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RESEARCH ARTICLE

Bihemispheric anodal transcranial direct-current stimulation over temporal cortex enhances auditory selective spatial attention

Jörg Lewald[1,2]

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Abstract
The capacity to selectively focus on a particular speaker of interest in a complex acoustic environment with multiple persons speaking simultaneously—a so-called "cocktail-party" situation—is of decisive importance for human verbal communication. Here, the efficacy of single-dose transcranial direct-current stimulation (tDCS) in improving this ability was tested in young healthy adults ($n = 24$), using a spatial task that required the localization of a target word in a simulated "cocktail-party" situation. In a sham-controlled crossover design, offline bihemispheric double-monopolar anodal tDCS was applied for 30 min at 1 mA over auditory regions of temporal lobe, and the participant's performance was assessed prior to tDCS, immediately after tDCS, and 1 h after tDCS. A significant increase in the amount of correct localizations by on average 3.7 percentage points ($d = 1.04$) was found after active, relative to sham, tDCS, with only insignificant reduction of the effect within 1 h after tDCS offset. Thus, the method of bihemispheric tDCS could be a promising tool for enhancement of human auditory attentional functions that are relevant for spatial orientation and communication in everyday life.

Keywords Sound localization · Cocktail-party effect · Selective spatial attention · Auditory segregation · Bihemispheric transcranial direct-current stimulation

Introduction

Currently, increasing efforts are being made to explore effects of non-invasive brain stimulation (NIBS), such as transcranial direct-current stimulation (tDCS) and transcranial magnetic stimulation (TMS), with the goal not only to apply these techniques in treatment and rehabilitation of neurological and psychiatric patients, but also preserve or enhance cognitive functions of healthy individuals suffering from age-related impairments. With regard to the latter aspect, previous studies have mainly focused on effects of NIBS on attention, learning, memory, reasoning, or executive functions (for review, see Perceval et al. 2016; Tatti et al. 2016). However, little is known about the possibilities for enhancing auditory capacities, the decline of which is one of the most common health problems associated with aging. A few studies have used application of tDCS, a NIBS technique that delivers weak electrical currents to the brain via anodal and cathodal electrodes attached to the scalp, over auditory cortex in order to modulate auditory spectrotemporal analysis. The results were partially inconsistent, as anodal tDCS was found to lead to improvement (Ladeira et al. 2011) or deterioration (Tang and Hammond 2013; Heimrath et al. 2014), while cathodal tDCS always induced deterioration (Loui et al. 2010; Mathys et al. 2010; Ladeira et al. 2011). Also, anodal tDCS was shown to enhance amplitudes of components of the auditory event-related potential, such as P1 (Zaehle et al. 2011), N2 (Hanenberg et al. 2017), and mismatch negativity (Heimrath et al. 2015; Impey and Knott 2015). Although previous results were far from being conclusive, the majority of studies thus suggested that anodal, rather than cathodal, tDCS may enhance auditory processing. Wöstmann et al. (2018) found that online transcranial alternating current (tACS) at alpha (10 Hz) or gamma (47 Hz) frequencies over left temporo-parietal cortex modulated the performance in a dichotic listening task requiring

✉ Jörg Lewald
joerg.lewald@rub.de

1 Auditory Cognitive Neuroscience Laboratory, Department of Cognitive Psychology, Faculty of Psychology, Ruhr University Bochum, Postfach 51-IB 6/61, 44780 Bochum, Germany

2 Leibniz Research Centre for Working Environment and Human Factors, Ardeystraße 67, 44139 Dortmund, Germany

participants to attend to spoken numbers presented to one ear, while ignoring numbers on the other ear: the recall of attended targets at the right ear was decreased by alpha-tACS and was increased by gamma-tACS.

In a recent study, tDCS was employed in combination with a task requiring spatial analysis of an auditory scene composed of multiple concurrent sound sources (Lewald 2016). This task simulated a so-called "cocktail-party" situation (Cherry 1953), in which an auditory object of interest has to be extracted out of multiple irrelevant distractors. With some modifications, the same task has been used in several further studies to investigate the neural basis of auditory selective spatial attention (Zündorf et al. 2011, 2013, 2014; Lewald and Getzmann 2015; Lewald et al. 2016). In the initial tDCS study of Lewald (2016), bihemispheric bipolar-balanced DC stimulation (cf. Brunoni et al. 2013; Nelson et al. 2014; Nasseri et al. 2015) was applied for 10 min at 0.4 mA with small electrodes (3.5 cm^2; Nitsche et al. 2007). During tDCS, there was a significant shift in localization of targets confined only to one hemispace when left-anode/right-cathode tDCS was delivered over superior temporal gyri, including plana temporalia and auditory cortices (Lewald 2016). However, the tDCS-induced perceptual shift was only slight and offline effects were not demonstrable, such that the question of whether tDCS could be a promising tool to improve hearing in a "cocktail-party" situation has remained unanswered.

On the basis of these previous findings (Lewald 2016), the present study aimed to optimize tDCS parameters, in order to clarify whether DC stimulation could induce stronger, longer lasting, and bilaterally symmetrical effects on performance in a "cocktail-party" task. While the target area of superior temporal gyrus (STG) was as in Lewald (2016), several modifications of tDCS application were made: First, anodal tDCS was used, since the literature cited above (e.g., Ladeira et al. 2011; Zaehle et al. 2011), though not very convincingly, suggested anodal, rather than cathodal, tDCS to induce beneficial effects on hearing functions. This corresponds to the classical view that anodal stimulation results in depolarization of the resting membrane potential of the cortical neurons under the electrode, thus increasing neuronal excitability, while cathodal stimulation results in a decreased excitability, caused by hyperpolarization of the resting potential. These excitability changes can be stable more than 1 h after the offset of tDCS if its duration is sufficient (Priori et al. 1998; Nitsche and Paulus 2000, 2001; Liebetanz et al. 2002; for review, see; Nitsche et al. 2008; Stagg and Nitsche 2011).

