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The Effects Of Transcranial Direct Current Stimulation On Beat Perception And Motor Performance

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Abstract

Humans have an intrinsic tendency to move to music. However, our understanding of the neural mechanisms underlying the music-movement connection remains limited, and most studies have used correlational methods. Here, we used transcranial direct current stimulation (tDCS) to causally investigate the role of four motor brain regions involved in movement timing and beat perception: the supplementary motor area (SMA), left and right premotor cortices (PMC), and cerebellum. Subjects were randomly assigned to a brain region to be stimulated and received anodal, cathodal, or sham stimulation on three different days while they reproduced rhythmic sequences. The sequences had either a strong beat percept, weak beat percept, or no beat percept. We predicted that SMA stimulation would affect reproduction of strong beat rhythms, whereas PMC and cerebellar stimulation would affect reproduction of weak or non-beat rhythms. No difference in reproduction accuracy was found based on brain region or type of stimulation.

Keywords: Music Cognition, Beat Perception, Transcranial Direct Current Stimulation, Supplementary Motor Area, Cerebellum, Premotor Cortex.

Summary for Lay Audience

Humans have an intrinsic tendency to move to music, perhaps because motor brain areas respond to beat perception. However, our understanding of the neural mechanisms underlying the music-movement connection remains limited, and most studies have used correlational methods, such as fMRI, and other neuroimages methods. Here, we investigated the role of four motor brain regions involved in the timing of movement and beat perception: the supplementary motor area (SMA), the left and right premotor cortex (PMC), and the right cerebellum, using transcranial direct current stimulation (tDCS). TDCS is a causal method that modulates brain responses in two opposite directions: anodal stimulation increases cortical excitability, and cathodal stimulation inhibits cortical excitability. Subjects were randomly assigned to receive stimulation in one of the four brain regions. They participated in three sessions separated from two to seven days, receiving anodal, cathodal, or sham stimulation in each session while they reproduced different types of rhythmic sequences. In some sequences, a beat was easily perceived; in others, the beat was unclear or absent. As the SMA plays a primary role in beat perception, while the premotor cortex and cerebellum appear to have a general role in timing, we predicted that the SMA stimulation would affect reproduction of rhythms with a beat, whereas premotor and cerebellar stimulation would affect reproduction of sequences with no beat. As expected, regardless of the brain region, improved reproduction was observed according to whether the rhythm had a beat or not, but no difference was found based on the stimulation received. Thus, we found no evidence that modulating brain excitability alters the accuracy of rhythm reproduction. We discuss the implications of these results and the future perspectives for this research.

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Chapter 1

1 Introduction

Humans have an intrinsic capacity to match their behavior to music through movements. Although some of these movements, like dancing and playing a musical instrument, are very complex, others, like foot tapping and nodding heads, occur spontaneously, and without training (Repp & Su, 2013). The rhythm and its consequent 'beat' perception may be the keys to this urge to move that some people experience when listening to songs. Whilst rhythm can be defined as "the serial pattern of variable note durations in a melody" (Schulkind, 1999), the feeling of a recurring pattern of salient pulses is defined as the beat (Levitin et al., 2018). We can further separate rhythms according to how clear a beat they have. A metric simple rhythm will have regular intervals arranged in such a way to give a clear beat (strong beat rhythm), a metric complex rhythm will have regular intervals but irregular accents, which makes a beat harder to detect (weak beat rhythm), and a non-metric rhythm will have irregular intervals and irregular accents so that no beat is perceived (non-beat rhythm) (Grahn & Brett, 2007). Here, I investigated the causal role of different brain areas in beat perception using rhythms that varied in beat strength.

Depending on the type of rhythm to be perceived, different timing mechanisms have been proposed to play a role. Humans have an absolute timing mechanism that encodes the absolute durations of time intervals. This mechanism is often conceived of as an internal clock that works like a stopwatch, with the length of each time interval stored in the memory (McAuley & Jones, 2003; Teki et al., 2011). In contrast, relative timing encodes intervals relative to a reference interval, such as a regular beat. Beat-based or entrainment-based models have been proposed as models of relative timing. In these models, intervals are encoded relative to the beat. This beat is perceived through 'accents', and sequences with regularly recurring accents that emphasize the beat are generally better encoded than sequences with less regular accents, which makes the beat interval more difficult to perceive (Povel & Essens, 1985; Teki et al., 2011). Even though we know that beat

perception engages relative timing mechanisms (Essens, 1986; Povel & Essens, 1985), the underlying mechanisms of relative vs. absolute (or beat-based vs. non-beat-based) timing are yet to be fully understood.

In terms of neural mechanisms, the link between rhythm and the motor system has been demonstrated by many studies of auditory rhythm (Bengtsson et al., 2009; Chen et al., 2008a; Grahn & Brett, 2007; Grahn & Rowe, 2009; Schubotz et al., 2000). Neuroimaging studies find that motor brain areas, such as the supplementary motor area (SMA), premotor cortices (PMC), the basal ganglia, and the cerebellum respond to auditory rhythms even when no movement is made (Bengtsson et al., 2009; Chen et al., 2008a; Grahn & Brett, 2007; Kornysheva et al., 2010; Schubotz et al., 2000). Rhythms with a strong beat generate greater activation in the basal ganglia, and the pre-SMA/SMA, showing the importance of the striato-thalamo-cortical loop for beat perception (Grahn & Brett, 2007). Moreover, a follow-up study showed that rhythm-responsive areas such as the PMC, prefrontal cortex, inferior parietal lobule, and cerebellum exhibited greater activity for complex rhythms, in which the beat is difficult to detect. In contrast, the basal ganglia showed greater activity for beat presence, and its activity was not modulated by rhythmic complexity (Grahn & Rowe, 2009). Therefore, although several motor regions respond to auditory rhythm, the basal ganglia and SMA appear to respond more when the rhythm has a beat, and other areas, including the PMC and cerebellum either don’t differentiate between beat and non-beat rhythms (Grahn & Brett, 2007), or respond more to non-beat than beat rhythms (Grahn & Rowe, 2009).

Neuropsychological work with Parkinson's disease (PD) patients has demonstrated the importance of the SMA and basal ganglia areas for beat perception. PD patients can serve as a model for basal ganglia dysfunction because the disease is marked by cell death in the substantia nigra, which projects to other basal ganglia structures, such as the putamen. When comparing PD patients to controls in a rhythm discrimination study composed of strong and weak beats, PD patients performed worse for strong beat rhythms but not for weak beat rhythms. Thus, the benefit of having a beat was significantly reduced for PD patients, supporting basal ganglia's role in beat perception. Additionally, it suggests that

the basal ganglia's full function might be necessary for understanding a beat structure and benefiting from it (Grahn & Brett, 2009).

Furthermore, a neuropsychological study comparing individuals with cerebellar degeneration to PD patients suggests that the neural mechanism for beat-based and non-beat-based timing are distinct (Breska & Ivry, 2018). Patients with cerebellar degeneration, PD patients, and healthy controls performed a temporal orienting task, where a target embedded in a visual stream needed to be detected in three different conditions. In the rhythmic condition, the target timing was predictable, as the target appeared "on the beat" induced by the timing of events prior to the target. In the single-interval condition, the target timing was also predictable but relied on encoding the single interval between events, and using that to predict the timing of the target. In the random condition, the target was unpredictable because the intervals were randomly jittered in time. Patients with cerebellar dysfunction performed worse in the single-interval condition, but not in the rhythmic condition, whereas the opposite was true for PD patients, who performed worse in the rhythmic condition but not in the single-interval condition (Breska & Ivry, 2018). This double dissociation supports the central role of the basal ganglia in beat-based timing and points to a cerebellar role in absolute timing (Nozaradan et al., 2017; Teki et al., 2011).

One theory that lays out the role of the motor system in timing is the action simulation for auditory prediction (ASAP) hypothesis, which suggests that the motor system responds in the anticipation of the next beat in a rhythm and that auditory-motor interactions are key for beat perception. Entrainment of neural activity to the beat occurs when periodic body movement simulations are planned in the motor system. This pattern of entrainment is passed from motor planning regions to auditory areas, serving as a predictive signal for upcoming beats. The auditory system response is thus enhanced by the motor system through expectations of the beat. The model can also be expanded into the function of specific brain areas, including the SMA and the dorsal striatum, with the SMA informing auditory expectations and the striatum structuring beat-based temporal anticipation. The process of anticipating the next beat in a rhythm is made through an SMA-dorsal striatum-globus pallidus-thalamus loop, and neural populations in the SMA are disinhibited by the thalamus through representations of the beat cycle internally generated in the striatum,

creating temporal dynamics that will anticipate the next beat, while the timing of a beat and the rhythm interpretation can be shaped by the auditory signals that arrive in those brain areas (Cannon & Patel, 2021; Patel & Iversen, 2014).

Notably, most studies of the neural mechanisms of beat perception have employed correlational neuroimaging methods (Grahn & Brett, 2007; Grahn & Rowe, 2009; Teki et al., 2011) or neuropsychological work in patient populations (Breska & Ivry, 2018; Grahn & Brett, 2009). Few studies have used causal methods in healthy humans (Leow et al., 2022). Transcranial direct current stimulation (tDCS) is one way to causally examine the role of different brain areas in different timing processes. Unlike transcranial magnetic current stimulation, tDCS does not cause neural firing: it modulates synaptic efficacy of neurons by altering resting membrane potential by passing a weak electric current between two brain areas (Purpura & McMurtry, 1965). TDCS can modulate brain responses in two directions: anodal stimulation increases cortical excitability by facilitating long-term potentiation (LTP) processes between activated neurons, and cathodal stimulation inhibits cortical excitability (Reinhart et al., 2017). Apart from that, tDCS has functionally specific effects because it only modulates the activity of task-relevant neuronal networks. Changing the excitability of irrelevant networks has no effect. Hence, despite its lack of spatial specificity, tDCS can be functionally specific (Bikson & Rahman, 2013).

