**The effect of jittered intervals and the role of supplementary motor area (SMA) in beat perception**

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**Abstract**

Rhythm is the foundational temporal component of music and the ability to perceive a beat in rhythm is innate in humans. Beat induction has shown to require regular perceptual accents and integer-ratio-related intervals in the rhythm. A neuroimaging study revealed differential activation of the supplementary motor area (SMA) when listening to simple or complex rhythms, but results were only correlational. This study aims to investigate the causal significance of SMA via transcranial direct current stimulation (tDCS) and the effect of non-integer-ratio-related (jittered) intervals on beat perception. We hypothesize that increased jitter from the integer ratio will decrease performance on a rhythm reproduction task, and tDCS of the SMA will have a neuro-modulatory effect on beat perception. Participants (N=27) were asked to listen to simple and complex rhythms with increasing levels of jitter (0, 0.2, 0.4, 0.6), reproduce them by tapping a key, then rate how clearly they felt the beat. The task was done without tDCS and then repeated with a randomly assigned polarity of stimulation. Higher jitter levels resulted in greater inaccuracy in the rhythm reproduction task in simple rhythms (p<0.05). Although complex rhythms were not significantly affected by jitter, but overall, they had significantly higher reproduction inaccuracy when compared to simple rhythms with no jitter (p<0.0001). Beat ratings show a similar trend – higher ratings were observed for rhythms with less jitter in simple rhythms only. In addition, cathodal stimulation showed a significant improvement in the task when compared to sham (p<0.05), but anodal stimulation was not significantly different from sham. To conclude, jittered intervals impaired beat perception in humans in a dose-dependent fashion, but only in rhythms with a strong beat. Cathodal tDCS of the SMA improved rhythm reproduction accuracy but not beat perception ratings, suggesting a possible role of SMA in the motor component of rhythm reproduction but not the cognitive component of beat perception.

**Keywords:** beat perception, tDCS, SMA, rhythm reproduction, jittered interval

**Introduction**

Perception of a stimuli requires not only the sensory mechanisms, but also the interpretation of the sensory signals by the brain. Humans are born with the ability to perceive beat – the underlying periodic pulse in music (Rajendran *et al.*, 2018), and this ability to recognize beat-based timing in rhythms has been suggested to be unique to humans (Merchant and Honing, 2014). It is important to note that beat is usually not induced by physical properties of the sound, such as differences in volume or pitch, but it is a perceptual pulse that occurs periodically and is constructed by the brain based on temporal patterns of the rhythm (Rajendran *et al.*, 2018). Beat induction in humans was shown to require both integer-ratio related inter-tone-intervals (ITIs) (e.g. 1:2:3 intervals would correspond to 250ms: 500ms: 750ms of intervals in length) and regular perceptual accents to be present in the rhythms (Povel and Essens, 1985; Grahn and Brett, 2007). Rhythms with non-integer-ratio related ITIs (non-metric rhythms) and rhythms with irregular accents (metric complex rhythms) were both shown to significantly impair rhythm reproduction accuracy in humans compared to rhythms with both of the beat-inducing properties (metric simple rhythms) (Grahn and Brett, 2007).

Numerous studies have undergone an investigation of the underlying mechanisms and the areas of the brain involved in beat perception (Rajendran *et al.*, 2018). Several areas of the brain have also been identified in which their activities were shown to be correlated with the perception of beats. Previous neuro-imaging data suggested brain areas like the basal ganglia, dorsal premotor cortex (dPMC), supplementary motor area (SMA) and pre-supplementary motor area are involved, displaying heightened activation when participants were instructed to listen to rhythms without movement, compared to the resting condition when no rhythm was presented (Grahn and Brett, 2007; Bengtsson *et al.*, 2009; Grahn, 2009). In particular, the SMA, that lies just in front of the primary motor cortex, has shown a significant increase in activation when listening to metric simple rhythms compared to metric complex rhythms or non-metric rhythms (Grahn and Brett, 2007). This suggests the SMA’s involvement in the temporal processing of beat inducing rhythmic stimuli with regular perceptual accents and integer-ratio related ITIs. SMA was also shown to have several other functions, such as: action, time and spatial processing, music and language processing, numerical cognition, sequence processing, and preplanning motor movement (Carlsen *et al.*, 2015; Cona and Semenza, 2017).