A bihemispheric double-monopolar montage of electrodes (over homologous areas of both cortical hemispheres) was used here since several studies have suggested advantages of this method compared to unihemispheric monopolar electrode montage (e.g., Vines et al. 2008; Klein et al. 2013; Lindenberg et al. 2013; Naros et al. 2016; Fiori et al. 2017). As the previous approaches that investigated effects of tDCS on "cocktail-party" sound localization using unihemispheric monopolar anodal (Hanenberg et al. 2017) or bihemispheric bipolar electrodes (Lewald 2016) resulted in relatively small modulation of performance, it was expected that the bihemispheric double-monopolar anodal montage would induce larger and more consistent improvements. Furthermore, since the present study was focused on offline effects, the duration of tDCS was extended to 30 min. This was based on the consideration that prolonged DC stimulation duration might generally increase the duration of aftereffects, even though a simple linear relation of tDCS duration and duration of aftereffects may not exist (for review, see Kuo et al. 2016).

Finally, in order to stimulate larger areas surrounding primary auditory cortices, conventional target electrodes of larger size (35 cm^2) were chosen, and current strength was only moderately increased to 1 mA to ensure safety and tolerability of tDCS (cf. Woods et al. 2016). The target electrode was centered to Heschl's gyrus and planum temporale, such that DC stimulation also covered anterior and posterior superior temporal areas surrounding this region. The posterior areas of superior temporal cortex, including planum temporale, were of particular interest since they are well-known to be part of the human auditory posterodorsal cortical stream. This so-called "where" pathway, targeting superior and inferior frontal cortices via inferior parietal lobule has been considered to play a crucial role in auditory spatial processing (e.g., Alain et al. 2001; Arnott et al. 2004; Ahveninen et al. 2006; Zündorf et al. 2016; for a recent review, see; Rauschecker 2018). The relevance of human posterior STG for spatial processing of single sound sources has also been shown by offline repetitive transcranial magnetic stimulation (Lewald et al. 2004a). Most importantly, there is converging evidence from several recent studies using "cocktail-party" sound-localization tasks in combination with functional magnetic resonance imaging (fMRI), event-related potential (ERP) recording, and voxel-based lesion-behavior mapping (VLBM) analyses that planum temporale (fMRI: Zündorf et al. 2013; VLBM: Zündorf et al. 2014) and posterior STG (fMRI: Zündorf et al. 2013; VLBM: Zündorf et al. 2014; ERP: Lewald and Getzmann 2015) are critically involved in cortical processing of auditory selective spatial attention at the temporal level.

In order to investigate effects of tDCS on auditory selective spatial attention in an experimental paradigm close to everyday life, four-syllable words (numerals) were used as stimuli, with four different words (one target and three distractors per trial) spoken simultaneously by four different speakers at four separate locations. Subjects had to indicate the location of the target word. The stimulus material was more complex than in previous studies applying tDCS over auditory cortex, which used pure tones (Ladeira et al. 2011; Zaehle et al. 2011; Impey and Knott 2015; Heimrath et al. 2015), noise (Heimrath et al. 2014), animal vocalizations (Lewald 2016), or one-syllable words (Hanenberg et al. 2017). As word recognition was an essential requirement for the task, it may have demanded cortical functions of speech processing in addition to spatial and attentional functions, thus involving both left and right lateralized auditory networks that were intended to be modulated by bihemispheric tDCS.

As the previous literature on effects of tDCS over auditory cortex was inconsistent and beneficial effects, if found at all, were quite small, the experimental design of the present study was primarily focused on the basic question of whether single-dose bihemispheric double-monopolar anodal DC stimulation is a technique suited to induce more substantial and longer lasting improvements of higher-order auditory functions than found in previous studies. It was hypothesized that performance in selective spatial attention, measured as percentage of correct localizations in the multi-speaker "cocktail-party" task, is enhanced after tDCS.

Materials and methods

Subjects

Twenty-four subjects (12 women, 12 men; mean age 22.6, SE 0.7, range 18–29 years), speaking German fluently, participated in the experiments. As directly comparable studies are not available, the sample size was a priori estimated, based on the group that received tDCS over STG in the study of Lewald (2016). A power analysis using G*Power Version 3.1.9.2 (Faul et al. 2007) was performed for a two-tailed matched-pairs (active vs. sham tDCS) t test ($\alpha = 0.05$; $n = 24$), assuming a large effect size ($d_z = 0.80$). This analysis showed a sufficiently high statistical power ($1 - \beta = 0.96$).

All subjects were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield 1971) and had normal hearing (mean hearing level ≤ 25 dB; 0.125–8 kHz; Oscilla USB100, Inmedico, Lystrup, Denmark). Following a single-blinded sham-controlled crossover design, each subject was tested with active and sham tDCS in two sessions, with intervals of 6–14 days. The crossover sequence of active and sham tDCS was counterbalanced across participants, such that active-first ($n = 12$; 6 women; mean age 22.8, SE 1.0, range 19–29 years) and sham-first groups ($n = 12$; 6 women; mean age 22.3, SE 0.9, range 18–27 years) did neither differ in age nor sex. Subjects received course credits or were paid for participation. All subjects gave their written informed consent to participate in this study, which was approved by the Ethical Committee of the Leibniz Research Centre for Working Environment and Human Factors, Dortmund. This study conformed to the Code of Ethics of the World Medical Association (Declaration of Helsinki), printed in the British Medical Journal (18 July 1964).