Therefore, based on the suggestion that the SMA is involved in the temporal processing of beat-based interval sequences and that the premotor cortex and cerebellum appear to respond in both beat and non-beat contexts (Grahn & Brett, 2007) or respond more to non-beat-based contexts (Breska & Ivry, 2018; Teki et al., 2012), it was hypothesized that the SMA plays a primary role in beat perception, thus, modulating the SMA excitability should influence the ability to reproduce beat-based rhythms accurately. Similarly, stimulation of the cerebellum or premotor cortex should influence the ability to reproduce non-beat-based rhythms accurately and have no larger effect on the accuracy of beat-based rhythms reproduction compared to SMA stimulation.

Indeed, a rhythm discrimination study has demonstrated the SMA's crucial role in beat perception (Leow et al., 2022). In this study, participants received both sham and active (either anodal or cathodal) tDCS stimulations on the same day, over one of four brain areas

(SMA, right cerebellum, left premotor cortex, and right premotor cortex). Participants judged whether successive presentations of strong and weak beat rhythms were the same or different. Rhythms were similar to the work of Grahn and Brett (2009) explored here previously. Participants in the SMA group were significantly affected by the stimulation in opposite directions when discriminating strong and weak beat rhythms: the anodal group performed better during stimulation than the sham while the cathodal performed worse than during sham stimulation. Overall, excitatory stimulation over the SMA seems to improve rhythm discrimination, while inhibitory stimulation seems to worsen discrimination. This result was not the same for cerebellar or premotor cortex stimulation. For the premotor cortex, no consistent effect of stimulation was found, and for the cerebellum, both anodal and cathodal stimulation worsened discrimination performance. These results evidence both SMA and cerebellum roles in rhythm discrimination, but they do not support SMA's role in beat-based timing because stimulation affected discrimination of both strong and weak beat rhythms (Leow et al., 2022).

It makes sense to follow up the rhythm discrimination results with a more sensitive measure of beat perception. Hence, here I investigated the causal role of four brain areas (SMA, right cerebellum, left PMC, and right PMC) in beat perception through a rhythm reproduction paradigm to assess the accuracy of sequences that could be timed using a beat-based timing system and those that could be timed using a non-beat-based timing system while causally altering their activity using the tDCS. Apart from strong and weak beat rhythms, non-beat rhythms might be necessary to study irregularities in the timing system, something that the previous discrimination study did not make use of. Therefore, I examined how rhythm reproduction of strong-beat, weak-beat, and non-beat sequences was affected by anodal and cathodal stimulation.

Because of the significant individual differences in both rhythm reproduction ability (Schuit & Grahn, 2012) as well as tDCS responsivity (Chew et al., 2015), a within-subject approach was used. Participants completed both placebo (sham) and two active tDCS sessions and were randomly assigned to one of four brain areas to be stimulated: SMA, left PMC, right PMC, or right cerebellum. Participants came to the laboratory on three different days and completed the rhythm reproduction task while receiving sham, anodal or cathodal

stimulation. Stimulating several different brain areas controls for effects unrelated to the tDCS and will help disentangle the role of different motor areas in beat-based and non-beat-based timing. Using a rhythm reproduction task allows this study to serve as a conceptual replication of past discrimination studies and provides a more sensitive measure of the beat perception since it reduces decisional effects (e.g., responses bias, item effects) involved in perception tasks (Grahn & Brett, 2007; Grahn & Rowe, 2009; Leow et al., 2022).

Findings from this study will shed light on the beat perception area, identifying SMA's role in beat perception may clarify whether the SMA is part of the beat-based timing system and whether the cerebellum and PMC are part of the non-beat-based timing system. Results can be further explored in clinical populations, such as those with motor impairments and people with Parkinson's disease. If our results are in accordance with our hypothesis, SMA tDCS anodal stimulation may be combined with strong beat songs in order to improve aspects of gait in the disability population, while cerebellum/PMC anodal stimulation may be used in combination with non-beat songs in cases where population need to improve absolute timing intervals estimation.

Chapter 2

2 Methods

2.1 Participants

In total, 67 participants took part in the study. Five participants were excluded for different reasons: one participant did not complete all three sessions, three participants felt uncomfortable in the active session, and one's participant session had technical issues. Therefore, the final sample consisted of 62 participants (age mean ± standard deviation: 18.5 ± 1.8, 42 women); 16 participants in the SMA stimulation group, 16 in the right cerebellar stimulation group, 15 in the right PMC stimulation group, and 15 in the left PMC stimulation group. Participants were additionally categorized into groups of high musical experience and low musical experience by performing a median split on scores from the Goldsmith MSI musical training subscale (Müllensiefen et al., 2014). This yielded 31 participants with high musical experience and 31 participants with low musical experience, however, they were not evenly split across groups: there were ten high musical experience participants in the SMA group, nine in the cerebellum group, seven in the right PMC group and six in the left PMC group.

To minimize potential risks, participants were excluded if they had a history of psychiatric or neurological problems such as epileptic seizures, Tourette's syndrome, ADHD, depression; any metallic implants, such as pacemakers, cerebral aneurysm clips, or other electronic implants; any active skin problems, such as eczema; any unstable medical condition and the susceptibility to migraine or other frequent headaches; any history of episodes of faintness; current use of a hearing aid; for female participants specifically, being pregnant, or trying to become pregnant.

Participants were primarily recruited through the Western University undergraduate participant pool (SONA) or through word of mouth. The Health Sciences Research Ethics Board at Western University approved the study under protocol number 104725 (Ethics

Approval – Appendix A), and the experiments were performed following relevant guidelines and regulations.

2.2 Material

2.2.1 Questionnaires

Musical training ability was assessed with the musical training subscale from the Goldsmiths Musical Sophistication Index (Müllensiefen et al., 2014), a self-report questionnaire that evaluates musical sophistication as a multidimensional construct. The subscale comprises seven items, and its score can range from 7 to 49 (Appendix D).

A demographic questionnaire with questions about educational level, language, and general health was used (Appendix C).

A questionnaire was developed following Schaal et al. (2021) to assess participants' awareness of the type of stimulation received in each session. Participants were asked to indicate whether they thought they had received active or sham stimulation. If they indicated active, they indicated whether they thought it was anodal or cathodal stimulation. They also indicated how sure they were on an adapted Likert scale, with 1 = ‘completely unsure’ and 10 = ‘completely sure’. Finally, they were also asked if they noticed any sensation difference (e.g., tingling, itching sensation) during or after the session (Appendix E).

2.2.2 Stimuli and tasks

Stimuli were presented using E-prime 2.0 Software (Psychology Software Tools, Pittsburgh, PA) on a Dell laptop. Participants listened to the auditory stimuli through Bose headphones. Rhythms were generated using Matlab Software (Matlab, 2016), tone frequency (pitch) was set to 500 Hz, linear rise and fall time of each rhythm was set to 0.008 seconds, the duration of silence following tone was set to 0.04 seconds, sampling frequency was set to 44.100 Hz, sample steps were set to 1 divided by the sampling

frequency (1/44.100), and the silent gap between samples was equal to the silence tone multiplied by the sampling frequency (0.04*44.100).

Stimuli comprised rhythms adapted from the previous work of Grahn & Brett (2007). Rhythms were separated into three categories according to their beat strength: strong beat, weak beat, and non-beat rhythms. The 'perceptual accents', or the feeling that a note is more prominent than its surrounding notes, causing the beat to be salient, were manipulated in each type of rhythm. Strong beat rhythms induced regularly occurring perceptual accents at the beginning of each group of four units, emphasizing the beat at predictable intervals. Weak-beat and non-beat rhythms induced a weak or no-beat sensation because the perceptual accents were irregular, making the beat less emphasized and hard to detect. While strong and weak-beat rhythms consist of integer-ratio intervals (e.g., 1:2:3:4), non-beat rhythms consist of non-integer ratios where the '2' and '3' intervals are replaced by '1.4' and '3.6' respectively (i.e., 1:1.4:3.6:4), eliminating any beat feeling since the time intervals as well as any perceptual accents are irregular (see Figure 1).

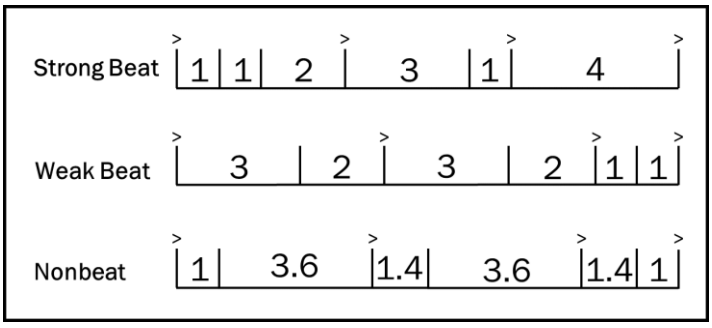

Figure 1. Schematic of sample stimuli. Vertical bars indicate interval onset, '>' indicate where perceptual accents should be heard (Povel & Okkerman, 1981). Numbers indicate the relationship between intervals. The base interval, or the shortest interval (e.g. '1') ranged from 225 ms to 275 ms, in steps of 25 ms. The other intervals are multiples of the base interval, for example, '2' is twice the duration of '1' (Hoddinott & Grahn, in Prep).

