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Pitch Memory in Nonmusicians and Musicians: Revealing Functional Differences Using Transcranial Direct Current Stimulation

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For music and language processing, memory for relative pitches is highly important. Functional imaging studies have shown activation of a complex neural system for pitch memory. One region that has been shown to be causally involved in the process for nonmusicians is the supramarginal gyrus (SMG). The present study aims at replicating this finding and at further examining the role of the SMG for pitch memory in musicians. Nonmusicians and musicians received cathodal transcranial direct current stimulation (tDCS) over the left SMG, right SMG, or sham stimulation, while completing a pitch recognition, pitch recall, and visual memory task. Cathodal tDCS over the left SMG led to a significant decrease in performance on both pitch memory tasks in nonmusicians. In musicians, cathodal stimulation over the left SMG had no effect, but stimulation over the right SMG impaired performance on the recognition task only. Furthermore, the results show a more pronounced deterioration effect for longer pitch sequences indicating that the SMG is involved in maintaining higher memory load. No stimulation effect was found in both groups on the visual control task. These findings provide evidence for a causal distinction of the left and right SMG function in musicians and nonmusicians.

Keywords: cathodal stimulation, expertise, functional involvement, plasticity, supramarginal gyrus

Introduction

The musicians' brain has been studied extensively as a model for neuroplasticity over the last 2 decades (Herholz and Zatorre 2012; Merette et al. 2013 for recent overviews). Findings from cross-sectional brain imaging studies comparing brain structures of musicians and nonmusicians suggest that multiple anatomical differences exist including motor areas (Jäncke et al. 1997), gray matter volume in Heschl's gyrus (Schneider et al. 2002) and the corpus callosum (Schlaug et al. 1995). Furthermore, studies have shown different activation patterns for musicians and nonmusicians for several cognitive tasks (e.g., verbal and tonal memory: Schulze, Zysset et al. 2011; processing rhythms: Herdener et al. 2014; pitch perception: Habibi et al. 2013). A longitudinal intervention study by Hyde et al. (2009) found that after 15 months of musical training children show anatomical differences in the motor hand area, corpus callosum, and right auditory cortex compared with a control group.

Even though such longitudinal studies are relatively sparse, the reasons behind the specialization of neural structures in individuals with musical training can be traced back to the fact that learning an instrument requires extensively regular and deliberate practice (Ericsson et al. 1993), often starting at a very young age. Furthermore, playing an instrument is a highly complex skill whereby one has to integrate higher-order cognitive functions and control very fine motor movements (Wan and Schlaug 2010). Evidence cited in support of a link between musical training and neuroplasticity includes consistent age of onset effects (Barrett et al. 2013 for a review). Thus, it is likely that the brain adapts to these exceptional demands (Münte et al. 2002; Gaser and Schlaug 2003).

Functional imaging studies investigating neural networks of pitch memory in nonmusicians have shown involvements of frontal, temporal, and parietal areas (Zatorre et al. 1994; Koelsch et al. 2009; Jerde et al. 2011). More specifically, in subjects with no or very little musical training, Gaab et al. (2003) showed that pitch memory recruits a network of neural regions, including the superior temporal gyri, bilateral posterior dorsolateral frontal regions, bilateral superior parietal regions, bilateral lobes V and VI of the cerebellum, the supramarginal gyri, and the left inferior frontal gyrus. The activation of the left supramarginal gyrus (SMG) was of particular interest as higher activation in this region was linked to superior pitch memory performance (Gaab et al. 2003).

To investigate the causal involvement of specific brain areas in pitch memory, noninvasive brain stimulation methods, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), are useful, as they enable the manipulation of cortical excitability in a targeted area (Nitsche and Paulus 2001; Antal et al. 2004). Whereas anodal tDCS leads to a facilitation of neural activity, cathodal tDCS suppresses the cortical excitability under the site of stimulation (Nitsche and Paulus 2000; Cohen Kadosh et al. 2010; Ladeira et al. 2011). Previous tDCS studies have supported the causal involvement of the left SMG in pitch memory recognition by showing a deterioration of performance after cathodal stimulation (Vines et al. 2006) and an improvement of pitch memory on a recognition and recall task (but not visual memory) after anodal stimulation in nonmusicians (Schaal et al. 2013). To date however, there are no tDCS studies of the SMG in trained musicians, so the causal role of the left SMG in superior pitch memory performance remains to be tested.

One other relevant feature of SMG activation during music processing in musicians and nonmusicians has been contrary hemispheric patterns. Gaab and Schlaug (2003) revealed stronger activation in the right SMG in musicians compared with nonmusicians during a pitch memory task when performances of both groups were matched, indicating different underlying cognitive processing. However, several other studies have reported stronger activation in the left SMG in musicians during music listening (Seung et al. 2005) and pitch memory (Ellis et al. 2013). Schulze, Zysset et al. (2011) compared verbal (memorizing syllables) and tonal (memorizing pitches) working memory in musicians and nonmusicians and revealed overlapping activation patterns including the left inferior parietal lobe (corresponding to the location of the SMG), in both groups for the memory processes. Furthermore, in the musician group, additional activation was found in the right globus pallidus, right caudate nucleus, and left cerebellum during tonal working memory suggesting that musicians use a specialized and more complex neural system for memorizing pitches.