Auditory task

In each of the two sessions (active tDCS; sham tDCS), the subjects' performance was assessed at three measurement points in time: (1) prior to tDCS (pre-tDCS block), which was taken as baseline; (2) immediately after tDCS (post-tDCS block); and (3) 1 h after tDCS (1-h post-tDCS block). The auditory task was a modification of that described in Lewald (2016). Subjects sat on a comfortable chair in a totally dark, anechoic and sound-proof room (for details, see Guski 1990), with the head stabilized by a chin rest. Four broad-band loudspeakers (SC 5.9, Visaton, Haan, Germany), located at − 30°, − 10° (to the left), 10°, and 30° azimuth (to the right) were used (Fig. 1). These loudspeakers were part of a semicircular array of 91 loudspeakers, mounted in front of the subject, at a distance of 1.5 m from the center of the subject's head at ear level, in steps of 2° (for details, see Lewald et al. 2004b). In each trial, one target and three distractors were presented simultaneously, each sound emitted by a different loudspeaker. Stimuli consisted of different German four-syllable numerals (duration around 1.5 s, range 1.1–2.0 s), spoken with neutral prosody by four different professional actors (two women, two men). One easy-to-remember numeral ("einhunderteins"; 101), spoken by each of these actors, was chosen as the target stimulus. Forty-eight other four-syllable numerals (12 numerals spoken by each actor) were distracters. Recordings of spoken numerals

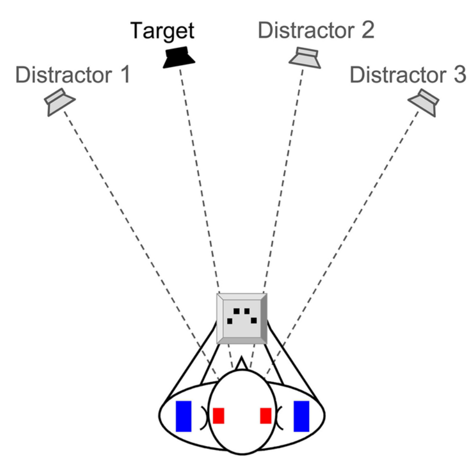

Fig. 1 Experimental setup. Four stimuli (German four-syllable numerals) were presented simultaneously from four loudspeakers located at 30° and 10° to the left and right. Subjects indicated the location of a predefined target stimulus using a response box with four keys. In a dual-channel montage, two target electrodes (anodes) were placed over temporal cortices, return electrodes (cathodes) over contralateral shoulders

were made using a condenser vocal microphone (MCE 91, Beyerdynamic, Heilbronn, Germany; about 20 cm distance) that was combined with a microphone preamplifier (1202-VLZ PRO, Mackie, Woodinville, USA). The recordings were digitized at 96 kHz sampling rate and 16-bit resolution via a PC-controlled soundcard (Terrasoniq TS88 PCI, TerraTec Electronic, Nettetal, Germany) and stored for offline processing, which was performed using the software Cool Edit 2000 (Syntrillium Software Corporation, Phoenix, AZ, USA). Spoken numerals were stored in separate WAV files, silent parts were cut out, and waveforms were normalized such that peak levels were identical for all files (except attenuated target levels, as described below).

The four different numerals presented in each trial from different positions were always spoken by different voices and were displayed with synchronous stimulus onset. Distracters were presented at constant sound pressure levels. In order to have different levels of task difficulty, the target was presented at three signal-to-noise ratios (0 dB; − 6 dB; − 12 dB) with reference to the mean sound-pressure level of individual distracters. This range was chosen on the basis of pilot experiments, showing that for most subjects correct localization of targets attenuated by − 12 dB was hardly possible or not at all. The target positions, the voices speaking the target numeral, and the target attenuations were balanced across trials. The overall sound-pressure level of combinations of target and distracters was about 58 dB(A), as was measured at the position of the subject's head, using a sound level meter with a 1/2–in. free-field measuring microphone (Types 2226 and 4175, Brüel & Kjær, Nærum, Denmark).

Each block of the auditory task comprised 240 trials (4 target positions × 4 target voices × 3 target attenuations × 5 distractor combinations) that were presented in a fixed quasi-random order. As in previous studies (see, e.g., Lewald 2016), a spatial four-alternative forced-choice method was chosen as the psychophysical method to assess localization performance. The subjects were informed that the target numeral was always presented in combination with three irrelevant numerals and that there were four possible positions of the target (slightly to the left; farther to the left; slightly to the right; farther to the right). According to these alternatives, the subjects were instructed to indicate the target position by pressing one out of four response keys on a response box within about 1 s after each stimulus presentation. The response keys were arranged in a semicircular manner, corresponding to the four possible positions of the target (Fig. 1). Subjects were instructed to respond in each trial, without omissions, and were encouraged to guess when they were unsure about the correct position. Each trial lasted 3.75 s, thus resulting in an overall duration of the block of 15 min plus repetitions of omitted trials. Trials with response times > 2.7 s with reference to stimulus onset were defined as omissions. Omitted trials were automatically repeated after 120 trials and at the end of each block until the complete set of responses was recorded. Usually, there were no or very few repetitions, extending the overall duration of the block only insignificantly. Prior to the experiment, subjects had to complete a few practice trials until they were familiarized with the task. No feedback was given to the subjects about their performance. The timing of the auditory stimuli and the recording of the subjects' responses were controlled by custom-written software.