Nevertheless, neuroimaging studies have a limited capacity in demonstrating a causal relationship between stimuli, the activity in specific areas of the brain, and subsequent behavioural responses. Other common techniques used to evaluate the causal significance of brain’s areas in carrying out motor tasks or behavioural modifications include brain stimulation techniques, such as transcranial direct current stimulation (tDCS). tDCS is a non-invasive technique that passes a weak current through the electrodes placed on the scalp to modulate neuronal activity in the brain’s area of interest (Woods *et al.*, 2016). It can induce a transient polarity-specific neuroplastic change lasting up to 1-hour post-stimulation (Carlsen *et al.*, 2015). The anodal polarity depolarizes neurons, increases cortical excitability and the likelihood of neurons firing in the stimulated area, as the membrane potential is brought closer to the firing threshold by the electric current. In contrast, the cathodal polarity does the exact opposite; it hyperpolarizes neurons, decreasing cortical excitability and the likelihood of neurons firing in the stimulated area (DaSilva *et al.*, 2011). A number of studies have used tDCS to investigate causal significance of areas of the brain in behavioural tasks. tDCS on the SMA was previously shown to be effective in improving various motor behaviours in healthy adults (Hupfeld *et al.*, 2017). In addition, several studies have tested tDCS as a therapeutic intervention to neurological diseases such as obsessive-compulsive disorder and Parkinson’s disease (Hupfeld *et al.*, 2017; Lu *et al.*, 2018). In terms of processing rhythmic stimuli, tDCS was shown to modulate the dorsolateral premotor cortex’s activation levels (Pollok *et al.*, 2017). Larger inter-tap intervals were seen in the rhythm continuation task with anodal stimulation, and the opposite effect was seen with cathodal stimulation (Pollok *et al.*, 2017).

Although past research had provided strong evidence that integer-ratio-related ITIs is a crucial component present in rhythms for inducing a beat in humans, there has been little research on how much deviation or jittering from the integer ratio in the rhythm will lead to a complete loss of beat perception. I hypothesize that there will be a decrease in rhythm reproduction accuracy with increased jittering from the integer-ratio related ITIs. Secondly, although imaging data has well supported that SMA activation is correlated with beat perception, without a brain stimulation study, it is hard to conclude a causal relationship between the SMA and the ability to perceive a beat. I hypothesized that tDCS stimulation of the SMA will alter the ability to perceive a beat and in turn, affect the performance accuracy in rhythm reproduction tasks by modulating cortical excitability. Specifically, anodal stimulation will increase rhythm reproduction accuracy and cathodal stimulation will decrease rhythm reproduction accuracy.

**Methods**

*Participants*

Participants (N=27, age 18-22, 20 females, 7 males) with normal hearing (no diagnosed hearing loss or abnormality) were recruited from the SONA psychology research participation pool. Participants were excluded from the study if they qualified for any of the following exclusion criteria for tDCS stimulation: 1) Subjects with metallic implants, such as pacemakers, cerebral aneurysm clips or other electronic implants, 2) Female subjects who were pregnant, trying to conceive, or who were sexually active and were not practicing an effective method of contraception, 3) Subjects with a history of psychiatric or neurological problems such as epileptic seizures, Tourette’s syndrome, ADHD, depression, 4) Subjects who required prescribed psychotropic medication or was taking other medication that makes them drowsy, 5) Subjects who got migraines and/ or were susceptible to headaches, 6) Subjects who were more susceptible to skin irritation, such as subjects with eczema.