Each rhythm comprised 5 to 7 intervals, and interval durations were multiples of the 'base interval', or shortest interval (i.e., '1' interval). Base intervals could be either 225, 250 or 275 ms, in order to eliminate any carry-over effects of a perceived beat rate from

one trial to another. For example, for a strong beat rhythm with a base interval of 250 ms, the sequence 112314 contains the intervals ‘250 250 500 750 250 1000’ in length (milliseconds). The reproduced interval durations were calculated by the inter-tap interval (subtracting the time of each tap from that of the previous tap). To ensure that the length of each reproduced interval in the rhythm could be measured, each rhythm ended with an additional tone equal to the ‘1’ interval that marked the end of the final interval. For example, a six-interval rhythm would have seven tone onsets, and thus seven tap times to determine the duration of those six intervals. Additionally, for each beat type, the stimuli comprised six rhythms with five intervals, seven rhythms with six intervals, and seven rhythms with seven intervals. 'The set of intervals used to create each rhythm was termed an 'interval set', and the same interval set (e.g., the interval set 11334) appeared across the three rhythm types the same number of times (see Table 2 for the complete list of rhythms).

Table 1. Rhythmic Sequences for Each Condition

	Interval Set	*Strong Beat*	*Weak Beat*	*Non-Beat*
5 Intervals	11334	31413	11343	1 1 3.6 4 3.6
	11334	41331	33141	3.6 3.6 1 4 1
	11334	43113	41133	4 1 1 3.6 3.6
	12234	22413	13242	1 3.6 1.4 4 1.4
	12234	31422	23241	1.4 1 3.6 1.4 4
	12234	43122	41232	4 1 1.4 3.6 1.4
6 Intervals	111234	112314	124113	1 1.4 4 1 1 3.6
	111234	211413	321411	3.6 1.4 1 4 1 1
	112233	221331	121233	1 1.4 1 1.4 3.6 3.6
	112233	311322	231123	1.4 3.6 1 1 1.4 3.6
	112224	112422	122142	1 1.4 1.4 1 4 1.4

	112224	211224	214221	1.4 1 4 1.4 1.4 1
	112224	422112	412212	4 1 1.4 1.4 1 1.4
7 Intervals	1111134	1111431	1314111	1 3.6 1 4 1 1 1
	1111233	2113113	2331111	1.4 3.6 3.6 1 1 1 1
	1111233	3121113	3113121	3.6 1 1 3.6 1 1.4 1
	1111224	1122114	1112412	1 1 1 1.4 4 1 1.4
	1111224	2211114	2141211	1.4 1 4 1 1.4 1 1
	1112223	1123122	1132212	1 1 3.6 1.4 1.4 1 1.4
	1112223	3122112	3221112	3.6 1.4 1.4 1 1 1 1.4

1 = 225–275 msec (in steps of 25 msec), chosen at random for each trial. All other intervals in that sequence are multiplied by the length chosen for the 1 interval.

Rhythms were presented in random order. Participants listened to the same rhythm three times, and then reproduced what they heard by tapping it back with their index finger on a computer keyboard. Immediately after their response, a new rhythm was presented, leading to 60 trials: 20 per rhythm type.

A self-paced tapping control task comprised of spontaneous tapping rate was presented at the beginning of each session. Participants were asked to tap ten times in a row at a comfortable rate, while the stimulation/sham was applied. They were told that there was no ‘right or wrong’ for this part of the task.

2.2.3 Transcranial Direct Current Stimulation (tDCS)

The Chattanooga Ionto Dual Channel Electrophoresis System was used to apply a 2 mA current over the participant's scalp with the tDCS. Two 4 x 6 cm rubber electrodes placed in saline-soaked sponges (current density of 0.04 mA/cm2; 0.9% NaCl) were secured to the scalp with rubber head straps. For the active tDCS conditions, the current

was gradually ramped up to 2 mA over 30 s upon commencing the task. The stimulation remained on during the task for a maximum of 20 minutes, and it was ramped down at the end of the session. For the sham tDCS conditions, the stimulation was similarly ramped up over 30 s to 2 mA but then immediately ramped back down to 0 over the next 30s. The sham condition mimics the tingling or itching feeling that some participants experience when stimulation is applied. This method is sufficient to achieve blinding in stimulation-naive participants, as it evokes the sensation of being stimulated but does not lead to a neurophysiological change (Ambrus et al., 2012). Anodal and cathodal stimulation were differentiated by whether the anode or cathode electrode was placed over the region of interest. During both anodal and cathodal stimulation, the current remained at 2 mA for the duration of the task.

The stimulation sites were located using the international electroencephalographic 10-20 system, as it is sufficient for tDCS using large electrodes such as the ones used here (Woods et al., 2016). As shown in Figure 2, for the SMA site, the active electrode was positioned 2 cm anterior to Cz, and the reference electrode was placed on the forehead above the right eye (Vollmann et al., 2013); for the cerebellum, the active electrode was positioned 3 cm right of the inion, and the reference electrode was positioned on the right buccinator muscle (Galea et al., 2009), for the PMC, as neuroimaging studies suggest that the dorsal premotor cortex is located about 15–25 mm anterior to the primary motor cortex (C3, C4) (Picard & Strick, 2001), the active electrode was positioned 2 cm rostral to C3 for right PMC, and 2cm rostral to C4 for right PMC (Boros et al., 2008; Nitsche et al., 2003), and the reference electrode was positioned on contralateral orbit for both right and left PMC.

A. tDCS Stimulation Sites **B.** tDCS Stimulator

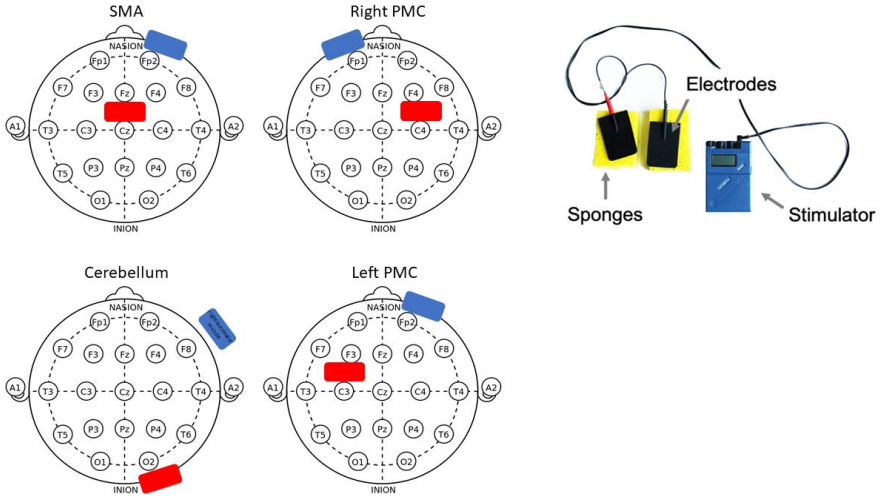

Figure 2. (A) Stimulation electrode positions, anodal electrodes in red and cathodal electrodes in blue. An anodal stimulation example is shown, as the anodal electrodes are positioned in the regions of interest, and the cathodal electrodes are positioned in the reference regions. **SMA:** 2 cm anterior to Cz, reference above right eye forehead. **PMC:** active electrode 2 cm anterior to C3 for right PMC, 2 cm anterior to C4 for left PMC, references in contralateral orbit. **Cerebellum:** 3 cm right of the inion, reference in right buccinator muscle. **(B)** tDCS Stimulator Chattanooga Ionto Dual Channel: stimulator, electrodes, and sponges are shown.

2.3 Procedure

Participants participated in three, one-hour sessions at the University of Western Ontario, with two to seven days between sessions. The three sessions were similar regarding the task procedure. The type of stimulation received (sham, anodal or cathodal) was counterbalanced across sessions, and in the first session, participants completed medical screening and demographic questionnaires as well as the musical training subscale of the Goldsmiths Musical Sophistication Index (see appendices).

A control task was completed at the beginning of each session to assess whether the tDCS stimulation interfered with tapping responses. Afterward, participants completed six practice trials where they listened to one rhythm three times and reproduced it by tapping a computer key. Then, the task started, and they reproduced each of the rhythms presented

while receiving a sham or active stimulation, depending on the session. Participants completed 60 trials, reproducing 20 strong beat rhythms, 20 weak beat rhythms, and 20 non-beat rhythms, presented in random order. The total reproduction task lasted 20 minutes.

At the end of each session, participants were asked whether they were aware of the type of stimulation they received (active or sham). At the end of the third day, participants were debriefed and had the opportunity to ask any questions of the experimenter.

2.4 Data Analysis

Data were first treated using R (R Core Team, 2020), and statistical analysis was performed using JASP (JASP Team, 2022).