During tDCS and in the break between post-tDCS and 1-h post-tDCS blocks, participants remained passively sitting on the chair in the silent anechoic room. To prevent drowsiness during the tDCS phase, the room was illuminated and the subjects had to read a text of their own choice on paper or tablet/notebook screen. All preparations for tDCS application were completed prior to the first block of the auditory task such that the subsequent tDCS phase was usually begun without delay, except a few cases where the impedance of the DC electrodes (see below) had to be further reduced before starting stimulation.

Transcranial direct-current stimulation

In a dual-channel electrode montage, bihemispheric double-monopolar anodal tDCS (cf. Nasseri et al. 2015) was applied using two Eldith DC stimulators (neuroConn, Ilmenau, Germany) connected to four conductive carbon–rubber DC electrodes. Target electrodes were two anodes (5×7 cm^2), each connected to a separate DC stimulator, which were placed symmetrically over temporal cortices of both hemispheres. Return electrodes were two cathodes (7×14 cm^2) that were positioned over the shoulders, each on the side contralateral to the anode that was connected to the same DC stimulator. The left target electrode was centered to the midpoint between C5 and T7 locations and the right target electrode was centered to the midpoint between C6 and T8 locations of the 10–10 EEG international electrode placement system (Talairach coordinates $x = -83$, $y = -16$, $z = 8$ and $x = 84$, $y = -16$, $z = 8$). Thus, the center of the rectangular target electrode was located over the posterior superior temporal region around planum temporale and auditory cortex. The corner points of the electrodes approximately corresponded to FC5/6, CP5/6, FT7/8, and TP7/8 locations, covering adjacent anterior temporal, frontal, and parietal regions in addition. The electrodes were placed under a standard EEG head cap, which was worn throughout the whole session. Electrodes were encased in saline-soaked sponges. In addition, a mixture of Ten20 Conductive Paste (Weaver and Company, Aurora, CO, USA) and lidocaine/prilocaine (2.5%/2.5%) topical anesthetic cream (Emla Creme, AstraZeneca, Wedel, Germany) was applied to the scalp under the electrodes. Topical anesthetic cream has been shown to significantly reduce cutaneous sensations elicited by DC stimulation (Nitsche et al. 2008; McFadden et al. 2011).

At each target electrode, anodal tDCS was simultaneously applied for 32 min, including a 30-min plateau phase at a current strength of 1 mA (resulting in current densities of 0.03 mA/cm^2 under the target electrodes and 0.01 mA/cm^2 under the return electrodes) and linear 60 s ramp-up/ramp-down phases. Sham stimulation consisted of a 32 min period that started with a 2.5-min phase of anodal tDCS (60-s ramp-up phase, 30-s plateau phase at 1 mA, 60-s ramp-down phase), without further application of tDCS. The impedance was controlled by the DC stimulator (impedance limit 20 kΩ).

Participants were informed that they would receive DC stimulation in each session, but did not receive any information about the duration of the application. That is, before and during the experiment, subjects were not aware of the existence of a sham condition. For the sham-tDCS procedure used here, several studies have shown that participants experience the sensations associated with current onset or offset, while cortical excitability changes from sustained DC are minimized due to its brief duration. When questioned, participants were unable to correctly identify whether the tDCS was active or sham in these studies (Kessler et al. 2012; Palm et al. 2013; Russo et al. 2013; Tang et al. 2016). As assessed by a short questionnaire after the experiment, 20 subjects (83.3%) of the present study reported experience of sensations of DC stimulation (slight burning, tingling, and itching under the electrodes) in conditions of both active and sham tDCS, 2 subjects (8.3%) reported no sensations at all, and 2 further subjects (8.3%) reported sensations of tDCS with active, but not sham, stimulation. There was no significant difference in frequency of occurrence of sensations between active and sham tDCS (McNemar test, $p = 0.5$). The proportion of subjects who correctly reported the sequence of stimulation conditions (either correct guess of active and sham tDCS or longer duration of sensations of tDCS in active, than sham, conditions) was at chance level ($n = 12$, 50%; binomial test, $p = 1$). No subject reported any serious discomfort during tDCS.

Data analysis

For the main analysis, the percentages of correct responses were transformed into rationalized arcsine units (RAUs; Studebaker 1985; Sherbecoe and Studebaker 2004). RAUs and percent-correct scores are nearly identical in the range between 20 and 80%, but have a greater range than the corresponding percent-correct scores for more extreme values. Thus, the variance of RAU values is more uniform than that of percent-correct scores. RAU values were normalized with reference to the pre-tDCS block (baseline); that is, data obtained in the pre-tDCS block were subtracted from post-tDCS and 1-h post-tDCS data.

Data were pooled across the two eccentric positions on each side. The pre-normalized RAU values were subjected to a five-factor repeated-measures ANOVA with the within-subject factors stimulation (active; sham), block (post; 1-h post), target attenuation (− 12 dB; − 6 dB; 0 dB), and hemispace (left; right) and the between-subjects factor crossover sequence of sessions (active prior to sham tDCS; sham prior to active tDCS). Post hoc *t* tests were applied to reveal effects in detail. Two-tailed testing was used in all analyses. If appropriate, Bonferroni-corrected α-levels were used to determine statistical significance.