An important note in this context is that the functional magnetic resonance imaging (fMRI) studies mentioned above all used recognition tasks to investigate neural correlates of pitch memory (Zatorre et al. 1994; Gaab et al. 2003; Gaab and Schlaug 2003; Koelsch et al. 2009; Jerde et al. 2011; Schulze, Zysset et al. 2011; Ellis et al. 2013). In general, short-term memory can be tested by 2 response methods, recognition and recall. Whereas recognition relies on a monitoring process for re-presented stimuli, recall tasks include more demanding production processes. A study comparing memory for auditorily and visually presented words has shown that underlying activity of neural structures varies depending whether recall or recognition processes were required (Cabeza et al. 2003). This is often traced back to different strategies used in different task procedures. Furthermore, activation differences found in studies using different recognition tasks may also be due to subtle but important task demand differences which require varying memory processes such as maintenance and rehearsal. For example, the study by Gaab et al. (2003) used a recognition task which only emphasized maintenance of pitch information, whereas the task demands in the study by Schulze, Zysset et al. (2011) required maintenance and explicitly instructed participants to use rehearsal processes. These task demand differences could explain why the activation found in the SMG in the study by Gaab et al. (2003) is more inferior than the inferior parietal activation found by Schulze, Zysset et al. (2011).

The aim of the present study is to investigate whether functional differences of the SMG can be found between musicians and nonmusicians in pitch memory and to clarify whether any such differences can be attributed to memory task demands. Therefore, performances on 2 pitch memory tasks (recognition and recall) and a visual control task were investigated following cathodal tDCS over the left SMG, right SMG, or sham stimulation. In line with previous studies, we hypothesized that in nonmusicians, cathodal stimulation over the left SMG would lead to a deterioration of performance on both pitch memory tasks (Vines et al. 2006; Schaal et al. 2013). Regarding the musicians group, 3 outcomes are possible: (1) cathodal stimulation over the left SMG results in deterioration of pitch memory performance, as stronger activation in the left SMG of musicians was found by Ellis et al. 2013, (2) cathodal tDCS over the right SMG would lead to a drop in pitch memory performance, as musicians show more right hemispheric activation for musical memory (Gaab and Schlaug 2003), or (3) no stimulation effect would be found as musicians activate a more complex neural system for the pitch memory process and can compensate for any stimulation modulations (Schulze, Zysset et al. 2011).

Materials and Methods

Participants

Forty-one nonmusicians and 38 musicians took part in the pretesting phase of the experiment and 36 participants from each group returned for the tDCS session (4 participants had to be excluded for health reasons and 3 subjects did not return for the second session). Nonmusicians were defined as individuals with <2 years of musical training in the past and who were not playing an instrument at present. They were all students, mostly psychology students, at the Heinrich-Heine-University in Düsseldorf, and received either course credits or 6 Euro per hour for their participation. The musicians were all students of a professional music college aiming to make music as their profession and all had at least 10 years of formal musical training. Six string players, 12 wind players, 8 singers, 7 pianists, and 3 musicians playing a plucked instrument comprised the musicians group. None of the musicians were absolute pitch possessors. Musicians received 6 Euro per hour for their participation as well as travel expenses.

All participants were self-report right-handed and reported normal hearing abilities. For the tDCS session, nonmusicians and musicians were split into 3 groups, depending on type and location of stimulation (i.e., left SMG vs. right SMG vs. sham). Groups were matched by age, sex, musical training, as evaluated by the dimension *Musical Training* from the Goldsmiths Musical Sophistication Index questionnaire (Gold-MSI, Müllensiefen et al. 2014), and general pitch memory abilities, which were evaluated in a pretest session. See Table 1 for full demographical details.

Additionally, 4 participants (2 nonmusicians and 2 musicians) came back a third time to take part in a neuronavigation session to control the location of stimulation targeting at either the left or right SMG. The ethics committee of the Medical Department of the Heinrich-Heine-University in Düsseldorf approved this study and all subjects gave their informed written consent to participate.

Materials and Procedure

All participants completed 2 parts, preliminary testing and the tDCS session, which were at least 48 h apart.

Table 1
Characteristics of participants

Group	Stimulation group	*N*	Sex	Mean age (in years)	Musical training score—Gold-MSI (range: 7–49)	Pretest pitch memory recognition task (in tones)
Nonmusicians	Cathodal lSMG	12	4 Males 8 Females	23.3 ± 4.5	12.83 ± 5.2	5.86 ± 1.1
	Cathodal rSMG	12	3 Males 9 Females	21.7 ± 2.3	14.58 ± 4.8	5.84 ± 1.5
	Sham lSMG	12	5 Males 7 Females	26.2 ± 8.3	15.50 ± 5.5	5.99 ± 1.2
Musicians	Cathodal lSMG	12	5 Males 7 Females	22.5 ± 2.7	42.08 ± 3.9	7.24 ± 0.9
	Cathodal rSMG	12	5 Males 7 Females	23.9 ± 4.2	42.42 ± 3.9	7.24 ± 1.0
	Sham lSMG	12	3 Males 9 Females	23.8 ± 3.0	41.50 ± 1.7	7.35 ± 1.2

Preliminary Testing

Preliminary testing was conducted in order to match the stimulation groups on musical training and general pitch memory abilities. The pitch memory span task (Williamson and Stewart 2010) was used to test general pitch memory capacity. The participants listened to the stimuli via headphones (AKG Pro Audio, K77). Tone sequences were formed of 10 triangle-waveform tones (equally tempered, whole tone steps) with fundamental pitches ranging from 262 Hz (C4) to 741 Hz (F#5). Tones were 500-ms long with a 383-ms pause between tones when they were in sequence. For each trial, 2 tone sequences of equal length were presented, with an intersequence interval pause of 2 s. On 50% of trials, the 2 sequences were identical and in 50% they varied; in the latter case 2 tones of the second sequence were presented in the reversed position (i.e., list probe method). The task was to decide whether the 2 sequences were the same or different. After the participant's decision was recorded, a 2-s long pink noise burst was presented to minimize carry-over effects before the next trial. Sequences were 2 tones long to start with and then increased and decreased according to the participant's performance. A 2-up, one-down adaptive tracking procedure (2 right answers = increase in sequence length by one tone, one wrong answer = decrease in sequence length by one tone) was used. The task was complete when the procedure had run for 8 reversals. The longest sequence played to this sample was 11 tones long.