Any trials with the incorrect number of taps (either too few or too many) were deemed incorrect and not further analyzed. For the remaining trials, the inter-tap time of each interval in a rhythmic sequence was compared to its corresponding presented interval in that rhythm, then a measure of the proportion of correctly reproduced trials was derived from the rhythm reproduction data. Trials with the correct number of taps (e.g., for a 6-interval rhythm, seven taps should be counted) and in which all interval durations were reproduced within 20% of the presented interval (e.g., for a 250 ms interval, a reproduced interval between 200 ms – 300 ms was accepted) were counted as a correct trial. For each participant, the proportion of correct trials was calculated for each beat type (strong, weak, and non-beat) for each stimulation condition (sham, anodal and cathodal). Higher values represent a better performance in the task, as lower values represent the opposite.

A mixed-measures ANOVA was conducted on the proportion of correct trials to investigate differences based on beat strength (strong beat vs. weak beat vs. non-beat rhythms) and stimulation type (sham vs. anodal vs. cathodal). Brain area stimulated (SMA, right cerebellum, right PMC or left PMC) and the musical experience (high vs. low) were included as the between-subject factors. Follow-up ANOVAs were run separately for each stimulation site, and pairwise tests were used to compare significant results.

For the self-paced tapping task, the inter-tap time marked each interval in the tapping sequence. The standard deviation of the intervals in each sequence was taken, and intervals that fell outside two standard deviations of the mean were removed from the analysis. Then, the coefficient of variation was calculated to measure the timing variability across each tap interval. A repeated-measures ANOVA was conducted on the coefficient of variation comparing the three stimulation sessions: sham, anodal and cathodal.

Chapter 3

3 Results

3.1 Rhythm Reproduction Task

The four brain stimulation groups did not differ in performance ($F(3,54) = 0.82$, $p = 0.49$, $\eta p2 = 0.04$). However, a main effect of music experience was observed ($F(1,54) = 7.85$, $p = 0.01$, $\eta p2 = 0.13$), as high musical experience participants performed better than low musical experience participants (Mdiff = 11.63, SE = 4.15).

A main effect for beat strength was seen ($F(2,108) = 96.09$, $p < .001$, $\eta p2 = 0.64$). Post hoc comparisons showed that strong beat rhythms had a higher percentage of correct trials than weak (Mdiff = 24.58, SE = 2.27, t = 10.81, $p < .001$) and non-beat rhythms (Mdiff = 29.38, SE = 2.27, t = 12.92, $p < .001$), and weak beat rhythms had a higher percent of correct trials than non-beat rhythms (M = 4.80, SE = 2.27, t = 2.11, p = 0.04). Additionally, an interaction between beat strength and music experience was observed ($F(2,108) = 5.28$, $p = 0.01$, $\eta p2 = 0.09$). Participants with high musical experience had better reproduction performance for strong beat rhythms than participants with low musical experience (Mdiff = 19.23, SE = 4.91, t = 3.91, p = .002), but no difference for weak beat rhythms (Mdiff = 11.20, SE = 4.91, t = 2.28, p = 0.12) nor for non-beat rhythms (Mdiff = 4.47, SE = 4.91, t = 0.91, p = 1.00) was see between participants with high and low musical experience.

Independently of the brain area, there was no main effect of stimulation type ($F(2,108) = 0.26$, $p = 0.77$, $\eta p2 = .005$). No interaction between the stimulation type and beat strength was observed ($F(4,108) = 0.83$, $p = 0.51$, $\eta p2 = 0.02$), nor between the stimulation type and brain area being stimulated ($F(6,108) = 1.59$, $p = 0.16$, $\eta p2 = 0.08$) nor between the stimulation type and music experience ($F(2,108) = 0.64$, $p = 0.53$, $\eta p2 = 0.01$).

Results from the separate ANOVAs for each stimulation site are as follow. For the SMA, as shown in Figure 3, there was a main effect of beat strength ($F(2,28) = 20.85$, $p < .001$, $\eta p2 = 0.60$). Strong beat rhythms had a higher percentage of correct trials than weak

(Mdiff = 19.61, SE = 4.55, t = 4.31, p < .001) and non-beat rhythms (Mdiff = 28.78, SE = 4.55, t = 6.32, p < .001), but the difference between weak and non-beat rhythms did not reach significance (Mdiff = 9.17, SE = 4.55, t = 2.01, p = 0.05). However, no effect of stimulation on performance was observed (F(2,28) = 0.03, p = 0.97, ηp2 = .002).

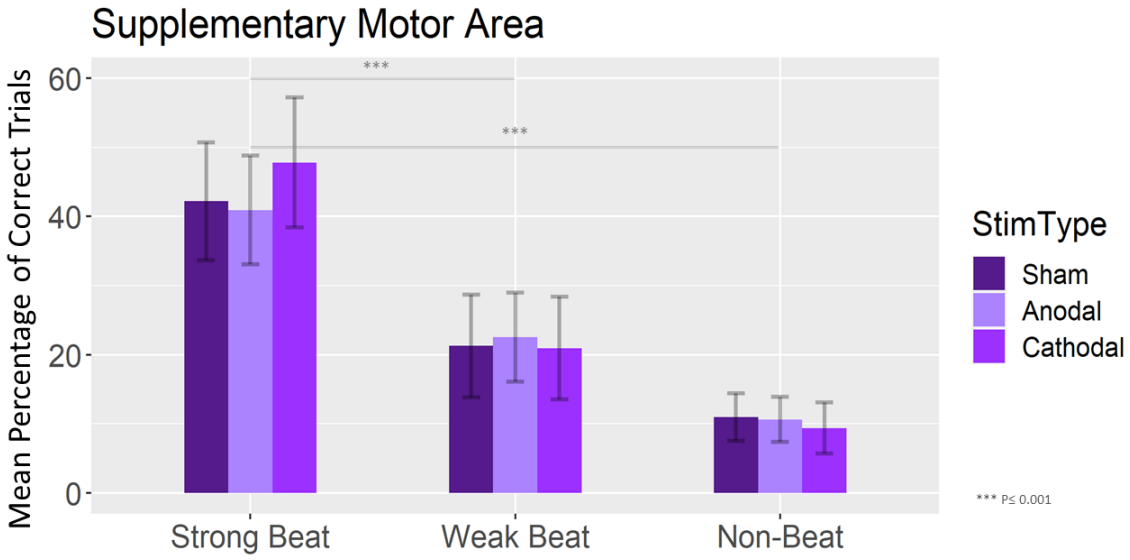

Figure 3. Response accuracy for the SMA group, separated according to beat strength. Stimulation type is differentiated through the different purple hues, sham is represented in darker purple, anodal in light purple, and cathodal in medium purple. Error bars represent the standard error of the mean. There are significant differences in accuracy when comparing beat strength but not when comparing different types of stimulation.

For the right cerebellum, as shown in Figure 4, there was a main effect of beat strength (F(2,28) = 48.63, p < .001, ηp2 = 0.78). Strong beat rhythms had a higher percentage of correct trials than weak (Mdiff = 32.08, SE = 3.99, t = 8.05, p < .001) and non-beat rhythms (Mdiff = 35.73, SE = 3.99, t = 8.96, p < .001), but weak beat rhythms did not differ from non-beat rhythms (Mdiff = 3.67, SE = 3.99, t = 0.91, p = 0.37). However, no effect of stimulation on performance was observed (F(2,28) = 1.75, p = 0.19, ηp2 = 0.11).

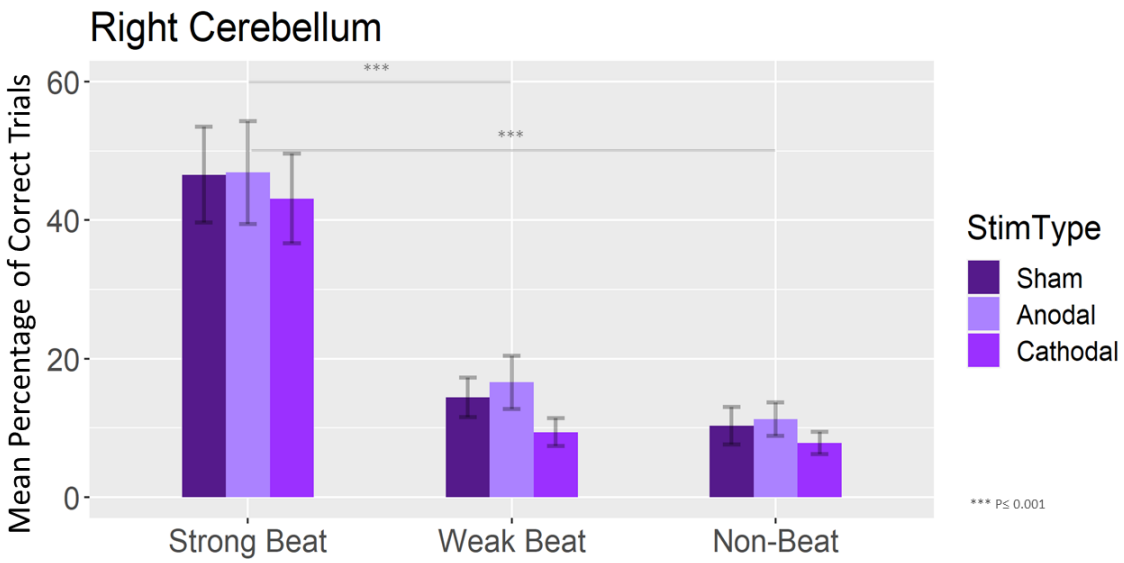

Figure 4. Response accuracy for the right cerebellum group, separated according to beat strength. Stimulation type is differentiated through the different purple hues, sham is represented in darker purple, anodal in light purple, and cathodal in medium purple. Error bars represent the standard error of the mean. There are significant differences in accuracy when comparing beat strength but not when comparing different types of stimulation.