Results

In the pre-tDCS block (baseline), the percentage of correct responses across all conditions was, on average, clearly above chance level (mean 68.2%, SE 2.8; $t[23] = 15.39$, $p < 0.0001$; Fig. 2a, b). However, the range of individual pre-tDCS performance was extremely wide, ranging from 34.2 to 95.0%. On the one hand, there was no significant difference in pre-tDCS performance between sessions with active (mean 66.9%, SE 3.6) and sham tDCS (mean 69.5%, SE 3.1; $t[23] = 0.72$, $p = 0.48$). On the other hand, mean pre-tDCS performance increased significantly from session 1 (56.4%, SE 3.3) to session 2 (68.2%, SE 3.4; $t[23] = 7.65$, $p < 0.0001$). An initial inspection of the non-normalized data using a three-factor ANOVA with the within-subjects factor block (pre; post; 1-h post) and session (first session; second session), and the between-subjects factor crossover sequence (session with active tDCS prior to sham tDCS; session with sham tDCS prior to active tDCS) revealed strong main effects of session ($F[1,22] = 77.09$, $p < 0.0001$, $\eta_p^2 = 0.78$) and block ($F[2,44] = 18.93$, $p < 0.0001$, $\eta_p^2 = 0.46$), as well as interactions of session × block ($F[2,44] = 15.66$, $p < 0.0001$, $\eta_p^2 = 0.42$), block × crossover sequence ($F[2,44] = 4.82$, $p = 0.013$, $\eta_p^2 = 0.18$), and session × block × crossover sequence ($F[2,44] = 4.55$, $p < 0.016$, $\eta_p^2 = 0.17$). In sum, these results indicated generally increasing performance as a function of time between first and second sessions (not shown) and between first and second blocks (Fig. 2a, b), independent of potential effects of tDCS, while the absence of a main effect of crossover sequence ($F[1,22] = 0.12$, $p = 0.73$, $\eta_p^2 = 0.01$) provided evidence for equality of crossover groups across all conditions.

For the main analysis, the percentages of correct responses were transformed into RAU values and normalized with reference to pre-tDCS performance (Fig. 2c, d), as described above (see "Data analysis"). Figure 3 shows the pre-normalized performance (pooled across groups) for the comparison of active vs. sham tDCS (Fig. 3a) and separated

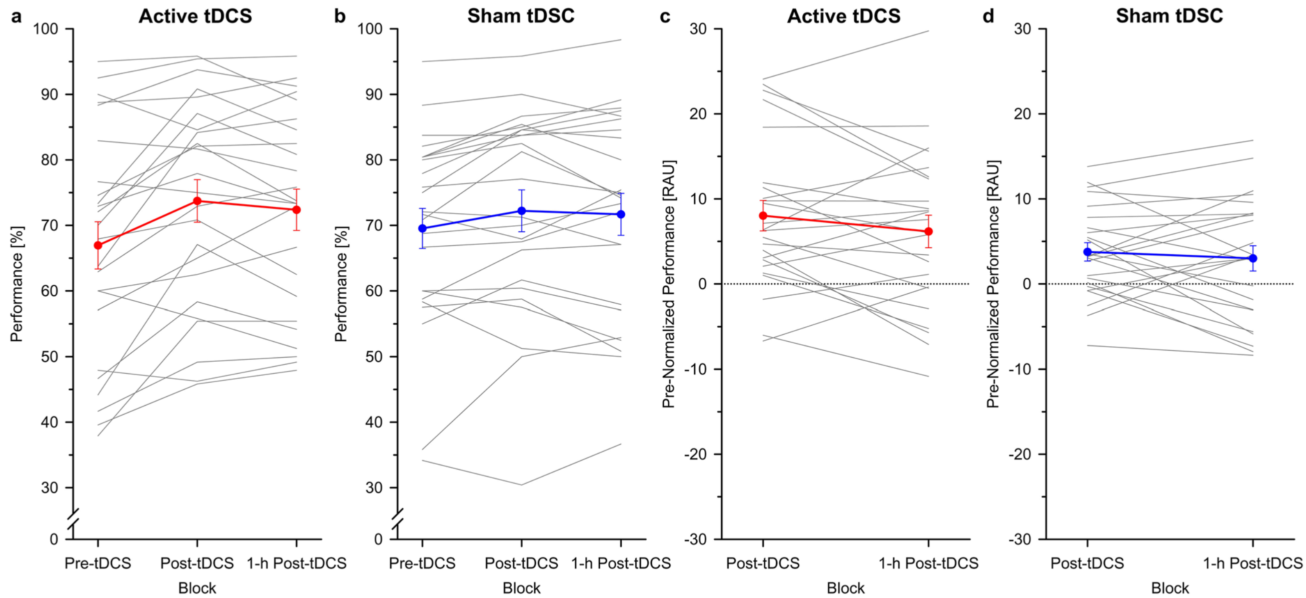

Fig. 2 Effect of bihemispheric double-monopolar anodal tDCS on sound-localization performance in a simulated "cocktail-party" situation. Percentages of correct responses obtained in active (**a**) and sham-tDCS conditions (**b**) prior to tDCS (pre-tDCS), immediately after tDCS (post-tDCS), and 1 h after tDCS (1-h post-tDCS). Pre-normalized performances resulting from data transformed into rationalized arcsine units (RAU values) for post-tDCS and 1-h post-tDCS blocks in active (**c**) and sham-tDCS conditions (**d**). Symbols and bold lines indicate mean values for all subjects (error bars, standard errors); thin lines indicate individual results