*Stimuli*

Fourteen different 6-interval-rhythms consisted equitones (tones with identical volume, frequency and duration) were generated using a MATLAB script. Each rhythm was made up of a mixture of ITIs that were integer-ratio related (i.e. 1:2:3:4). The base unit of one was defined as the smallest interval between two tones. For example, for a rhythm consisted of integer-ratioed intervals 2,1,1,3,1,4 with a base unit of 1 = 250 ms, the intervals lengths in milliseconds would be 500, 250, 250, 750, 250, 1000 ms respectively. An additional tone was added at the end of each rhythm to ensure that the last interval can be captured in the rhythm reproduction task. The base unit of each rhythm was randomly assigned to be either 230, 250, or 270 ms, and the amount of rhythms with each base unit were balanced across conditions to ensure participants were not just better at reproducing faster or slower rhythms. Rhythms also had two levels of beat strength: 7 were metric simple rhythms and another 7 were metric complex rhythms. Metric simple rhythms had regular accents occurring at every 4base units, whereas metric complex rhythms had irregular accents, as not every 4th base unit had a tone in these rhythms. The 14 rhythms shown in Table 1 were selected from the 24 rhythms used in a piloting study (N=7) without tDCS, and the metric rhythms with the highest or lowest percent error compared with the mean percent error in that condition were excluded from the actual study. Additionally, each of the 7 rhythms had four increasing levels of jitter from the integer-ratio-related ITIs (0, 0.2, 0.4, 0.6 jitter). Only intervals of length 2 and 3 were modified, with the base unit of 1 left unchanged to provide participants with a point of reference, and the interval of length 4 left unchanged, because changing the longest tone has produced extremely poor performance in past studies in the lab. Interval 2 was always decreased by the jitter level and interval 3 was always increased by the jitter level. For example, for the same ratios as the previous example 2, 1, 1, 3, 1 (Table 1), 4 with a base unit of 250 ms, the rhythm with 0.4 level of jitter would have interval ratios of 1.6, 1, 1, 3.4, 1, 4, hence, the interval lengths in milliseconds would be 400, 250, 250, 850, 250, 1000 ms respectively. A full list of treatment conditions is shown in Table 2. Participants were instructed to reproducing a total of 56 different rhythms in random order in each block of the experiment.

**Table 1**. Interval ratios of rhythms used in the experiment

|  |  |
| --- | --- |
| **Simple Rhythms** | **Complex Rhythms** |
| 1\_1\_2\_3\_1\_4 | 1\_2\_1\_2\_3\_3 |
| 1\_1\_2\_4\_2\_2 | 1\_3\_2\_3\_2\_1 |
| 2\_1\_1\_1\_3\_4 | 1\_2\_4\_1\_1\_3 |
| 2\_1\_1\_2\_2\_4 | 2\_1\_4\_3\_1\_1 |
| 2\_2\_3\_1\_1\_3 | 2\_2\_1\_2\_4\_1 |
| 3\_1\_2\_2\_1\_3 | 3\_2\_1\_4\_1\_1 |
| 4\_1\_1\_2\_3\_1 | 4\_1\_2\_2\_1\_2 |

**Table 2**. List of variables in the rhythm stimuli

|  |  |  |
| --- | --- | --- |
|  | Sham | tDCS stimulation(Cathodal or Anodal) |
| **Beat Strength** | **Levels of Jitter** |
| **Simple Rhythm** | 0 | 0 |
| 0.2 | 0.2 |
| 0.4 | 0.4 |
| 0.6 | 0.6 |
| **Complex rhythm** | 0 | 0 |
| 0.2 | 0.2 |
| 0.4 | 0.4 |
| 0.6 | 0.6 |

*Transcranial Direct Current Stimulation (tDCS)*

 To target the supplementary motor area (SMA), participants’ heads were measured using a measuring tape from the naison (a bump on the nose bridge) to the inion (a bump at the lower back of the head at the occipital bone), and from just in front of the left ear to the right ear. The SMA is located 2 cm rostral (closer to the nose) of the intersection between those lines. The desired stimulation mode, either anode or cathode was sandwiched inside a Baxter isotonic 0.9% sodium chloride irrigation-soaked sponge placed on the SMA area. The other electrode was also sandwiched inside a soaked sponge and was placed on the forehead above the right eyebrow. Both electrodes were secured using Velcro tapes around the head.

 The Chattanooga IontoTM Dual Channel Electrophoresis System was used to deliver the electric current. An initial ramp up from 0 to 2 mA and a final ramp down from 2 to 0 mA each lasting 10 seconds was done in the beginning and end of stimulation respectively. A consistent current of 2 mA/min was delivered for 20 min for the second block of the experiment.