For the right premotor cortex, as shown in Figure 5, there was a main effect of beat strength ($F(2,26) = 16.84$, $p < .001$, $\eta p2 = 0.56$). Strong beat rhythms had a higher percent of correct trials than weak (Mdiff = 22.54, SE = 5.17, $t = 4.36$, $p < .001$) and non-beat rhythms (Mdiff = 28.48, SE = 5.17, $t = 5.50$, $p < .001$), but weak beat rhythms did not differ from non-beat rhythms (Mdiff = 5.89, SE = 5.17, $t = 1.14$, $p = 0.26$). However, no effect of stimulation on performance was observed ($F(2,26) = 2.38$, $p = 0.11$, $\eta p2 = 0.15$).

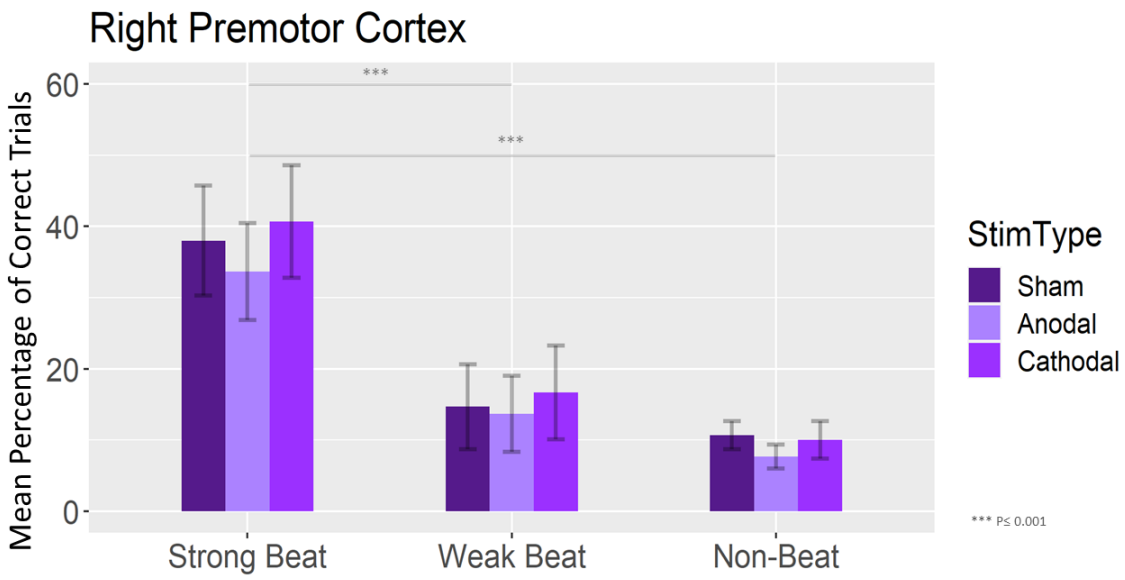

Figure 5. Response accuracy for the right PMC group, separated according to beat strength. Stimulation type is differentiated through the different purple hues, sham is represented in darker purple, anodal in light purple, and cathodal in medium purple. Error bars represent the standard error of the mean. There are significant differences in accuracy when comparing beat strength but not when comparing different types of stimulation.

For the left premotor cortex, as shown in Figure 6, there was a main effect of beat strength ($F(2,26) = 20.32$, $p < .001$, $\eta p2 = 0.61$). Strong beat rhythms had a higher percent of correct trials than weak (Mdiff = 24.08, SE = 4.41, $t = 5.46$, $p < .001$) and non-beat rhythms (Mdiff = 24.58, SE = 4.41, $t = 5.58$, $p < .001$), but weak beat rhythms did not differ from non-beat rhythms (Mdiff = 0.50, SE = 4.41, $t = 0.11$, $p = 0.91$). However, no effect of stimulation on performance was observed ($F(2,26) = 0.69$, $p = 0.51$, $\eta p2 = 0.05$).

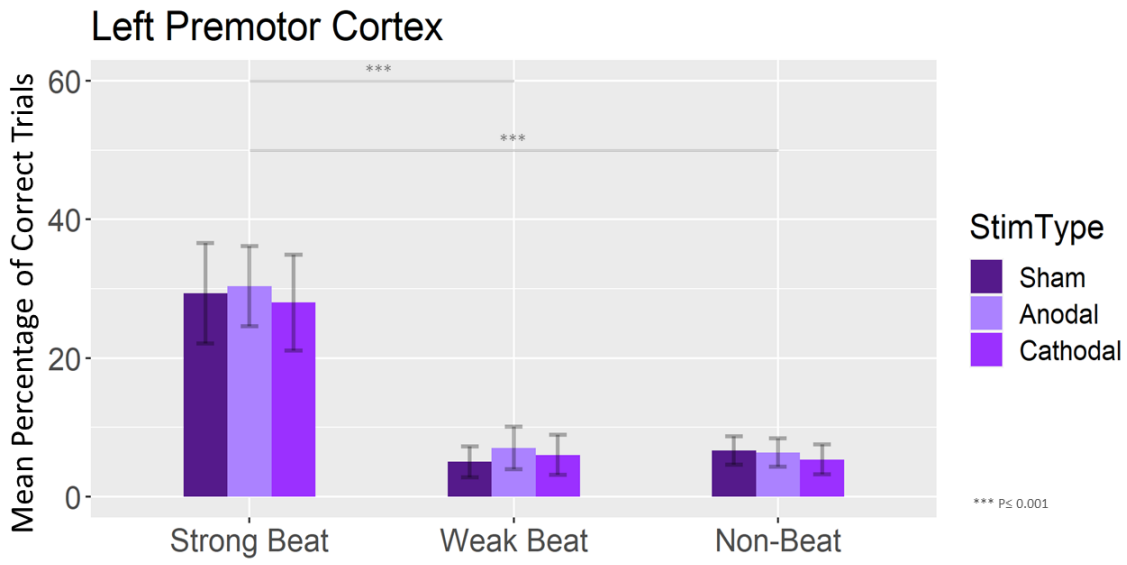

Figure 6. Response accuracy for the left PMC group, separated according to beat strength. Stimulation type is differentiated through the different purple hues, sham is represented in darker purple, anodal in light purple, and cathodal in medium purple. Error bars represent the standard error of the mean. There are significant differences in accuracy when comparing beat strength but not when comparing different types of stimulation.

Musical experience had a main effect on task performance for the SMA group ($F(1,14) = 9.00$, $p = 0.01$, $\eta p2 = 0.39$), but not for the right cerebellum ($F(1,14) = 0.21$, $p = 0.66$, $\eta p2 = 0.01$), nor for the left premotor cortex ($F(1,13) = 0.17$, $p = 0.69$, $\eta p2 = 0.01$), nor for the right premotor cortex group ($F(1,13) = 0.21$, $p = 0.22$, $\eta p2 = 0.11$). For the SMA group, a significant interaction between musical experience and beat strength was seen ($F(2,28) = 8.03$, $p = .002$, $\eta p2 = 0.36$), but no interaction between musical experience and stimulation type was seen ($F(2,28) = 1.40$, $p = 0.26$, $\eta p2 = 0.09$). For the right cerebellum group, no interaction between musical experience and beat strength was seen ($F(2,28) = 0.16$, $p = 0.85$, $\eta p2 = 0.01$), nor between musical experience and stimulation type ($F(2,28) = 0.10$, $p = 0.19$, $\eta p2 = 0.11$). For the left PMC group, no interaction between musical experience and beat strength was seen ($F(2,26) = 0.51$, $p = 0.61$, $\eta p2 = 0.04$), nor between musical experience and stimulation type ($F(2,26) = 1.86$, $p = 0.18$, $\eta p2 = 0.12$). For the right PMC group, no interaction between musical experience and beat strength was seen ($F(2,26) = 0.88$, $p = 0.42$, $\eta p2 = 0.06$), nor between musical experience and stimulation type ($F(2,26) = 1.38$, $p = 0.27$, $\eta p2 = 0.10$). See Figure 7.