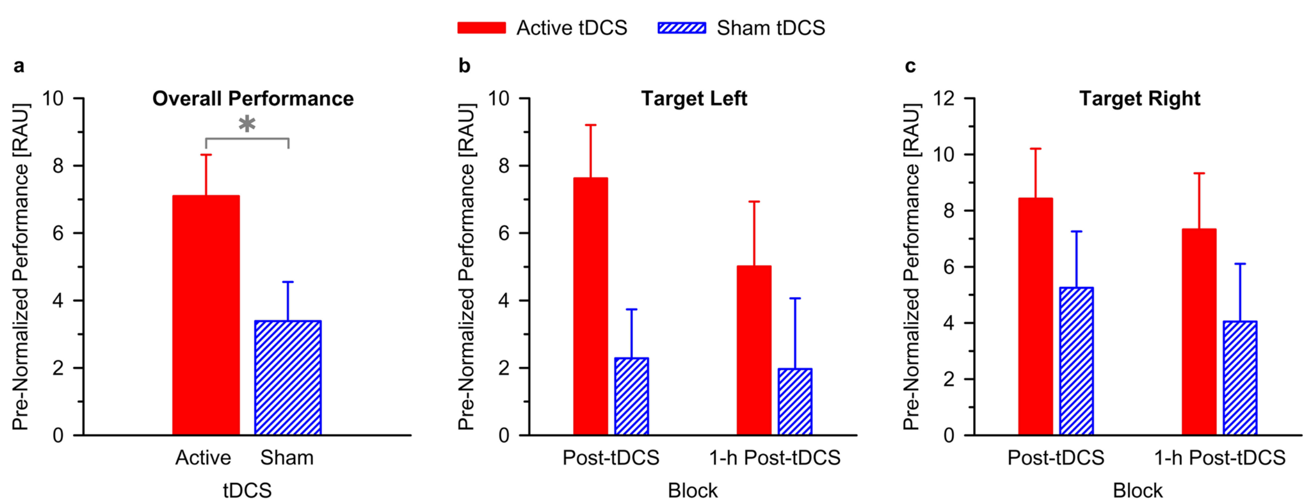

Fig. 3 Pre-normalized performances after active and sham tDCS. **a** Mean performances across blocks and conditions of auditory stimulation. **b, c** Data shown separately for post-tDCS and 1-h post-tDCS blocks and for targets to the left (**b**) and right (**c**). *$p < 0.05$; error bars, standard errors

according to condition of stimulation, block, and hemispace of target presentation (Fig. 3b, c). The pre-normalized RAU values were submitted to a five-factor repeated-measures ANOVA with the within-subject factors stimulation (active; sham), block (post; 1-h post), target attenuation (− 12 dB; − 6 dB; 0 dB), and hemispace (left; right) and the between-subjects factor crossover sequence (active prior to sham tDCS; sham prior to active tDCS). The ANOVA revealed a main effect of stimulation ($F[1,22] = 5.91$, $p = 0.024$, $\eta_p^2 = 0.21$), indicating better performance after active tDCS than after sham tDCS. The mean difference between conditions of stimulations was 3.7 RAU (SE 1.5), corresponding to 3.7% (SE 1.4; Fig. 3a). Also, there was a main effect of crossover sequence ($F[1,22] = 6.88$, $p = 0.016$, $\eta_p^2 = 0.23$) and interactions of stimulation × crossover sequence ($F[1,22] = 23.47$, $p = 0.0001$, $\eta_p^2 = 0.52$) and target attenuation × crossover sequence ($F[2,44] = 3.32$, $p = 0.045$, $\eta_p^2 = 0.13$). Finally, a fourfold interaction of stimulation × block × target attenuation × hemispace ($F[2,44] = 5.52$, $p = 0.007$, $\eta_p^2 = 0.20$) was found. There were no further main effects or interactions (all $F \leq 2.86$, $p \geq 0.07$, $\eta_p^2 \leq 0.12$).

In order to dissolve the interaction involving the factors stimulation, block, hemispace, and target attenuation, three post hoc ANOVAs with the within-subject factors stimulation, block, and hemispace were conducted separately for each target attenuation. A significant result was found for the medium target attenuation of − 6 dB: a threefold interaction of all factors ($F[1,23] = 8.77$, $p = 0.007$, $\eta_p^2 = 0.28$; Bonferroni-corrected $\alpha = 0.0167$), but no further main effects or interactions (all $F \leq 2.68$, $p \geq 0.12$, $\eta_p^2 \leq 0.10$). Subsequent post hoc *t* tests comparing active and sham tDCS separately for each block and each hemispace for − 6 dB target attenuation showed merely a trend of an effect of tDCS for targets in left hemispace in the post-tDCS block ($t[23] = 2.28$, $p = 0.03$), which did not survive Bonferroni correction ($\alpha = 0.0125$). Thus, the question of how the effect of tDCS depended on the factors block and hemispace remained largely unanswered.