*Experimental Design*

First, participants were asked to fill out a medical questionnaire to ensure that they didn’t qualify for any of the exclusion criteria for tDCS brain stimulation. If they were eligible for the study, the experimental procedure and potential risks were explained to them verbally as well as through a letter of information. They were informed that they could withdraw from the experiment at any time, and they were asked to sign a consent form if they still wished to proceed.

The participant was randomly assigned to receive either anodal stimulation (N = 13) or cathodal stimulation (N = 14) during the second block. The respective tDCS electrodes were placed on the SMA and the forehead of the participant as described previously. The tDCS was turned on in the beginning of the first block until the current reaches 2 mA and was subsequently turned off out of the participant’s sight. If pain or discomfort were reported, adjustments were made by adding more saline solution to the sponges or voluntary withdrawal from the study. The participant was instructed to follow instructions on the screen to complete the rhythm reproduction task which lasted 20 minutes for each block of the study. The tDCS was off during the first block (sham) and was turned on for the second block (either cathodal or anodal stimulation). The participants were blind to which block the tDCS was on. The initial ramp up of current in the beginning created a tingly sensation that was shown to be an effective blinding procedure (Gandiga *et al.*, 2006). The participants were instructed to do the same rhythm reproduction task during the sham and stimulation block.

The rhythm reproduction task was designed using an EPrime script. The task had 3 steps: 1) Listening to each rhythm twice, 2) Reproducing that rhythm to the best of their ability immediately, by pressing a key on a keyboard, and 3) Rating how clearly they felt the beat in that particular rhythm from a scale of 1 to 9 (1 = very weak; 9 = very strong). The task was done for each of the 56 rhythms, and the order of which the rhythms were presented was randomized for both blocks. There were also practice trials before consisting of 3 rhythms that were different from the rhythms used in the actual study, before the first block began. Participants could ask questions or repeat the practice trial as needed until they felt comfortable with the task before proceeding with the first block of the experiment. After they finished both blocks of the experiment, they were asked to fill out a brief questionnaire about their past music or dance training, and which block they felt had the tDCS stimulation on.

A debriefing form outlining the purpose of the study and researcher’s contact information were given at the end of the testing session. Any questions regarding the experiment were addressed, and they were compensated with 1.0 research credit on the SONA psychology research participation pool system.

*Statistical Analysis*

The subject data files obtained from the EPrime script was merged using EMerge, and was cleaned by a MATLAB script that deleted unnecessary variables for analysis such as time and date of the experiment and eliminated invalid trials where the participant tapped less or more times than they should.

The mean percent error of each rhythm they reproduced was calculated using formula 1 and 2. The mean percent error of each experimental condition for each subject was then calculated by averaging all the rhythm % errors of rhythms under that condition. The mean beat rating data was calculated by averaging the ratings for rhythms under each condition.

**Formula 1**: $Interval \% Error= \frac{\left|tapped interval length- stimuli inerval length\right|}{stimuli interval legnth} × 100\%$

**Formula 2**: $Rhythm \% Error=\frac{\% Error\_{interval 1}+ \% Error\_{interval 2}+…+ \% Error\_{interval 6}}{6}$

 Each rhythm was also assessed using a threshold approach, where the rhythm with a % error less than a threshold value of (15 % or 20%) were considered a “pass” trial. The sum of “passed” trials for each condition was used to divide the total number of trials in that condition, in order to calculate the proportion of trials passed with a certain percent error.

A four-way (2 x 2 x 2 x 4) mixed ANOVA was run on the mean percent error, mean beat rating and proportion of trials passed with 15% and 20% error with the following variables: type of stimulation (anodal vs. cathodal), presence of stimulation (sham vs. stimulation), presence of regular accents (simple vs. complex) and levels of jitter (0, 0.2, 0.4, 0.6) using IBM SPSS statistics. Multiple post-hoc Tukey’s tests were run where we found interactions, and all figures were generated with GraphPad Prism 8.0.