To ensure that participants were able to discriminate the 3 different tones that were used in the main pitch recall task (Williamson et al. 2010), which was part of the tDCS session, the participants also completed a short single pitch recognition test. In the exposure phase of this preliminary test, participants heard a C-major (C4, E4, G4) chord followed by a sequence of the 3 tones (low-C4, medium-G4, and high-B4) played in succession, 10 times. In the test phase, a C-major chord was played as a get-ready signal, followed after a 2-s pause by one of the 3 tones. The participant was required to mark on a grid, if the tone was the low, medium, or high one. There were 12 trials, where each tone was randomly presented 4 times. Participants had to score at least 10 out of 12 to qualify for the main tDCS phase of the study.

After the 2 pitch memory tasks, the participants filled in a German version of the self-report questionnaire of the Gold-MSI version 1.0 (Müllensiefen et al. 2014) to evaluate their level of musical training. The participants scored statements on a 7-point scale from "completely disagree" to "completely agree". The questionnaire consists of 38 statements and comprises 5 dimensions: *Active Engagement*, *Perceptual Abilities*, *Musical Training*, *Emotions* and *Singing Abilities*. The dimension of interest *Musical Training* contains 7 statements, so the score range is 7–49 points.

tDCS Session

At least 2 days after the preliminary test, participants returned to complete the tDCS session. The participants from both groups (nonmusicians and musicians) were matched as described above and randomly split into 3 stimulation groups: one group receiving cathodal tDCS over the left SMG, another group receiving cathodal stimulation over the right SMG and the third group receiving sham stimulation over the left SMG.

The active electrode (5×5 cm = 25 cm^2) was placed over either the left or right SMG. The areas were located using area CP3 for the left and CP4 for the right hemisphere according to the international 10–20 system for electroencephalogram electrode placement, successfully used in previous studies to place the electrodes over the targeted site (Antal et al. 2004, Rogalewski et al. 2004, Vines et al. 2006). CP3 and CP4 are common locations for targeting the SMG on either hemisphere (Mottaghy et al. 2002; Schaal et al. 2013). The reference electrode (5×7 cm = 35 cm^2) was placed over the contralateral supraorbital area. A slightly smaller active electrode compared with the size of the reference electrode was used to receive a more selective and focally precise stimulation (Nitsche et al. 2007). The electrodes were covered in saline-soaked sponges. The 2 active stimulation groups received 20 min of 2-mA stimulation including 15 s fade-in and fade-out time. An identical setup was used for the sham group, but the stimulator was only turned on for the first 30 s. This evokes the sensation of being stimulated but does not lead to a neurophysiological change that can influence performance. It has been shown that naive subjects cannot distinguish between sham and active tDCS stimulation (Gandiga et al. 2006).

The first 10 min of the stimulation period were used to familiarize the participants with the memory tasks. Altogether the 3 memory tasks of the tDCS session took ~35–40 min. The order of the 3 memory tasks was counterbalanced using a latin-square design.

The pitch memory recognition task (pitch span task) was conducted exactly in the same manner as in the preliminary test. For the pitch memory recall task (Williamson et al. 2010), 3 tones (C4 = 262 Hz, G4 = 392 Hz, and B4 = 494 Hz) were recorded, played by a piano (Disklavier Pro, Yamaha Corporation), and edited to .wav files using Adobe Audition. Each tone was 800-ms long, edited in Adobe Audition, and a 200-ms pause was added to the end so that every file was 1-s long. Pitch sequences were 4–8 tones long and made up of the 3 different tones (low: C4, medium: G4, high: B4) without direct repetition (there was always a movement in the contour). There were 5 blocks (one for each sequence length: 4, 5, 6, 7, and 8 tones) with 6 trials each. To ensure that task demands were clear, a short practice phase with 5 trials (one for each sequence length) was conducted before the first test block. The stimuli were presented via speakers and the participants received an answer booklet, containing blank grids of 3 rows in height (representing high, medium, and low tones) and a number of columns according to the sequence length, and a pen for their responses. To signal the onset of a test sequence, a C-major chord (C4, E4, and G4) was played at the beginning of a trial. Participants then listened to the first sequence (4 tones long), while the answer booklet was turned upside-down and were instructed to listen to the contour (movement of the tones) and try to memorize it. They were instructed to turn over the booklet as soon as the sequence finished and to tick the boxes to record their memory of the pitch sequence. For example, if for a 4-tone-long sequence, the tones "C4–G4–B4–C4" were played, the correct answer would be to tick the boxes "low–medium–high–low" on the grid. When happy with their response, the subjects turned over the booklet again and triggered the next sequence by pressing the spacebar.