The effects including the factor crossover sequence were further examined by post hoc testing. Across both conditions of stimulation, there was a general trend of stronger improvement with reference to baseline in the first, than in the second, session ($t[23] = 4.40$, $p = 0.0002$). Statistical comparisons of active-first vs. sham-first groups were computed separately for the first and the second session. For data obtained in the first session, the group that received active tDCS showed a significantly stronger improvement than the group that received sham tDCS (mean difference 8.5 RAU, SE 2.7; $t[22] = 3.11$, $p = 0.005$; Bonferroni-corrected $\alpha = 0.025$), thus confirming the effect of tDCS that was demonstrated by the analysis of the complete data set, as described above. On the other hand, a related analysis of the data obtained in the second session failed to reveal significant differences between active-tDCS and sham-tDCS groups (mean difference 1.1 RAU, SE 2.0; $t[22] = 0.56$, $p = 0.58$; Bonferroni-corrected $\alpha = 0.025$).

Since the range of individual pre-tDCS (baseline) performance was wide (see above), it was furthermore examined whether the efficacy of tDCS depended on baseline performance. The difference of pre-normalized performances obtained with active minus sham tDCS was taken as a measure of improvement by tDCS, and the Spearman rank correlation between the resulting values and non-normalized pre-tDCS performance was calculated. This analysis did not reveal a significant result ($r_S[22] = -0.23$, $p = 0.27$), thus suggesting that the improvement induced by tDCS was largely independent of pre-tDCS performance.

Finally, the difference of pre-normalized performances obtained with active minus sham tDCS was compared between the group of subjects who correctly guessed the sequence of stimulation conditions and those who were wrong (each group $n = 12$; see "Data analysis"). The result of this analysis was far from being significant ($t[22] = 0.61$, $p = 0.55$), indicating that the experience of active, compared with sham, tDCS was not a confounding variable in this study.

Discussion

Offline bihemispheric double-monopolar anodal tDCS applied for 30 min at 1 mA over the region of posterior STG, including plana temporalia and auditory cortices, significantly improved the performance in localizing a target speaker in a simulated "cocktail-party" situation. The effect size of the main effect of stimulation was found to be large (equal to Cohen's $d = 1.04$), indicating an average increase in correct responses by 3.7% after active, relative to sham, tDCS. There was merely a non-significant tendency that effects were most pronounced for targets in left hemispace immediately after tDCS, but no clear statistical evidence of a significant bilateral asymmetry of the effect or disappearance within 1 h after tDCS offset. The results generally confirm recent studies that reported online effects of either tDCS (Lewald 2016) or tACS (Wöstmann et al. 2018) over temporal/temporoparietal cortex on auditory spatial attention, but extend these findings by demonstrating substantial offline improvement of performance. Thus, it seems reasonable to assume that bihemispheric anodal tDCS could be a promising tool to enhance human auditory attentional functions that are relevant for hearing in "cocktail-party" situations.

The traditional model of tDCS, derived from the motor system, assumes that the depolarizing effects of anodal stimulation on the neuronal resting potentials resulted in enhanced cortical excitability that remained stable after tDCS offset (for review, see Nitsche et al. 2008; Stagg and Nitsche 2011). Following this view, the long-lasting post-stimulation improvement in performance observed here might have been caused by increased excitability of the auditory network involved in selective spatial attention in a multispeaker environment. Currently, still little is known about the neural mechanisms mediating this capability at the level of auditory cortex and planum temporale, and almost nothing about the potential effects of tDCS on these mechanisms (see Lewald 2016). It is assumed that sound location is encoded by an opponent-channel population-code, which involves two opponent channels consisting of two populations of neurons in left and right hemispheres that are tuned to sound locations in contralateral hemispaces (so-called "opponent-channel model"; Woods et al. 2006; von Kriegstein et al. 2008; Werner-Reiss and Groh 2008; Miller and Recanzone 2009; Magezi and Krumbholz 2010; Salminen et al. 2010; Zhang et al. 2015; for review, see Salminen et al.

2012). Correlates of opponent-channel location coding have been identified in human planum temporale (Derey et al. 2016), which was also suggested to be a key region involved in selective spatial attention (Zündorf et al. 2013, 2014). In the cat auditory cortex, it has been shown that the neuronal spatial tuning can be sharpened depending on task conditions, and it has been suggested that this sharpening reflects mainly an increase in inhibitory mechanisms (Lee and Middlebrooks 2011). Recently, task-dependent modulations of spatial sensitivity have been also demonstrated in human primary auditory cortex (Van der Heijden et al. 2018). As cortical spatial sensitivity has been shown to be dynamic, one may thus speculate that the improved behavioral performance found in the present study after tDCS was related to a sharpening of spatial tuning of the neuronal populations in auditory cortex/planum temporale by DC stimulation. More specifically, it is possible that tDCS caused increased suppression of distractor sources, such that spatial tuning to the target source was sharpened. Based on results showing effects of cathodal tDCS on visual motion perception in the presence of multiple distractors, Antal et al. (2004) also assumed that in a complex task, when neuronal patterns encoding concurrent distractors are activated in addition to the patterns encoding the target stimulus, DC stimulation could suppress the distractor, rather than the target, patterns, thus resulting in a neuronal activity being more focused on the target. At the first glance, the model of anodal-excitation and cathodal-inhibition effects might argue against this explanation of the present results. However, as already outlined above (see "Introduction"), previous studies using tDCS over auditory cortex have led to inconclusive results regarding polarity-specific effects of DC stimulation, rather arguing against a clear-cut anodal-excitation/cathodal-inhibition dichotomy in this domain (Tang and Hammond 2013; Loui et al. 2010; Mathys et al. 2010; Ladeira et al. 2011; Lewald 2016; cf. also; Jacobson et al. 2012). Also, it has been assumed that suppression of irrelevant information generally involves mechanisms of depression of activity via inhibitory cortical interneurons (e.g., Gazzaley et al. 2005). Therefore, it seems conceivable that in the present study the anodal tDCS specifically increased the excitability of inhibitory interneurons that are necessary for the sharpening of spatial tuning by suppression of irrelevant sound sources, thus facilitating effects of selective attention.