**Results**

*Mean Percent Error*

 The mean percent error of reproduced ITIs showed a main effect of regular accents (Figure 1a), a main effect of jittered intervals (Figure 1b), an interaction between presence and the polarity of tDCS (Figure 2), and an interaction between regularity of accents and level of jitter (Figure 3). Complex rhythms, on average, showed a significantly higher mean percent error compared to simple rhythms (p<0.0001, Figure 1a). Mean percent errors of rhythms with jitter levels 0 and 0.2 were significantly lower compared to rhythms with 0.6 jitter level (p<0.01, Figure 1b). The mean percent error in simple rhythms had an increasing trend with the increase in jitter levels. Metric simple rhythms (0 jitter) had a significantly lower mean percent error compared to all complex rhythms (p<0.0001, Figure 2) and simple rhythms with 0.6 jitter (p<0.01, Figure 2). However, complex rhythms with different jitter levels were not significantly different from each other. Figure 2 shows details of significantly different conditions. In addition, cathodal stimulation showed a significantly lower mean percent error compared to sham condition (p<0.05), but the mean percent error of anodal stimulation was not significantly different from the sham condition (Figure 3).

*Beat Rating*

The mean beat ratings had a main effect on presence of regular accents (simple vs. complex) and a main effect on different jittering levels (0, 0.2, 0.4, 0.6). Simple rhythms had a significantly higher mean beat rating than complex rhythms (p<0.001, Figure 4a). Also, rhythms with 0 jitter had a significantly higher ratings when compared to rhythms with 0.4 or 0.6 jitter (p<0.01, Figure 4b). There was also an interaction between the presence regular accents and jitter levels. The beat ratings for simple rhythms with no jitter or 0.2 jitter were significantly higher than all the complex rhythms and simple

**a)** **b)** 

**Fig 1**. Participants (N = 27, 20 females, 7 males) were asked to reproduce rhythms with regular or irregular accents (simple and complex rhythms) and different jitter levels (0, 0.2, 0.4, 0.6), first without tDCS and then with either cathodal or anodal tDCS. Their reproduced inter-tap intervals (ITIs) were measured. Data shown is the mean percent error ± SD of reproduced ITIs **a)** over simple and complex rhythms and **b)** over different levels of jitter. A four-way mixed ANOVA demonstrated a significant main effect of the presence of a regular accent and levels of jitter. Specifically, complex rhythms had a significantly higher mean percent error compared to simple rhythms (p<0.0001, \*\*\*\*), and 0.6 level of jitter had a significantly higher mean percent error compared to 0 and 0.2 levels of jitter (p< 0.01, \*\*).



**Fig 2**. Participants (N = 27, 20 females, 7 males) were asked to reproduce rhythms with regular or irregular accents (simple or complex) and different jitter levels (0, 0.2, 0.4, 0.6), first without tDCS and then with either cathodal or anodal tDCS. Their reproduced inter-tap intervals (ITIs) were measured. Data shown is the mean percent error ± SD of reproduced ITIs over different levels of jitters and grouped into simple and complex rhythms. A four-way mixed ANOVA revealed an interaction between presence of regular accents and the level of jitter. Subsequent Tukey’s post-hoc test showed that the complex rhythms produced mean percent errors that were not significantly different from each other, but they all had a significantly higher average percent error compared to simple rhythms with 0 or 0.2 level of jitter (p<0.01). Jitter level 0.4 in simple rhythms also had a significantly lower mean percent error compared to complex rhythms with a jittered level of 0, 0.4 and 0.6 (p<0.01). Means with different letters are significantly different from each other (p<0.01).



**Fig 3**. Participants (N = 27, 20 females, 7 males) were asked to reproduce rhythms with regular or irregular accents (simple or complex) and different jitter levels (0, 0.2, 0.4, 0.6), first without tDCS and then with either cathodal (N=14) or anodal (N=13) tDCS. Their reproduced inter-tap intervals (ITIs) were measured. Data shown is the mean percent error ± SD of reproduced ITIs the presence of tDCS (sham vs. stimulation) and grouped according to the polarity of stimulation (cathodal vs. anodal). A mixed four-way ANOVA revealed an interaction between the presence and the polarity of stimulation. Subsequent Tukey’s post-hoc tests showed that cathodal tDCS group had a significantly lower mean percent error compared to the sham condition (p<0.05, \*), but no significant difference was found between sham and anodal stimulation group (p = 0.73).