A visual task was included as control condition. The Cambridge Face Memory Test—long form (CFMT+, Russell et al. 2009) was chosen as it does not require any auditory or phonological encoding, but has previously been shown to be sensitive to detecting differences in face memory performance (e.g., Russell et al. 2009). In this task participants were instructed to memorize 6 unfamiliar male faces from 3 different views and were then tested on their ability to recognize them in a 3-alternative forced-choice task. The test comprises 102 trials (proceeded by 3 practice trials), subdivided into 4 sections varying in difficulty. The first section of the task tested recognition with the same images that were used during training. This was followed by a section involving presentation of novel images that show the target faces from untrained views and lighting conditions in the test phase. A third section consisting of novel images with visual noise added. The final section contained trials in which distractor images repeated more frequently, targets and distractors contained more visual noise than the images in the third section, cropped (only showing internal features) and uncropped images (showing hair, ears, and necks, which had not been shown in the previous sections) were used, and images showing the targets and distractors making emotional expressions were included. The first and second sections used a trial-by-trial recognition paradigm, whereas sections 3 and 4 employed a more long-term memory approach. The percentage of correct responses was measured.

Neuronavigation

To validate the location of stimulation and to show that the electrode was placed over the targeted area of the SMG (Brodmann area 40) a Neuronavigation session was conducted with a small exemplary sample of 4 participants (2 musicians and 2 nonmusicians). To reconstruct the procedure of the tDCS session the international 10–20 system was used to locate the area of the left (CP3) and right (CP4) SMG on the participant's scalp. After marking this localization with a highlighter, the Neuronavigation (Localite GmbH, Sankt Augustin, Germany) procedure began with measuring the head using predefined points (i.e., left and right preauricular points and nasion). After mapping the anatomical landmarks onto a standardized brain, 2 markers were inserted according to the highlighted points on the scalp located at CP3 and CP4. The program then identified the Talairach coordinates for the markers.

Results

Pitch Memory Recognition Task

As participants completed the pitch span task twice (in the preliminary session and after tDCS) a mixed factorial analysis of variance (ANOVA) with *time* (pre vs. poststimulation) as a within subject factor and *group* (nonmusicians vs. musicians) and *stimulation group* (cathodal left SMG vs. cathodal right SMG vs. sham) as between subject factors was conducted. The analysis revealed a trend for the factor *time*, $F_{1,66} = 3.67$, $P = 0.06$, and a nonsignificant result for factor *stimulation group*, $F_{2,66} = 1.18$, $P = 0.32$, whereas the main effect of factor *group* was significant, $F_{1,66} = 31.21$, $P < 0.001$. The interactions *time* × *group*, *time* × *stimulation group* and *group* × *stimulation group* are all nonsignificant ($P > 0.14$) but the *time* × *group* × *stimulation group* interaction yielded a significant result, $F_{2,66} = 4.73$, $P = 0.012$. Data are summarized in Table 2.

In order to explore the significant *time* × *group* × *stimulation group* interaction, 2 univariate ANOVAs were applied, one for the prestimulation and one for the poststimulation phase. Where appropriate, all post hoc tests were subject to sequential Bonferroni correction (Holm 1979) in order to compensate for multiple tests and to protect type I errors. Therefore, for every post hoc set *P*-values were ranked and the smallest *P*-value was tested with a Bonferroni correction including all tests, the second smallest was tested involving one less test and so forth for the remaining tests.

Table 2
Overview of performances for all 3 stimulation groups in nonmusicians and musicians

Group	Stimulation group	Pitch memory recognition task (in tones)	Pitch memory recall task (percent correct)	CFMT+ percent correct)
Nonmusicians	Cathodal lSMG	**5.04** ± 0.8	**72.56** ± 8.2	62.26 ± 11.4
	Cathodal rSMG	6.08 ± 1.0	80.95 ± 4.9	66.58 ± 8.0
	Sham lSMG	6.26 ± 1.1	80.75 ± 6.2	63.24 ± 12.8
Musicians	Cathodal lSMG	7.11 ± 0.9	90.37 ± 5.8	60.93 ± 15.3
	Cathodal rSMG	**6.42** ± 0.9	91.67 ± 4.5	62.83 ± 6.8
	Sham lSMG	7.25 ± 1.0	91.09 ± 4.3	66.99 ± 8.9

Note: The bold values highlight the group performances which show a significant deterioration after cathodal stimulation.

Before stimulation a significant main effect of *group*, $F_{1,66} = 24.16$, $P < 0.001$ was revealed. The main effect of *stimulation group* as well as the *group* × *stimulation group* interaction were nonsignificant (*P*-values > 0.92). Poststimulation, the ANOVA revealed a significant main effect of *group*, $F_{1,66} = 25.72$, $P < 0.001$ and a significant *group* × *stimulation group* interaction, $F_{2,66} = 5.16$, $P = 0.016$. The main effect of *stimulation group* was nonsignificant ($P = 0.082$).

Furthermore, independent sample *t*-tests were applied in order to dissolve the significant *group* × *stimulation group* interaction of the poststimulation session. In the stimulation group receiving cathodal tDCS over the left SMG, a highly significant difference of the factor *group* was revealed, $t_{(22)} = 5.96$, $P < 0.001$. In the stimulation group receiving cathodal tDCS over the right SMG, the result was nonsignificant, $t_{(22)} = 0.88$, $P = 0.39$, and in the sham group, a trend towards superior performance of the musicians compared with the performance of nonmusicians was present, $t_{(22)} = 2.32$, $P = 0.06$. This series of results suggests that the musicians' superior performance in all stimulation groups before stimulation was not present anymore after stimulation only in the group who received cathodal tDCS over the right SMG.