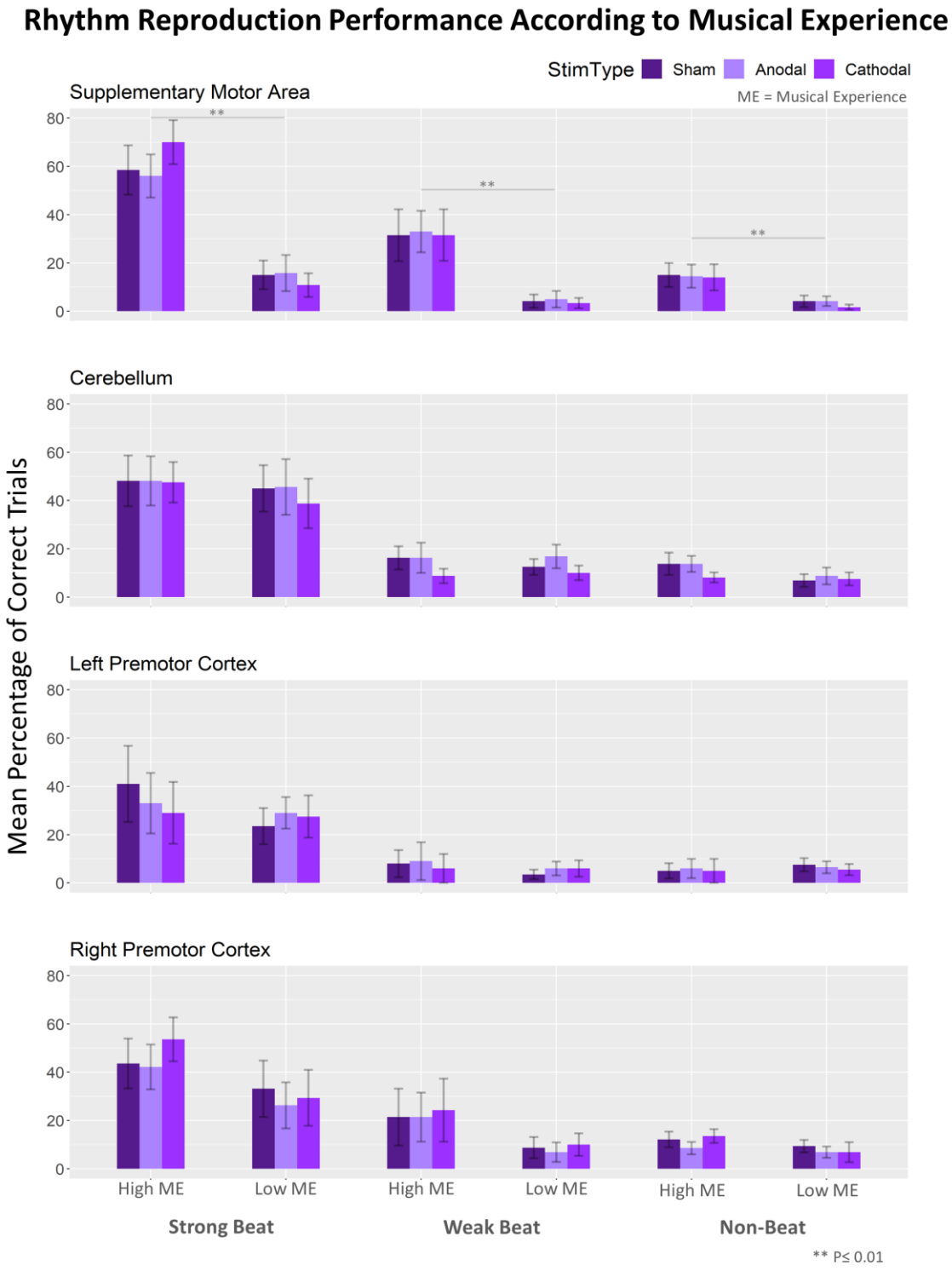

Figure 7. Response accuracy for the four groups (SMA, right cerebellum, left PMC, and right PMC). Participants are divided according to their musical experience (high and low): 10 participants with high

musical experience in the SMA group and 6 with low musical experience, 9 participants with high musical experience in the right cerebellum group and 7 with low musical experience, 6 participants with high musical experience in the left PMC and 9 with low musical experience and 7 participants with high musical experience in the right PMC group and 8 with low musical experience. Rhythms are separated according to beat strength: strong beat rhythms in the first 2 columns, weak beat rhythms in the middle columns and non-beat rhythms in the last 2 columns. Stimulation type is differentiated through the different purple hues, sham is represented in darker purple, anodal in light purple, and cathodal in medium purple. Error bars represent the standard error of the mean. Participants with high musical experience had higher accuracy for the SMA group but not for the remaining groups.

3.2 Self-Paced Tapping Control Task

The four brain stimulation groups did not differ in variability of self-paced tapping ($F(3,54) = 2.01$, $p = 0.12$, $\eta p2 = 0.10$). There was no main effect of stimulation when comparing sham vs. anodal vs. cathodal sessions ($F(2,108) = 0.73$, $p = 0.49$, $\eta p2 = 0.01$). No interaction between stimulation type and musical experience was seen ($F(2,108) = 0.84$, $p = 0.44$, $\eta p2 = 0.02$), nor between stimulation type and brain area being stimulated ($F(6,108) = 1.68$, $p = 0.13$, $\eta p2 = 0.09$).

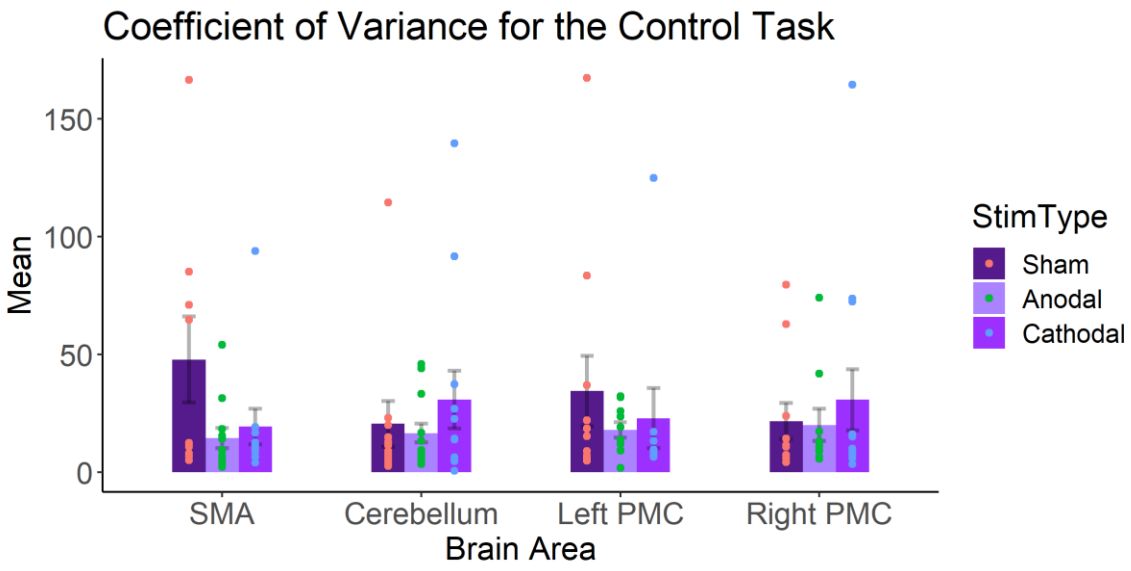

Figure 8. Control task, self-paced rhythm. Mean Coefficient of Variance for the four groups (SMA, right cerebellum, left PMC, and right PMC). Sham is in dark purple, anodal in light purple, and cathodal in medium purple. Individual coefficient of variance is shown by data points in orange for sham, green for anodal, and

blue for cathodal stimulations. Error bars represent the standard error of the mean. No significant difference was seen between stimulation types and groups.

3.3 Guessed Stimulation

Participants correctly guessed they received sham stimulation in 33.33% of sessions, while for anodal stimulation they correctly guessed it was an active anodal stimulation in 40.32% of sessions, and for cathodal, they correctly guessed it was an active cathodal stimulation in 21.31% of sessions. On a scale of how sure they were about their answer, with 1 = ‘completely unsure’ and 10 = ‘completely sure’, the average was 2.90 for all participants in the three sessions. These results indicate that participants were probably blind towards stimulation type.

Chapter 4

4 Discussion

In this study, we investigated the causal role of four brain areas: SMA, right cerebellum, left PMC, and right PMC in beat perception. A rhythm reproduction paradigm was used to assess the accuracy of sequences that could be timed using a beat-based timing versus a non-beat-based timing system. We examined how rhythm reproduction was affected by both anodal and cathodal stimulation compared to sham. Participants received sham, anodal, and cathodal stimulations in counterbalanced order on different days while they reproduced 20 trials each of strong-beat, weak-beat, and non-beat rhythms. They also performed a self-paced tapping task (our control task) while receiving stimulation. Our results did not support our hypothesis that modulating SMA excitability would influence the ability to reproduce beat-based rhythms accurately, nor that stimulation of the cerebellum or premotor cortex would influence the ability to reproduce non-beat-based rhythms accurately. Instead, anodal and cathodal stimulation of the four brain areas did not significantly alter the reproduction accuracy. Furthermore, our control task did not show any effect of stimulation. On the other hand, as predicted and shown in a previous study (Grahn & Brett, 2007), here, participants had an overall better performance for strong beat rhythms than for weak and non-beat rhythms. Particularly for the SMA group, participants with high musical experience had a better performance when reproducing the rhythms than participants with low musical experience.

4.1 SMA role in beat perception

Although the results do not support our predictions, it is undeniable that SMA is an important area for beat perception as has been shown by previous studies (Grahn & Brett, 2007, 2009; Leow et al., 2022). Apart from that, the SMA has also been implicated in a variety of functions, from simple and complex motor activities, such as sequencing actions, learning new motor abilities, and movement control when dealing with distractions (Nachev et al., 2008; Nguyen et al., 2014; Vollmann et al., 2013).

It has been suggested that SMA networks, specifically striato-thalamo-cortical loops, are important for temporal predictions especially for the production and discrimination of a time interval, with a primary role in the encoding of temporal sequences (Macar et al., 1999, 2004). Thus, SMA may help to anticipate the next beat in a sequence, sending direct signals to the dorsal striatum such that the dorsal striatum creates representations of the beat cycle intervals closing this network loop through the activation of new SMA neural subpopulations via the thalamus (Cannon & Patel, 2021). Having this in mind, it is clearer that SMA subserves beat-based timing sequences more in the sense of planning where the next beat will fall, having a role of beat maintenance.

