and slower reaction times as the task went on. Vigilance decrement becomes significant within the first 15 minutes of completing attention-demanding cognitive tasks (Teichner, 1974). To test this notion, the reaction time and accuracy on each trial should have been recorded and analyzed as a function of time-on-task to reveal any emerging trends. However, this was not done in the present study, so no inferences can be drawn. In contrast, the finding that exposure to noise (both WN and tDCS) increased attentiveness, may conversely have abated any vigilance decrements. At least this could be a possibility if vigilance decrements arouse out of boredom, as it is argued in the Mindlessness theory (Helton and Russell, 2011). With such an easy task as the Go/No-Go Task, it is possible that participants may have experienced some boredom. This could have been combated by reducing the number of trials in the task. Another thing to consider is that because participants performed the same task three times, their performance may have improved in the latter conditions as a result of practice. However, any practice effects that might have occurred would likely be small, considering the very easy task difficulty. Furthermore, research shows that repeated performance of a Go/No-Go Task only leads to slightly higher accuracy and negligible faster reaction times (Schapkin, Falkenstein, Marks, and Griefahn, 2007). In addition, because all conditions were counterbalanced, any potential order effects that might have occurred would have been spread equally across all conditions, thus no longer constituting a confounding variable. Practice and boredom-related effects were therefore of little concern, and did not significantly threaten the internal validity of the study.

Another limitation is that since the participants elected to take part in the study, there is likely to be a degree of self-selection bias. For instance, significantly lower scores on the SNAP-IV attention subscale was observed, with scores on the scale being skewed towards high attentiveness. Alternatively, the skewness could stem from the fact that participants were sampled from a population (i.e., university students) that presumably would score higher on an attentiveness scale because their occupation as students likely demands a high level of attentiveness or because those with a high level of attentiveness are more motivated to attend university. Utilizing a sample with a greater spread in scores on the SNAP-IV attentiveness subscale may have revealed even greater effect sizes. As the sample used in this study is not perfectly representative of the general population, and the sampling method employed adds another layer of potential bias, these findings cannot be completely generalized to a wider population.

Having participants undergo all three conditions also means that they were more likely to form an interpretation of the experiment's purpose and act in accordance with their interpretation. Of particular concern was that participants would become aware of the sham tDCS in the WN and no-noise conditions. To combat this, participants were deceived about the exposure to tDCS, and were presented with a post-experimental item assessing their awareness of this deception. As only five participants reported being aware of sham tDCS, and their performance on the cognitive task did not significanlty differ from those who reported being unaware of the deception, this was ruled out as a extraneous variable.

There is also the possibility that the effects of the briefly administered tDCS in the WN and control condition carried over to the following testing sessions and slightly improved reaction times. Unfortunately, no studies to date have explored how long briefly administered tDCS persists, so the effects of the sham tDCS are unknown. Regardless, as sham tDCS was performed across all conditions, this was not of great concern, and any changes in effect sizes that might have occurred would probably have been minimal.

These findings support the first notion from the MBA model that noise can be induced into the CNS through the perceptive system and enhance signal detection. However, the present study did not address the role that DA function plays in this relationship, and thus cannot fully support the MBA model. More research is needed to confirm that the effect of noise is determined by individual differences in DA function. Future studies could perhaps measure extracellular dopamine levels and investigate how these levels correlate with individuals' required noise levels for peak cognitive functioning.

Conclusion

Despite these limitations, these findings tentatively support the notion that WN and tDCS can have positive implications for cognitive performance, contrary to previous literature. Any future work assessing the effect of WN and tDCS on cognitive performance should take into account the role that attentiveness plays in this relationship, and perhaps consider dividing study data into groups based on attentiveness level, thereby potentially revealing any effects hidden in mean values. The possibility that adding WN to individuals' environment may lead to improvements in attentiveness has major practical significance. For instance, it could offer a cheap and non-invasive way of enhancing school performance in individuals with attentional problems, such as children with ADHD. It could also be used to complement other treatment types for ADHD such as medication. Even though tDCS has also demonstrated a positive impact on cognitive performance, it is not an ideal option in these scenarios due to its costliness and inaccessibility. The effects of tDCS might also be different and possibly even harmful if administered to the brain during a critical stage of development such as adolescence when the prefrontal cortex has yet to fully mature (Bennabi et al., 2014). Regardless, the finding that noise can benefit cognitive performance, whether it be in the form of auditory or electrical noise, is important because it attests to the possibility that adapting environments to the needs of individuals could lead to improvements in cognitive performance, something that is considered especially valuable in school settings.

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Appendix A

Swanson, Nolan, and Pelham IV Rating Scale (SNAP-IV)

This questionnaire assesses your level of attentiveness.

Instructions: Please complete the following questions by crossing the box next to the question that best reflects your situation on a scale from “not at all”, “just a little”, “often”, to “very often”. Mark only one box for each question.

Your information will be kept strictly confidential.

		Not at all	Just a little	Often	Very often
1	I make careless mistakes				
2	I have difficulty sustaining attention				
3	I do not listen				
4	I fail to finish work				
5	I am disorganized				
6	I cannot concentrate				
7	I lose things				
8	I am easily distracted				
9	I am forgetful				