To explore this interesting finding, a pre- and poststimulation comparison in the musicians group receiving cathodal stimulation of the right SMG was applied and showed a significant result, $t_{(11)} = 2.76$, $P = 0.02$ indicating that cathodal stimulation over the right SMG in musicians led to a deterioration of pitch memory performance. Additionally, in nonmusicians a pre- and poststimulation comparison in the group receiving cathodal tDCS over the left SMG revealed a significant deterioration of pitch memory, $t_{(11)} = 3.67$, $P = 0.008$ (see Fig. 1).

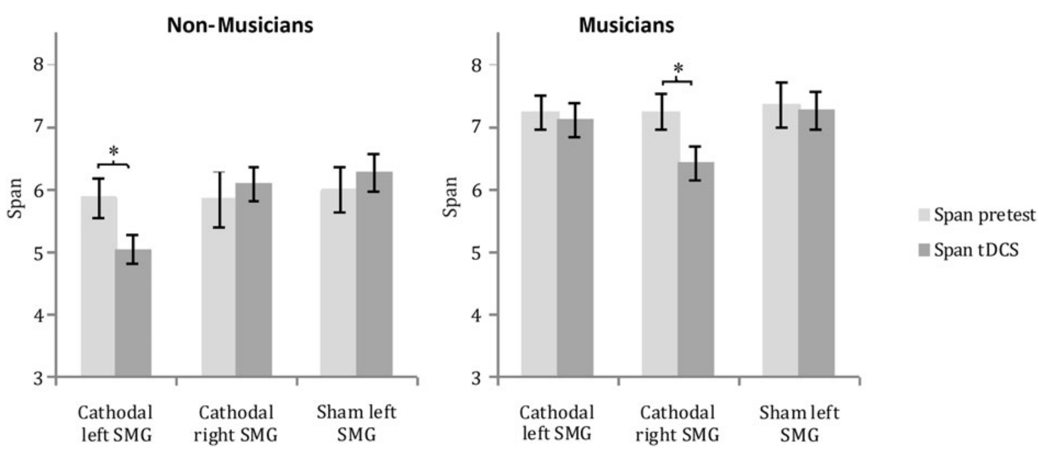

Figure 1. Bargraphs representing the results of the pitch memory recognition task. A mixed factorial ANOVA with the factors *time* (pre vs. poststimulation), *group* (nonmusicians vs. musicians) and *stimulation group* (cathodal left SMG vs. cathodal right SMG vs. sham) reveals a significant *time* × *group* × *stimulation group* interaction, $F_{2,66} = 4.73$, $P = 0.012$. In nonmusicians, cathodal tDCS over the left SMG leads to a significant deterioration of pitch recognition ($t_{(11)} = 3.67$, $P = 0.008$), while in musicians cathodal tDCS over the right SMG results in declined performance ($t_{(11)} = 2.76$, $P = 0.02$).

Pitch Memory Recall Task

An ANOVA with factors *group* (nonmusicians vs. musicians) and *stimulation group* (cathodal left SMG vs. cathodal right SMG vs. sham) on overall recall performance scores yielded main effects of *group*, $F_{1,66} = 89.5$, $P < 0.001$, and *stimulation group*, $F_{2,66} = 5.14$, $P = 0.008$, and a significant *group* × *stimulation group* interaction, $F_{2,66} = 3.15$, $P = 0.049$. Data are summarized in Table 2.

Post hoc independent sample *t*-tests with sequential Bonferroni correction (Holm 1979) in nonmusicians showed significant differences between the group receiving cathodal stimulation over the left SMG and the groups receiving stimulation over the right SMG, $t_{(22)} = 3.04$, $P = 0.018$, and sham stimulation, $t_{(22)} = 2.76$, $P = 0.024$. The group with cathodal tDCS over the left SMG performed significantly below the sham group, and the group stimulated with cathodal tDCS over the right SMG (Fig. 2*A*). The difference between the groups receiving cathodal tDCS over the right SMG and sham stimulation was nonsignificant, $t_{(22)} = 0.08$, $P = 0.93$.

For the musicians group, no significant differences in overall performance could be found in the 3 stimulation groups ($P > 0.55$), indicating that cathodal stimulation over the left or right SMG did not affect task performance.

A 5 × 2 × 3 mixed factorial ANOVA with *sequence length (5)* as the repeated measure variable and *group (2)* and *stimulation group (3)* as between subject variables revealed a significant main effect of *sequence length*, $F_{4,264} = 144.35$, $P < 0.001$, and a follow-up trend analysis revealed a significant linear trend ($P < 0.001$) indicating that performances decreased as sequence length increased. Furthermore, the ANOVA confirmed significant main effects of *group* ($P < 0.001$) and *stimulation group* ($P = 0.017$) and also showed significant interaction effects of *sequence length* × *group* ($P < 0.001$) and *group* × *stimulation group* ($P = 0.023$). The *sequence length* × *stimulation group* as well as the 3-way interaction *sequence length* × *group* × *stimulation group* were nonsignificant (*P*-values > 0.155).