Studies of synchronization-continuation support SMA's importance for timing in a sequence (Halsband et al., 1993; Lewis et al., 2004; Rao, 1997). Participants synchronize their finger taps with an external auditory cue (synchronization) and then continue the tapping in the absence of the auditory cue (continuation). Neuroimaging studies revealed that the SMA has higher activation for continuation than synchronization (Lewis et al., 2004; Rao, 1997). Moreover, patients with SMA lesions are impaired at continuation but not synchronization. It has been suggested that the SMA is key for an intentional process that depends on internal contexts, such as the generation of the next beat in a sequence (Goldberg, 1985).

Different from the synchronization-continuation studies, where participants can tap along with the rhythm before having to tap on their own, here, participants needed to tap on their own after listening to the rhythm three times. From a behaviorally perspective only, memory may play a role in their performance, since participants needed to remember each sequence before reproducing the rhythms. Evidence in that direction points out the importance of the ‘working memory’ – the use of short-term memory in an oriented task – for rhythm reproduction tasks (Saito & Ishio, 1998). Probably the ‘cognitive load’, which is closely related to working memory, since it refers to the amount of information one can retain at one time (Bannert, 2002), is higher in our type of task than in those synchronization-continuation studies. It is true that anodal tDCS over the auditory cortex

has been shown to affect memory for melodies (Schaal et al., 2021), but no effect of tDCS over the SMA has been shown to impact memory for rhythmic sequences until now.

As previously mentioned, the main idea of this study was to serve as a conceptual extension of the rhythm discrimination results from a tDCS study (Leow et al., 2022). In that study, although SMA stimulation had an effect in the discrimination of rhythms, with anodal stimulation improving participant's performance and cathodal stimulation worsening performance when compared to sham stimulation, then, the results did not only support SMA's role in beat-based timing as strong and weak beat rhythms were equally affected by stimulation. As SMA has been implicated in beat-based timing (Grahn & Brett, 2007), it was expected that SMA stimulation would affect the strong beat rhythms and not weak beat rhythms. A possible reason for these results may be the fact that weak beat rhythms were not irregular enough to disarrange the non-beat-based timing system, it might be the case that the weak-beat rhythms were processed by the brain as beat-based timing sequences. For this reason, we decided to include non-beat rhythms in order to have sequences that would not depend on the beat-based timing system, but regardless of stimulation, no difference in participants' performance was seen when comparing the different types of rhythms.

When comparing to the rhythm discrimination results, it is possible that no difference was seen in our rhythm reproduction task because SMA's role in timing is more clearly observed with a perceptual task. Perhaps, in order to have movement, other supporting brain areas are recruited, vanishing small temporal changes produced by stimulation of the SMA. Another possible simple reason for our null results could be that the SMA is not responsive to the specific task of rhythm reproduction used here.

Future work may focus on incorporating non-beat rhythms into a rhythm discrimination study so that the hypothesis that SMA tDCS affects beat-based time only might be tested in light of the comparison between less (weak beat rhythms) and more (non-beat rhythms) complex rhythmic sequences. Moreover, future work can explore the effects of tDCS over the SMA in clinical populations, such as those with motor impairments and people with

Parkinson's disease, and see whether the SMA anodal stimulation would improve their gait pattern when they are asked to follow strong beat rhythms.

4.2 TDCS effects on the cerebellum

Contrary to predictions, tDCS over the right cerebellum did not affect the reproduction of non-beat rhythms (or any rhythms), thus no benefits or costs for the absolute timing system were observed. However, previous research has indicated conflicting results regarding cerebellum stimulation (Oldrati & Schutter, 2018; van Dun et al., 2016). It might be because of cerebellar anatomical differences relative to the cerebral cortex; although it represents a small part of the brain's mass, it contains the majority of the brain's neurons, that in turn are organized differently than in the cortex (Herculano-Houzel, 2009). Therefore, polarity differences (anodal versus cathodal) in cerebellum tDCS are less common, and the direction of changes in behavior is less frequently predicted (Oldrati & Schutter, 2018; Woods et al., 2016). However, here we did not see any effect of stimulation, anodal or cathodal, thus an entirely null effect.

Previous studies have shown tDCS effects independent of the type of stimulation being applied (anodal or cathodal) over a variety of tasks measuring cognitive and motor processes, such as tasks of reaction time, working memory, motor learning, and motor memory (Ferrucci et al., 2008; Shah et al., 2013; Taubert et al., 2016). Cerebellar tDCS null effects have also been extensively reported (Beyer et al., 2017; Van Wessel et al., 2016; Verhage et al., 2017). In a task of associative learning with eyeblink conditioning, no effects of stimulation were seen; tDCS during the extinction phase of the learning did not predict changes in the extinction or reacquisition of the learned behavior (Beyer et al., 2017). In a working memory study using the N-back task, no significant effects of tDCS were observed on performance (Van Wessel et al., 2016). Another study comparing sham to anodal stimulation did not find any difference in the performance of an implicit learning task (Verhage et al., 2017). In a study with cerebellar patients, anodal stimulation showed no effect on a task of motor adaptation (Hulst et al., 2017). Moreover, a study that assessed cognitive function through the Stroop and Sternberg tasks predicted that cathodal

stimulation would impair the performance, but no effect of stimulation was seen (Maldonado et al., 2019).

The cerebellum plays an important role in motor control and movement precision in the time domain (Glickstein & Doron, 2008; Salman, 2002), which is partly why it has also been linked to the absolute timing system (Nozaradan et al., 2017; Teki et al., 2011). The fact that our study showed a null result for cerebellar stimulation does not mean that cerebellum is not important for its aforementioned functions. It might be that the cerebellum is not responsive to the type of task used here, a rhythm reproduction task.

Given the wide variety of cerebellar tDCS results, a possible future direction would be to align cerebellar tDCS studies with neuroimaging and verify whether the stimulation is being applied to the target area as assumed. Apart from that, including the whole cerebellum is an important step as results in the left cerebellum should be also explored. Specifically for our study, future research could include functional near-infrared spectroscopy (fNIRS) as a way of correlationally measuring brain activity through the brain's hemodynamic response and include the stimulation of the left cerebellum in order to investigate whether the results for a rhythm reproduction task would be the same or different when compared to the right cerebellum stimulation.

4.3 Premotor cortex role in beat perception and motor synchronization

Similarly to our cerebellar stimulation predictions, we expected to see tDCS effects in non-beat rhythms when stimulating the premotor cortex, but no effect of anodal or cathodal stimulation was seen for either left or right premotor cortices. It has been suggested that the PMC has a primary role in the synchronization and motor control of movements following external cues, rather than in beat perception (Leow et al., 2022), and this might be the reason why we had no significant effect on stimulation.

Given the PMC's general role in motor sequencing, there is evidence linking the PMC role to both beat-based and absolute timing in studies of rhythm synchronization (Chen et

al., 2006, 2008a, 2008b, 2009). Moreover, there is evidence for different subregions of the PMC subserving roles in rhythm synchronization. In an fMRI study, ventral PMC was only activated when participants listened to the rhythms before synchronizing to them, while the dorsal PMC was responsive during synchronization and more activated when rhythms were more temporally complex. The mid-PMC along with the SMA and cerebellum were activated when participants just listened to rhythms without knowing that they would need to synchronize to them, thus these brain regions were activated when no motor action was needed (Chen et al., 2008a). In another fMRI study, when manipulating the saliency of accentuation in a rhythm, it was shown that dorsal PMC activity had higher activation when the beat of a rhythm was made clearer by making it louder (Chen et al., 2006). Although it seems to contradict the previous results of the PMC being activated by complex characteristics of a rhythm (Chen et al., 2008a), it also indicates dorsal PMC's role in interactions between motor and auditory systems during movement sequencing (Chen et al., 2006).

The null effects seen in the current study may be explained in light of PMC's general role in motor-time synchronization. As the PMC appears to be important to beat-based and non-beat-based timing sequences, it might be the case that our task failed to incorporate an important aspect of the PMC role, the motor synchronization to an auditory stimulus. Here, participants did not have the chance to synchronize to the rhythmic sequences, they needed to reproduce each rhythm by memory after hearing it three times. Future work should analyze PMC stimulation with tDCS in a rhythm synchronization paradigm.

4.4 Limitations

A limitation of our study is the fact that we failed to add a control task that has been shown to have consistent results for the SMA stimulation in a timing task. Our control task failed to demonstrate any effect for stimulation. On the one hand, it might demonstrate that tDCS over the four brain areas studied here does not impact self-paced rhythm or motor output, then, if we had any difference in the rhythm reproduction task, we could affirm that it was indeed due to the stimulation, but since it is not the case, we do not confirm our

predictions. Perhaps a future direction is to find a control task with well-known results for the stimulation of the four brain areas, maybe a different control task for each brain area. In case we did see an effect of stimulation in a consistent control task but not in our rhythm reproduction task, we could confirm that the four brain areas do not have a causal role in beat perception through a rhythm reproduction task.