An important limitation that has to be considered when interpreting these results is that reliable conclusions about the brain area that was relevant for the effect shown cannot be drawn. Although current density may have been maximal in the areas located directly under the electrodes, namely auditory cortices and plana temporalia, DC stimulation could have also affected temporal, insular, parietal, and frontal areas adjacent to this region, due to the relatively large size of the DC electrodes used, as well as more distant areas by electrical conduction via the cerebrospinal fluid (Wagner et al. 2014). In addition to direct functional effects of tDCS, remote effects of tDCS are also possible, that is, modulations of functional interactions via long-range intra- and interhemispheric cortico-cortical and cortico-subcortical connections of the target area (Baudewig et al. 2001; Lang et al. 2005; Stagg et al. 2009, 2013; Zheng et al. 2011). Thus, even though the conclusion that tDCS modulated the neuronal excitability in the postero-dorsal stream, namely planum temporale, might be highly plausible, it must be treated with maximum caution. This issue has to be clarified by future studies combining tDCS with neuroimaging techniques. In this context, it has also to be noted that DC stimulation of STG areas anterior to the primary auditory cortex could be of benefit for selective spatial attention. These areas are part of the auditory antero-ventral ("what") stream, which targets inferior frontal cortex and is assumed to preferentially process non-spatial (spectrotemporal) sound features. Localization of a sound source of interest in a "cocktail-party" situation necessarily requires its identification and segregation from distractors by spectrotemporal analyses, in addition to genuine spatial mechanisms supporting organization of the concurrent sound sources into separate streams and focusing of selective attention onto the target source. Thus, it is possible that tDCS-induced improvement of non-spatial auditory processing, as has been demonstrated with anodal DC stimulation at the behavioral (Ladeira et al. 2011) and electrophysiological levels (Zaehle et al. 2011; Heimrath et al. 2015; Impey and Knott 2015; Hanenberg et al. 2017; see above), was a factor in the outcome of this study.

A further point that needs to be discussed is the unexpectedly strong effect of crossover sequence, which obviously superimposed the effect of tDCS. As the interval between sessions was sufficiently long (≥ 6 days), the occurrence of carry-over effects of single-dose tDCS (i.e., effects of active tDCS applied in the first session on the subject's performance assessed in the second session with sham tDCS) may be unlikely (cf. Monte-Silva et al. 2013). Rather, carry-over effects of familiarization with the task, resulting in stronger improvements in the second, than in the first, session, may have played a substantial role, even though no feedback about correct responses was given. Retrospectively, a crossover design, as used here, thus might not have been optimal, and a parallel-group design should rather be used in future studies.

Finally, a limitation of this study was that only anodal tDCS was applied with active stimulation. It still remains to be clarified whether or not bihemispheric cathodal tDCS can induce deterioration of performance in the task used here, as was suggested by previous research (cf. Lewald 2016). An additional issue is that, although the common procedure for sham tDCS was used here and participants could obviously not distinguish between conditions of tDCS, active stimulation might have induced longer lasting or more intense sensations compared with sham stimulation (Palm et al. 2013). Whether or not this potential difference in experience of tDCS had any impact on the present results is not completely clear. Alternatively, follow-up studies could use off-target tDCS instead of sham tDCS as a control condition (cf. Lewald 2016).

In conclusion, these results provided convincing evidence of a beneficial effect of bihemispheric anodal tDCS on selective spatial attention in a "cocktail-party" situation already after a single-dose application. However, further questions have been raised. Several studies have demonstrated that repeated (mostly daily) application of tDCS over multiple sessions can lead to long-lasting behavioral effects, based on processes of long-term cortical plasticity induced by DC stimulation (e.g., Boggio et al. 2007, 2008; Monte-Silva et al. 2010, 2013; Fricke et al. 2011; Meinzer et al. 2014; for review, see; Huang et al. 2017). Thus, one may expect that cumulative effects of repeated tDCS could occur in approaches such as that of the present study. Also, it is noteworthy that in the offline protocol used here tDCS was applied while subjects did not perform any task requiring auditory attention. There is some evidence that cognitive tasks performed during tDCS could additionally increase the effect of DC stimulation (Martin et al. 2013), and it has been suggested that the combination of anodal tDCS with task execution could act like a co-activation of a specific network, thus inducing Hebbian-like plasticity (Miniussi et al. 2013). Follow-up studies will have to clarify whether or not the offline effect demonstrated here can be further enhanced, when a "cocktail-party" task is executed during tDCS application. Finally, it must be noted that age could be a factor affecting the efficacy of tDCS in cognitive tasks. There are reports indicating that tDCS can be more efficient in elderly, than in younger, persons (Meinzer et al. 2013, 2014; Fiori et al. 2017). As the effect shown here was found in young healthy subjects, the question arises whether older people, frequently suffering from deficits in selective auditory spatial attention (cf. Lewald and Hausmann 2013), can benefit even more from DC stimulation. This issue, which needs further clarification, might be promising with respect to the potential use of tDCS in compensating for the age-related decline of auditory cognitive functions.

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Compliance with ethical standards

Conflict of interest The author declares that he has no conflict of interest.

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