In order to further investigate the significant *sequence length* × *group* and *group* × *stimulation group* interaction, performance on the pitch memory recall task for every sequence length (percent correct for 4-tone-long sequences, 5-tone-long sequences etc.) was analyzed. In nonmusicians, the ANOVA revealed nonsignificant main effects of factor *stimulation group* for 4-, 5- and 6-tone-long sequences (*P*-values > 0.10). For the 7-tone sequences a significant main effect of factor *stimulation group* was found, $F_{2,35} = 5.86$, $P < 0.01$, $\eta^2_p = 0.26$. Post hoc comparisons (Tukey-HSD) revealed significant differences between the group receiving tDCS over the left SMG and the sham group ($P < 0.01$) and a marginally significant difference between the groups receiving cathodal tDCS over the left or right SMG ($P = 0.054$). For 8-tone-long sequences, also a significant main effect of factor *stimulation group* was found, $F_{2,35} = 8.25$, $P < 0.001$, $\eta^2_p = 0.33$, with significant differences between the group receiving tDCS over the left SMG and the other 2 groups (cathodal tDCS over right SMG vs. sham stimulation, *P*-values < 0.01). These results indicate that the group who received cathodal tDCS over the left SMG showed a deterioration in their performance on longer sequences with higher memory load only (Fig. 2*B*). When conducting the same analysis for every sequence length in the musicians group, all 5 ANOVAs reported *P*-values > 0.381 for the main effect of *stimulation group*, confirming that on the recall task no stimulation effects could be found on the performance of any sequence length in the musicians group.

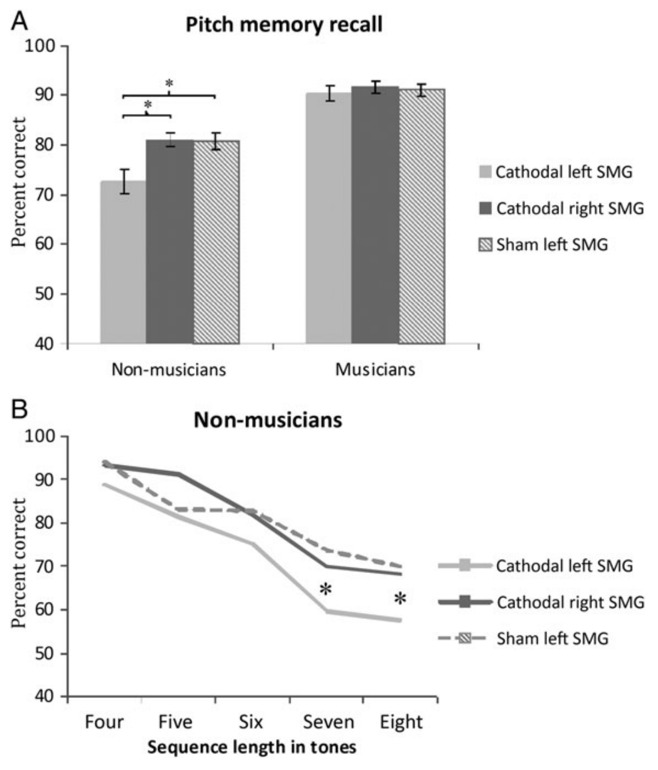

Figure 2. (*A*) For the pitch recall task, there is a significant main effect of stimulation group in nonmusicians showing that performance of the group receiving cathodal tDCS over the left SMG is below the group receiving cathodal stimulation over the right SMG and sham stimulation (*P*-values < 0.05). (*B*) When looking at the performance in nonmusicians for every sequence length, the analysis reveals significant differences of the factor stimulation group for longer sequences (7 and 8 tones) indicating that the deterioration of pitch memory after cathodal stimulation over the left SMG is more pronounced in trials with higher memory load.

Cambridge Face Memory Test—Long Form

For the CFMT+, an ANOVA was conducted with factors *group* (nonmusicians vs. musicians) and *stimulation group* (cathodal left SMG vs. cathodal right SMG vs. sham). The results revealed neither significant main effects nor interaction (*P*-values > 0.48). Data are summarized in Table 2. As the CFMT+ uses 2 different recognition memory paradigms, a trial-by-trial paradigm in Part 1 (blocks 1 and 2) and a more long-term memory approach in Part 2 (blocks 3 and 4), separate ANOVAs were conducted on the percent correct scores for each part with the factors *group* and *stimulation group*: no significant main effects or interactions were found (*P*-values > 0.19). Overall, the evidence strongly suggests that there is no effect of stimulation on the visual control task in either musicians or nonmusicians, thereby indicating that the SMG are not causally involved in the process of remembering faces.

Neuronavigation

The evaluation of the targeted site of all 4 sample participants confirmed that the site which was stimulated corresponds to Brodmann area 40, the location of the SMG. The averaged Talairach coordinates were −44; −43; 49 for the left SMG and 45; −48; 55 for the right SMG corresponding to Brodmann area 40 (Fig. 3).