A possibility for our null results can be attributed to the complexity of the task used here, a rhythm reproduction task provides a more sensitive measure of the beat perception since it reduces decisional effects, and it might be considered a complex task because participants have more cognitive load; they need to pay attention to the rhythmic sequences and memorize them in order to reproduce the sequences correctly after hearing them. For this reason, future work should include a pre-task of rhythm reproduction and separate participants into 'strong beat perceivers' – people that have higher accuracy in the reproduction task, and 'weak beat perceivers' – people that have lower accuracy in the reproduction task, and then apply the stimulation into the separated groups. In this way, we could confirm that any stimulation effect (or null effect) is due to stimulation itself and not because the task is too hard to complete. However, the fact that no effect of musical experience was seen for the cerebellum and premotor cortex groups might be indicative that we would still see no difference between strong and weak beat perceivers.

Another important limitation is the lack of a double-blind design, where the type of stimulation is not known by the participant nor by the experimenter, here we employed a single-blind design, with only the participant blind to the type of stimulation. Blinding tDCS is a hard task, even when using double-blinding designs (O'Connell et al., 2012), especially because of the tingling and itching sensation that most participants experience (Poreisz et al., 2007). An indicator that participants were probably blind towards stimulation is the lower rates of correctly guessing the type of stimulation received, and the lower ratings for 'how sure' they were when guessing the type of stimulation.

Finally, participants were not evenly distributed in the four groups regarding their musical experience, and this might be the reason why we had a significant difference in

performance between participants with high musical experience and participants with low musical experience only for the SMA group. Although participants were counterbalanced to the brain area being stimulated, there was no counterbalancing for their musical experience, and the SMA group was the one with more participants with high musical experience (ten) when compared to other groups (nine in the cerebellum, seven in the right PMC and six in the left PMC). Future work should include an even distribution of participants according to their musical experience.

4.5 General Conclusions

A null result like the one we obtained in our rhythm reproduction task cannot lead us to conclude that the SMA is not necessary for beat perception. Beat perception can be measured by different tasks and functions and taken together with the results of SMA tDCS during rhythm discrimination, as opposed to reproduction, it appears the effects of stimulation are too weak to be observed during reproduction. Similarly, effects of stimulation on rhythm discrimination were seen for the cerebellum (Leow et al., 2022), but not during reproduction here. The different roles of motor brain regions in rhythm perception and production therefore may be easier to observe with tDCS when more sensory, rather than sensorimotor, tasks are used.

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Appendices

Appendix A. Research Ethics Approval

Western Research

Date: 4 January 2021

To: Dr. Jessica Grahn

Project ID: 104725

Study Title: Effects of brain stimulation on beat perception and motor performance

Application Type: Continuing Ethics Review (CER) Form

Review Type: Delegated

REB Meeting Date: 26/Jan/2021

Date Approval Issued: 04/Jan/2021

REB Approval Expiry Date: 09/Jan/2022

Dear Dr. Jessica Grahn,

The Western University Research Ethics Board has reviewed the application. This study, including all currently approved documents, has been re-approved until the expiry date noted above.

REB members involved in the research project do not participate in the review, discussion or decision.

Western University REB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The REB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Sincerely,

The Office of Human Research Ethics

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Appendix B. Medical Screening Questionnaire

Do any of the following apply to you?

- Any neurological or psychiatric problem, such as ADHD, epilepsy, Tourette's syndrome, etc.
- Implantation of metallic objects in the brain (e.g., deep brain stimulators).
- Use of psychoactive medication
- Any active skin problems (such as eczema)
- Any unstable medical condition
- Migraine or other frequent headaches
- Any history of episodes of faintness
- Any metal implants or devices in your body (e.g. surgical clip, coronary stent)
- These do not include metal dental fillings and metal dental braces.
- Current use of a hearing aid
- Pregnant, or trying to become pregnant

☐ **None of the above apply to me.**

Appendix C. Demographic Questionnaire

Demographic information

Important: You are free to leave any question blank

Are you (circle one): Male Female Other

Age: _____

Which hand do you write with (circle one): Right Left

What level did you attain in school (please check one):

□ Elementary School.
□ Less than Grade 12.
□ High school diploma.
□ Some university undergraduate schooling
□ College Degree (2 years)
□ Bachelor's degree.
□ Postgraduate degree.
□ Other (please specify): _____

What is your first language?
What other languages do you know?
Please also rank the degree of fluency (1 – very fluent, 6 – Slightly).

_____
_____

How would you describe your musical skills/experiences (please cycle one number)?
(not skilled/experienced) 1 2 3 4 5 6 (very skilled/experienced)

Have you ever played a musical instrument? Yes No
If yes, which instrument(s)?

_____
For how many years did/have you played? _____
What type of training did you receive? (ex. conservatory, private lessons, self-taught)?

_____

Are you currently practicing music? Yes No
If yes, how many hours per week do you practice?

How is your general health? Poor Average Good Excellent

Do you have any hearing impairment? Yes No

Is it corrected? (ex. Wear hearing aid) Yes No NA

Do you have any vision impairment? Yes No

Is it corrected? (ex. Glasses, contact lenses) Yes No NA

Appendix D. Musical Training Subscale

The Goldsmith Musical Sophistication Index, V1.0

October 11, 2012

Factor 3 – Musical Training

Please circle the most appropriatecategory:	**1 Completely Disagree**	**2 Strongly Disagree**	**3 Disagree**	**4 Neither Agree nor Disagree**	**5 Agree**	**6 Strongly Agree**	**7 Completely Agree**
14. I have never been complimented formy talents as a musical performer.	1	2	3	4	5	6	7
27. I would not consider myself a musician.	1	2	3	4	5	6	7

Please circle the most appropriate category:

32. I engaged in regular, daily practice of a musical instrument (including voice) for **0 / 1 / 2 / 3 / 4-5 / 6-9 / 10 or more** years.

33. At the peak of my interest, I practiced **0 / 0.5 / 1 / 1.5 / 2 / 3-4 / 5 or more** hours per day on my primary instrument.

35. I have had formal training in music theory for **0 / 0.5 / 1 / 2 / 3 / 4-6 / 7 or more** years.

36. I have had **0 / 0.5 / 1 / 2 / 3-5 / 6-9 / 10 or more** years of formal training on a musical instrument (including voice) during my lifetime.

37. I can play **0 / 1 / 2 / 3 / 4 / 5 / 6 or more** musical instruments

Appendix E. Stimulation Check Questionnaire

Question	Answer
About the stimulation type you received, if you could guess, do you think you received active or sham stimulation?	
In case you guessed active, what type of stimulation do you think you received?	Anodal Cathodal
Select a number according to how sure you're about it - 1 = Completely unsure; 10 = Completely sure	
Did you note any difference during the stimulation? Please describe.	
Did you note any difference after the stimulation? Please describe.	

Curriculum Vitae

Name: Marina de Oliveira Emerick

Post-secondary Education and Degrees:

Federal University of ABC
São Bernardo do Campo, São Paulo, Brazil
2013-2017 Bachelor of Science and Technology

Federal University of ABC
São Bernardo do Campo, São Paulo, Brazil
2013-2018 Bachelor of Neuroscience

The University of Western Ontario
London, Ontario, Canada
2020-2022 Graduate Specialization, Music Cognition

The University of Western Ontario
London, Ontario, Canada
2020-2022 M.Sc., Neuroscience

Honours and Awards:

Brazilian National Council for Scientific and Technological Development (CNPq) – 10.000 CAD
2018-2019

Globalink Research Internship funded by Mitacs – 8.000 CAD
2019

Globalink Graduate Fellowship funded by Mitacs – 15.000 CAD
2020-2021

NSERC - Complex Dynamics of Brain and Behaviour Award
2020-2021, 2021-2022 – 26.000 CAD, 21.000 CAD

Related Work Experience

Innovation Trainee
Natura Cosmetics S.A.
2018-2019

Globalink Research Intern

The University of Western Ontario
2019

Complex Dynamics Intern
Oscilloscape LLC
2021

Teaching Assistant
The University of Western Ontario
2022-Present

Publications:

Leow, L.-A., Rinchon, C., Emerick, M., & Grahn, J. A. (2022). Supplementary motor area contributions to rhythm perception. *BioRxiv*, 2021.11.25.470060.

Presentations:

Emerick M. & Caetano M.S. (2016). *Temporal Modulation through affective images*. Poster presentation at the 6th Scientific Symposium of Federal University of ABC, Brazil

Emerick M., Hoddinott J. & Grahn J. (2021). *Supplementary Motor Area Role in Beat Perception: A Transcranial Direct Current Stimulation Study*. Poster presented at the Symposium on Nonlinear Dynamics in Brain and Behaviour, remotely

Emerick M. & Grahn J. (2022). *The Effects Of Transcranial Direct Current Stimulation On Beat Perception And Motor Performance*. Poster presented at the Society for Music Perception and Cognition Conference, Portland, OR, USA

Emerick M. & Grahn J. (2022). *The Effects Of Transcranial Direct Current Stimulation On Beat Perception And Motor Performance*. Poster presented at the Symposium on Nonlinear Dynamics in Brain and Behaviour, remotely

Attended Events:

2015 3rd Brazilian Meeting on Brain and Cognition (BMBC)
Federal University of ABC, Brazil

2017 4th Brazilian Meeting on Brain and Cognition (BMBC)
Federal University of ABC, Brazil

2018 4th Week of the Center of Mathematics, Computation and Cognition of Federal University of ABC: Job Market and Innovation

Brazil – Speaker

2020 Symposium on Nonlinear Dynamics in Brain and Behaviour
NSERC – CREATE, McGill, remote