1. **b)** 

**Fig 4**. Participants (N = 27, 20 females, 7 males) were asked to listen to rhythms and rate how clearly they felt the beat from a scale of 1 – 9 (1 = very weak, 9 = very strong). The rhythms had regular or irregular accents (simple or complex) and different jitter levels (0, 0.2, 0.4, 0.6). They rated the rhythms first without tDCS and then rated the same rhythms with either cathodal or anodal tDCS. Data shown is the mean beat rating ± SD over **a)** simple and complex rhythms, **b)** rhythms with different levels of jitter (0, 0.2, 0.4, 0.6). A mixed four-way ANOVA yielded a significant main effect of regular accents and level of jitter. Specifically, the mean beat rating of simple rhythms was significantly higher than complex rhythms (p<0.001, \*\*\*). Rhythms with no jitter and rhythms with 0.2 jitter both had a significantly higher rating than rhythms with 0.4 or 0.6 level of jitter (p<0.01, \*\*).

rhythms with 0.6 jitter (p<0.001, Figure 5). Simple rhythms with no jitter also had significantly higher beat ratings than simple rhythms with 0.4 jitter (p<0.05, Figure 5). However, there was no significant main effect or interaction with the presence or the polarity of tDCS in mean beat ratings (Figure 5).

*Proportion of Trials Passed with a threshold of percent error*

 The mean proportion of trials passed with 20% error yielded similar results to the previous two analyses – a main effect of beat strength (Figure 6a), a main effect of jitter level (Figure 6b), and an interaction between beat strength and jitter (Figure 7). There was a significant reduction in proportion of trials passed with 20% error in complex rhythms compared to simple rhythms (p<0.0001, Figure 6a). Rhythms with jitter levels 0 and 0.2 also had significantly higher proportion of trial passed with 20% error compared to rhythms with jitter level 0.4 and 0.6 (p<0.05, Figure 6b). The complex rhythms did not differ significantly between jitter levels, but they had a lower proportion of trials passed with 20% error on average compared to the simple rhythms (Figure 7). Simple rhythms with no jitter had a significantly higher proportion passed compared to complex rhythms and simple rhythms with 0.4 and 0.5 jitter (p<0.001, Figure 7). There was also a decreasing trend in the proportion of trials passed in simple rhythms as the jitter level increased (Figure 7). With tDCS stimulation, there was a significantly higher proportion of trial passed with 15% error compared to sham (p<0.05, Figure 8a), but the complex rhythms did not show a significant difference between sham and stimulation. Proportion of trials passed with 20% error also showed no significant difference between sham and stimulation in both simple and complex rhythms, but there was a slight increasing trend

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**Fig 5**. Participants (N = 27, 20 females, 7 males) were asked to listen to rhythms and rate how clearly they felt the beat from a scale of 1 – 9 (1 = very weak, 9 = very strong). The rhythms had regular or irregular accents (simple or complex) and different jitter levels (0, 0.2, 0.4, 0.6). They rated the rhythms first without tDCS and then rated the same rhythms with either cathodal or anodal tDCS. Data shown is the mean beat rating ± SD over different levels of jitter (0, 0.2, 0.4, 0.6) grouped into simple and complex rhythms. A mixed four-way ANOVA yielded an interaction between regular accents and levels of jitter. A subsequent Tukey’s post-hoc test showed that the beat ratings for simple rhythms with no jitter or 0.2 jitter were significantly higher than all of the complex rhythms and simple rhythms with 0.6 jitter (p<0.001). Simple rhythm with no jitter also had significantly higher beat ratings than simple rhythms with 0.4 jitter (p<0.05). Means with different letters are significantly different from each other (p<0.05).

**a)**  **b)** ****

**Fig 6**. Participants (N = 27, 20 females, 7 males) were asked to reproduce rhythms with or without regular accents (simple or complex) and different jitter levels (0, 0.2, 0.4, 0.6), first without tDCS and then with either cathodal or anodal tDCS. Their reproduced inter-tap intervals (ITIs) were measured, and mean percent error were calculated. Data shown is the mean proportion of trials passed with 20% error (%) ± SEM **a)** over simple and complex rhythms and **b)** over different levels of jitter. A four-way mixed ANOVA demonstrated a significant main effect of the presence of a regular accent and levels of jitter. Subsequent Tukey’s Post Hoc test revealed that complex rhythms had a significantly higher mean proportion of trials passed with 20% error compared to simple rhythms (p<0.0001, \*\*\*\*), and 0.6 level of jitter had a significantly lower mean proportion of trials passed compared to 0 and 0.2 levels of jitter (p< 0.05). Means with different letters are significantly different from each other (p<0.05).



