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Modulation of human auditory spatial scene analysis by transcranial direct current stimulation

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Localizing and selectively attending to the source of a sound of interest in a complex auditory environment is an important capacity of the human auditory system. The underlying neural mechanisms have, however, still not been clarified in detail. This issue was addressed by using bilateral bipolar-balanced transcranial direct current stimulation (tDCS) in combination with a task demanding free-field sound localization in the presence of multiple sound sources, thus providing a realistic simulation of the so-called "cocktail-party" situation. With left-anode/right-cathode, but not with right-anode/left-cathode, montage of bilateral electrodes, tDCS over superior temporal gyrus, including planum temporale and auditory cortices, was found to improve the accuracy of target localization in left hemispace. No effects were found for tDCS over inferior parietal lobule or with off-target active stimulation over somatosensory-motor cortex that was used to control for non-specific effects. Also, the absolute error in localization remained unaffected by tDCS, thus suggesting that general response precision was not modulated by brain polarization. This finding can be explained in the framework of a model assuming that brain polarization modulated the suppression of irrelevant sound sources, thus resulting in more effective spatial separation of the target from the interfering sound in the complex auditory scene.

1. Introduction

In everyday life, listening to a specific auditory object of interest is almost always hampered by the omnipresence of concurrent sound sources. Nevertheless, humans are easily capable of detecting, identifying and localizing the sound of interest, and focusing their spatial attention to its source, even if disturbing sounds have considerably higher levels (Bregman, 1990; Carlyon, 2004; McDermott, 2009). The neural basis of this ability, which has been termed "cocktail-party effect" (Cherry, 1953), is still insufficiently understood. While this topic has long been subject of neuroscience research (for review, see Alain and Arnott, 2000), in recent years a rapidly growing number of studies addressed this subject using more elaborate methods, such as human functional magnetic resonance imaging (fMRI; e.g., Cusack, 2005; Gutschalk et al., 2007; Zaehle et al., 2008; Hill and Miller, 2010; Schadwinkel and Gutschalk, 2011; Teki et al., 2011; Zündorf et al., 2013), magnetoencephalography (e.g., Gutschalk et al., 2005, 2007, 2015; Schadwinkel and Gutschalk, 2010; Xiang et al., 2010), high-density electroencephalography (e.g., Gamble and Luck, 2011; Gamble and Woldorff, 2015; Lewald and Getzmann, 2015; O'Sullivan et al., 2015), and voxel-based lesion-behavior mapping analysis (VLBM; Zündorf et al., 2014), as well as animal research at the single-neuron level (e.g., Kurt et al., 2008; Malone et al., 2015). The vast majority of previous studies on this topic has dealt with non-spatial aspects of stream segregation in auditory scene analysis, in particular spectro-temporal processing of speech and non-speech sounds (for review, see Shamma et al., 2011). Compared to that, the spatial aspects of scene analysis have been investigated to a far lesser extent, although sound localization in a "cocktail-party" situation may require, in addition to processes of location coding, specific spatial mechanisms organizing the concurrent sound sources into spatially separate streams and segregating the source of interest from the disturbing distractor sources. The present study focused on the neural basis of these spatial analyses in "cocktail-party" listening. For this purpose, psychophysical measures of spatial performance were combined with transcranial direct current stimulation (tDCS), a non-invasive neuromodulatory technique that delivers weak electrical currents to the brain via electrodes (anode and cathode) attached to the scalp. Based on animal research (Creutzfeld et al., 1962; Eccles et al., 1962; Bindmann et al., 1964; Landau et al., 1964; Purpura and McMurtry, 1965; Gorman,1966), this type of brain stimulation is assumed to

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modulate the resting membrane potential of cortical neurons and thus their excitability, depending on the polarity of the overlying electrode in relation to neuronal orientation: classically, positioning the anode over the target region results in an increase, and reversing polarity of stimulation (cathode placed over the target region) in a decrease of excitability (Priori et al., 1998; Nitsche and Paulus, 2000, 2001; for review, see Nitsche et al., 2008; Stagg and Nitsche, 2011).