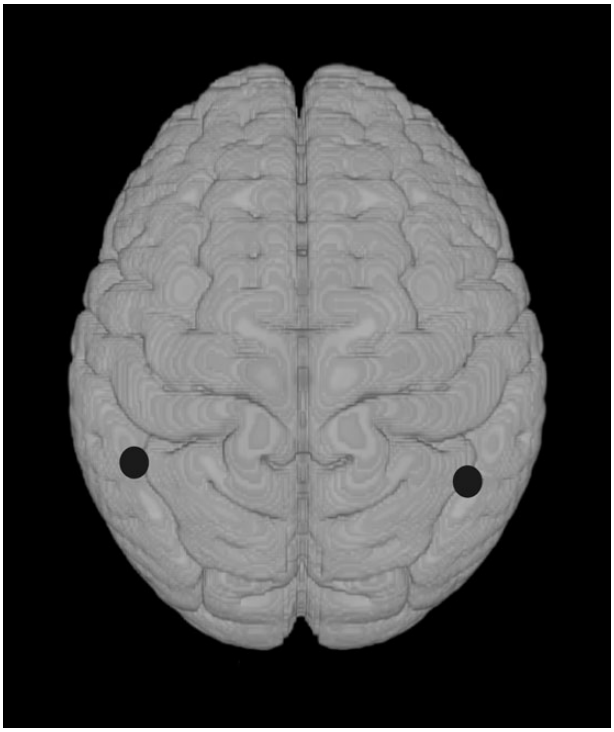

Figure 3. Localization of the left (−44; −43; 49) and right SMG (45; −48; 55) averaged across an exemplary sample of 4 participants (2 nonmusicians and 2 musicians) using neuronavigation.

Discussion

The present study investigated the causal involvement of the left and right SMG in pitch memory ability, as determined by pitch memory recall and recognition paradigms, and how this involvement varies in musicians and nonmusicians indicating functional differences. Whereas cathodal stimulation over the left SMG led to a deterioration of performance in both pitch memory tasks in nonmusicians, the musicians showed a decline only in recognition pitch memory performance and interestingly, only after cathodal tDCS over the right SMG.

In the nonmusicians group, cathodal tDCS over the left SMG led to a significant deterioration of task performance on the pitch recognition task as well as on the pitch recall task compared with the groups receiving cathodal tDCS over the right SMG or sham stimulation. These findings are in line with previous studies showing the activation and causal involvement of specifically the left SMG in the pitch memory process in nonmusicians (Gaab et al. 2003; Vines et al. 2006). These results also extend previous findings showing that anodal tDCS over the left SMG leads to superior pitch memory in nonmusicians (Schaal et al. 2013). In addition, the more detailed analysis of the sequence lengths used in the pitch recall task of the present study showed that the effect of cathodal tDCS over the left SMG is significant for longer pitch sequences only. This new evidence adds to the literature by suggesting that nonmusicians rely more heavily on the left SMG when they are required to either store or rehearse a large amount of material in pitch memory (Sakurai et al. 1998; Gaab et al. 2003; Vines et al. 2006).

The present study also revealed key differences between the effects of SMG tDCS on musicians and nonmusicians. A variety of studies have looked at musicians' brains as a model of neuroplasticity and revealed structural differences compared with nonmusicians (e.g., Schlaug et al. 1995; Jäncke et al. 1997; Schneider et al. 2002; Gaser and Schlaug 2003; Hyde et al. 2009), but to our best knowledge this is the first study to show functional differences in pitch memory tasks using noninvasive brain stimulation. As opposed to the nonmusicians, the pitch memory performance of the musicians group did not show a detrimental effect of cathodal tDCS over the left SMG, neither in the recognition nor recall task. But, cathodal stimulation to the right SMG led to a decrease in their pitch recognition span.

A recent electroencephalography study by Habibi et al. (2013) suggested that the left hemisphere involved in tasks differentiated nonmusicians and musicians, as they found behavioral and electrophysiological differences when stimuli were presented to the right ear. The present data are in line with this idea, showing that musicians and nonmusicians have a differentiated causal involvement of the left SMG during pitch memory tasks. However, when looking at the involvement of the right SMG in the present study, a causal distinction was found as well, indicating that the neural distinction for the pitch memory process between musicians and nonmusicians is not limited to the left hemisphere.

The fact that musicians do not demonstrate a causal involvement of the left SMG in pitch memory is surprising as several fMRI studies have shown increased activation of the left SMG in musicians and in participants after receiving musical training (Gaab et al. 2006; Ellis et al. 2013). One possible explanation for this apparent contradiction is that trained musicians are able to compensate the suppression of a particular brain area during tDCS by activating other areas of their complex neural network for pitch memory. Schulze, Zysset et al. (2011) showed that musicians activate unique and additional neural areas for tonal memory including the right globus pallidus, right caudate nucleus, and left cerebellum. Furthermore, Andoh and Zatorre (2013) have shown an interhemispheric compensation effect by combining TMS and fMRI during a melody discrimination task. When they applied repetitive TMS over the right Heschl's gyrus, an increase of activation was identified in the left hemisphere, thereby revealing potential compensation mechanisms across brain areas, in addition, the same study found positive correlation between the extent of compensated increase of activation in the left Heschl's gyrus and faster reaction times (Andoh and Zatorre 2013).

Another possible explanation for the lack of a left SMG tDCS effect in musicians relates to the way in which this population reacts to brain stimulation. A recent study revealed that bilateral tDCS over the primary motor cortex showed no effect on fine finger movements of pianists (Furuya et al. 2013), while bihemispheric tDCS over the motor cortex in nonmusicians led to a facilitation of such movements (Vines et al. 2008). The results of the musicians were explained to be traced back either simply to a ceiling effect as pianists have developed extremely exact finger movements during their many years of training and deliberate practice or to the neuroplasticity of a musician's brain, which has already optimized its function to highly complex musical demands and is therefore less sensitive to stimulation effects (Furuya et al. 2013).