**Fig 7**. Participants (N = 27, 20 females, 7 males) were asked to reproduce rhythms with or without regular accents (simple or complex) and different jitter levels (0, 0.2, 0.4, 0.6), first without tDCS and then with either cathodal or anodal tDCS. Their reproduced inter-tap intervals (ITIs) were measured, and mean percent error were calculated. Data shown is the mean proportion of trials passed with 20% error (%) ± SEM over different levels of jitters and grouped into simple and complex rhythms. A four-way mixed ANOVA revealed an interaction between the presence of regular accents and the level of jitter. Subsequent Tukey’s post-hoc tests showed that the complex-rhythms-produced means were not significantly different from each other, but they all had a significantly lower proportion of trial passed with 20% error compared to simple rhythms with 0 jitter (p<0.001) or 0.2 level of jitter (p<0.001). There is also a gradual decreasing trend in the proportion of trial passed with 20% error in simple rhythms. Means with different letters are significantly different from each other (p<0.05).

**a)** **b)** 

**Fig 8**. Participants (N = 27, 20 females, 7 males) were asked to reproduce rhythms with or without regular accents (simple or complex) and different jitter levels (0, 0.2, 0.4, 0.6), first without tDCS and then with either cathodal (N = 14) or anodal tDCS (N = 13). Their reproduced inter-tap intervals (ITIs) were measured, and mean percent error were calculated. Data shown is the mean proportion of trials passed with **a)** 15% error and **b)** 20% error (%) ± SEM over sham vs. stimulation (cathodal and anodal stimulation combined), grouped into simple and complex rhythms. A four-way mixed ANOVA revealed an interaction between presence of regular accents (beat complexity) and the presence of stimulation (regardless of polarity). Subsequent Tukey’s post-hoc tests showed that the complex rhythms produced significantly lower proportion of trials passed with 20% error compared to simple rhythms (p < 0.0001), but there was no significant difference between sham and stimulation conditions with 20% error threshold. However, stimulation resulted in an increasing trend in proportion of trials passed with 20% error in simple rhythms, but a decreasing trend in complex rhythms. Proportion of trials passed with 15% error significant increased with stimulation compared to sham in simple rhythms (p<0.05). Means with different letters are significantly different from each other (p<0.05).

with stimulation compared to sham in simple rhythms and a slight decreasing trend with stimulation compared to sham in complex rhythms (Figure 8b).

**Discussion**

 Our results showed that increased jitter decreased participants’ performance in the rhythm reproduction task and impaired perception of a beat in simple rhythms. The impairment seemed to be “dose-dependent”, as there was an increasing trend in the mean percent error and a decreasing trend in the beat ratings of simple rhythms as the jitter level increased. This supported our first hypothesis, and it suggested that significant differences in impairment started at 0.4 level of jitter in simple rhythms. In complex rhythms however, reproduction accuracy and beat ratings were not significantly affected by jitter levels, but they had an overall significantly higher reproduction inaccuracy and significantly lower beat ratings compared to the simple rhythms. This finding is consistent with previous research that beat induction in humans requires both integer-ratio related intervals and regular perceptual accents to be present in the rhythm (Povel and Essens, 1985; Grahn and Brett, 2007; Rajendran *et al.*, 2018). Our results also suggested that the ability to perceive integer-ratio-related intervals of a rhythm requires the presence of regular perceptual accents, as having irregular perceptual accents with integer-ratio-related intervals resulted in similar levels of impairment in rhythm reproduction and beat perception as having high levels of jitter with regular accents.