In the musician group of the present study, suppression of the right SMG with cathodal tDCS resulted in a deterioration of pitch memory recognition performance and leads to the assumption that musicians evoke a more right lateralized network for pitch memory. It has been shown that musicians dispose a more equalized neuroanatomy and function in both hemispheres (Patston et al. 2007; Bermudez et al. 2009). Furthermore, Gaab and Schlaug (2003) reported higher activation of the right SMG in musicians compared with nonmusicians when behavioral performance was matched. The pitch memory span task of the present study measures the capacity of pitch memory information that can be held in the memory system and adapts to individual performance level. Therefore, it ensures that every nonmusician and musician is pushed to their limit of memory ability. The results of the pitch span task indicate that the right SMG is involved particularly in higher task demands in musicians, while in nonmusicians the left SMG may be more strongly involved in such tasks. In this context, Foster and Zatorre (2010) conducted an fMRI study on melody transposition with musicians and nonmusicians and revealed a key role of the intraparietal sulcus (IPS) for melody transposition (also see Foster et al. 2013) and showed that the activation of the right IPS could predict task performance in both groups. As the IPS is located adjacent to the SMG, this correlational finding is very interesting, especially, as melody transposition also requires pitch memory and relies on maintaining relative pitch information.

Another possible explanation for the involvement of the right SMG in the pitch memory recognition task of this group could be that the musicians usually use their visual-motor representation to memorize pitch sequences: the right SMG has been shown to be activated during sight reading in musicians (Sergent et al. 1992). When interrupting this additional memory resource by suppressing the activity of the right SMG by cathodal tDCS, the musicians' performance deteriorates to the level of the nonmusicians ability as shown in the present results.

As well as specific differences, general task demands differences between recall and recognition tasks must also be considered. Schulze, Mueller et al. (2011) showed that different neural activation patterns emerged in musicians during a pitch memory recognition task depending on whether unstructured (atonal) or structured (tonal) material was used. Similar differentiations have also been shown for a spatial task (Bor et al. 2003) and when using audio-visual material (Bor et al. 2004). Both these studies indicate that strategy is an important factor in memory tasks which could also be responsible for the lack of effect on the present recall task (which uses a tonal and structured approach) after cathodal stimulation of the right SMG in musicians. It is likely that musicians were able to chunk the pitch information in the recall task (Schulze, Mueller et al. 2011) and that this strategy relies on other neural systems, which are less sensitive to stimulation effects.

No effect of stimulation was found on the pitch recall task in musicians. One factor that may contribute to this finding is that musicians performed at ceiling (91% accuracy). However, another consideration is that different memory tasks, and task demands may recruit different neural networks. For example, a tDCS study by Berryhill et al. (2010) showed impaired working memory performance on a recognition but not a recall task, after cathodal stimulation over the right inferior parietal cortex, therefore indicating that different processes and underlying neural circuits were involved. Moreover, in the present nonmusicians group, the diminished performance in the pitch recall task after cathodal tDCS over the left SMG was only significant for longer sequences with higher memory demands.

All the above evidence leads to the conclusion that the SMG in general is involved in more demanding pitch memory processes and—particularly—in the storage of pitch information (Sakurai et al. 1998; Rinne et al. 2009). This is also in accordance with a study by Wehrum et al. (2011) who reported the activation of the SMG in a pitch discrimination task in children only in harder trials with subtle pitch changes and not during easier trials with robust changes. Furthermore, a review of behavioral performances in fMRI studies, reveals that those which reported activation in the SMG also found lower performances on the pitch memory task (Gaab et al. 2003; Rinne et al. 2009; Schulze, Zysset et al. 2011) compared with studies which do not show an activation of the SMG and high task performances of 90% (Zatorre et al. 1994; Jerde et al. 2011).

Regarding the CFMT+ (Russell et al. 2009), the results show, as expected, no effect of cathodal stimulation (Schaal et al. 2013), neither over the left nor right SMG, indicating that the causal involvement of the left and right SMG, respectively, is specific to pitch memory in the present study. Even though the visual control task is not perfectly matched in terms of task procedure and demands, the lack of modulation effect across conditions, the trial-by-trial working memory paradigm in Part 1 and the more long-term memory approach in Part 2, strongly supports the specific involvement of the SMG in pitch memory. Furthermore, the performance on the visual control task did not differ between musicians and nonmusicians, confirming that musicians do not show overall superior memory abilities (Tierney et al. 2008).

Finally, the present data show that the musicians outperformed the nonmusicians on both pitch memory tasks indicating that, as experts in the auditory domain, they have developed and dispose a pronounced memory system that allows them to memorize more musical material (Williamson et al. 2010; Schulze et al. 2011). However, the analysis of the recall task also shows that musicians as well as nonmusicians show a linear decline of pitch memory performance, as sequence length increases, showing that memory capacity is limited (Baddeley 1986). It can be proposed that the decline in performance in nonmusicians after cathodal tDCS over the left SMG that was only significant in longer sequences with higher memory load might also be found in the musicians group (probably with right hemispheric specialization) if sequences were longer (up to 10 tones per sequence). This hypothesis needs to be investigated in future research. In this context, it is also important to note that the study uses a cross-section approach by comparing musicians and nonmusicians, and therefore we cannot rule out preexisting structural and functional differences. In order to shed further light on this issue a study including participants with a broader range of musical experience and a correlation analysis with years of training would be desirable.

In summary, the present study provides evidence for the different and distinctive causal involvement of the SMG in nonmusicians and musicians in the pitch memory process. A significant downward modulation of pitch memory performance (recognition and recall) after cathodal tDCS over the left SMG was only found in nonmusicians. In the musicians group, a selective effect was found on the pitch recognition task but only after stimulation of the right SMG. These combined results suggest a hemispheric specialization of the SMG for pitch memory depending on musical expertise and training.

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Notes

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