 In addition, negative mean synchrony is defined as the tendency for humans to anticipate and tap before the onset of each sound stimuli in the rhythm (Aschersleben, 2002). Humans also tend to underestimate longer intervals and overestimate shorter intervals in rhythms (Rajendran *et al.*, 2018). The analysis of data in the form of proportion of trial passed with a threshold percent error is able to account for these natural tendencies that exist in humans, as they define error within a certain range to be acceptable and categorizes the results for each rhythm into a pass or a fail. The proportion of passed rhythms would be a good representation of how well the participant is able to produce rhythms in each condition. In fact, this analysis showed very similar results as the mean percent error analysis. Also, it showed an interaction between having regular accents and the presence of stimulation regardless of polarity for thresholds of 15% and 20%. Interestingly, at 20% error threshold, although the difference between sham and stimulation were not significant, stimulation showed a slight increase in the accuracy of reproduction in simple rhythms but a slight decrease in complex rhythms compared to sham. However, at 15% error threshold, stimulation significantly improved reproduction accuracy in simple rhythms, but no significant effect of stimulation was shown in complex rhythms. This is suggesting that effects of stimulation of either polarity is more prominent in simple rhythms. This re-articulates the importance of regular perceptual accents in beat induction, as it seems with irregular perceptual accents, there will be a significant amount of impairment such that other factors inducing the beat would not elicit a significant improvement.

 tDCS of the SMA did not modulate reproduction in an expected manner. Specifically, cathodal stimulation showed a significant improvement in rhythm reproduction compared to sham, but anodal stimulation was not significantly different from sham. However, stimulation of the SMA did not affect the ability to perceive beat in participants, as beat rating data did not show any interactions or main effects related to stimulation. Reproduction requires a motor component which is responsible for tapping the rhythm with a finger, whereas perception requires a cognitive component to recognize the underlying pulse and patterns in the rhythm. One possible explanation is that the SMA may play a role in the activation of motor systems after the cognitive process has recognized the beat, but it does not necessarily play a direct role in the perception of beats. A previous study that have suggested that the SMA has a role in pre-planning of movements and the prepared activation level of the motor system (Carlsen *et al.*, 2015), and it is supported by the results of this study because the rhythm reproduction task in this study requires the participants to plan the temporal positions of each finger tapping movement according to the rhythm. However, this does not explain why the SMA had significant heightened activity in fMRI studies when people were instructed to listen to beat inducing rhythms without movement (Grahn and Brett, 2007).

 Moreover, cathodal stimulation showed the opposite effect of hyperpolarization and decreasing cortical excitability of the SMA, as it improved rhythm reproduction accuracy compared to sham. Our results are not sufficient to suggest a causal relationship between SMA activation and beat perception. However, this may be due to the dosage regime of tDCS used. One study found that 2mA cathodal stimulation of the motor cortex over 20 minutes had similar increasing effects in cortical excitability comparing with 2mA of anodal stimulation, whereas 1mA of cathodal stimulation showed decreased cortical excitability which is congruent with common beliefs. tDCS was used in many brain stimulation studies aiming to decipher the functional significance of areas of the brain, but studies have shown mixed results in effectiveness. Studies that have shown significance may employ a dosage regime that allows stimulation over consecutive days. In fact, a study has shown that stimulation effects of tDCS is greater post-stimulation compared to during stimulation. My study is done with 2mA of tDCS over 20 minutes while the participants perform the rhythm reproduction task, which may have been affected by either the elevated dose of 2mA rather than 1mA, or the single session stimulation while doing the task, or both. Hence, further studies need to be conducted in order to conclude SMA’s causal relationship with rhythm reproduction or beat perception.

 My study is limited, in that the stimulation block always followed the sham block due to concerns regarding stimulation effects lasting post-stimulation and affecting sham block performance if the order were to be switched. This study design may have introduced a confounding variable of practice effect. Future studies should focus on implementing better randomization of the order of sham and stimulation blocks, experimenting with various dosage regimes such as 1mA of tDCS over 40 minutes, and stimulation over consecutive days. Using a HD-tDCS may also improve the accuracy of delivering stimulation to the specific brain area of interest as my study used silicone electrodes with a large contact area.

 This study confirmed previous findings that beat induction requires both integer-ratio related intervals and regular perceptual accents to be present in rhythms. We found that beat perception and rhythm reproduction performance is adversely affected by jittered intervals in a “dose-dependent fashion”. tDCS of the SMA suggested that it has a potential role in the motor component of rhythm reproduction, but not in the cognitive process of beat perception.

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