On the basis of previous research on "cocktail-party" sound localization, several brain regions appeared to be candidate target areas. Studies using fMRI revealed activation in bilateral planum temporale and left inferior frontal gyrus for the contrast of "cocktail-party" sound localization vs. single-source localization (Zündorf et al., 2013). The analysis of event-related potentials indicated the most prominent electrical sources resulting from this contrast in right posterior superior temporal gyrus (STG) at the P1 component, right inferior parietal lobule (IPL) at the P1-N1-P2 components, right pre- and postcentral areas at the P2 component, and left dorso-frontal and cingulate cortices at the N2 (Lewald and Getzmann, 2015). In a VLBM study with stroke patients, localization deficits in the presence of multiple distractor sound sources, compared with localization of individually presented sound sources, was found to be associated with right planum temporale and left inferior frontal and pre- and postcentral lesions (Zündorf et al., 2014). Taken together, critical roles of the STG, including planum temporale, and the IPL in sound localization in complex acoustic environments are most consistent across studies. Posterior STG and IPL are well-known to be part of the so-called postero-dorsal auditory stream, which preferentially processes location information (Arnott et al., 2004). In accordance, online single-pulse transcranial magnetic stimulation (TMS; At et al., 2011) and offline repetitive transcranial magnetic stimulation (rTMS; Lewald et al., 2002, 2004a, 2004b, 2011; Karhson et al., 2015) have demonstrated relevance of these areas for human auditory spatial processing with single sound sources. Thus, these regions were chosen as target areas for tDCS. For maximum focality of tDCS, a small electrode size (3.5 cm^2) was used (Nitsche et al., 2007), thus allowing more reliable conclusions to be drawn concerning the stimulated anatomical structures than with conventional tDCS electrodes. A bilateral bipolar-balanced type of electrode montage for tDCS was employed, that is, two electrodes with opposite polarities were placed symmetrically over homonymous cortical areas of both hemispheres. The rationale for choosing this montage was that it is supposed to simultaneously activating a specific area while inhibiting its contralateral counter-part (Brunoni et al., 2013; Nelson et al., 2014; Nasseri et al., 2015). Due to the contralaterality of auditory spatial processing in cortex (Jenkins and Masterton, 1982; Woldorff et al., 1999; Ungan et al., 2001; Palomäki et al., 2005; Krumbholz et al., 2005, 2007; Lewald and Getzmann, 2011), it was expected that, in each hemispace, inverse configurations of electrode polarities may result in opposite effects of tDCS on auditory performance.

The tDCS method was combined here with an auditory stimulation technique using simultaneous presentation of multiple sound sources. Auditory stimuli were delivered via four equidistant loudspeakers, mounted along a semicircle centered to the subject's head, in an anechoic room. The subject's task was to focus on one particular sound and to indicate its position (Zündorf et al., 2011). Under these conditions of auditory stimulation, the interference between sound sources can result in effects of displacement of apparent location, fusion of spatially separated sound locations, or broadening of the fused sound image (Gardner, 1969). Although target localization is generally still possible, very large angular errors of up to 180° can occur (see, e.g., Zündorf et al., 2011). In particular, previous studies that used simultaneous presentation of target and distractor sounds demonstrated a perceptual attraction between target and distractor, the so-called spatial "pulling" effect (Butler and Naunton, 1962; Gardner, 1969; Best et al., 2007; Lewald and Hausmann, 2013; for detailed discussion, see Lee et al., 2009). These effects of "pulling" or fusion may reflect perceptual integration as a result of the obligatory grouping of spatial information from different sound sources that occurs when there are no cues indicating the presence of two or more distinct sound sources, other than the spatial cues themselves (Best et al., 2007; Lee et al., 2009; Lewald and Hausmann, 2013). Vice versa, an effect of "pushing" or repulsion of the auditory object of interest away from distractors can occur in the same conditions, reflecting perceptual segregation between sound locations (Lorenzi et al., 1999; Best et al., 2005; Lee et al., 2009). In the present study, the experimental design was focused on very large perceptual displacements of a target relative to its physical location or fusion of target and distractors while ignoring smaller systematic errors as are associated with sound localization (cf. Lewald et al., 2000). This was realized by using a four-alternative forced-choice method corresponding to the four possible loudspeaker locations (Lewald and Getzmann, 2015). According to the effects described above, it was expected that a modulation of the performance in auditory spatial analysis by brain polarization would become evident in a change of the frequency of large perceptual displacements of the target towards one of the three distractors or the center of gravity of multiple fused sources. Thus, the mean bias in target localization, which may be toward the majority of the distractor locations, was taken as a measure of the degree of integration of the target with the distractors. A reduction or increase of this bias with reference to the physical position of the target may indicate that spatial separation of the target from the interfering sound and the accuracy of target localization were, respectively, improved or deteriorated.

2. Material and methods

2.1. Subjects

Seventy four subjects (mean age 23.72 years, SE 0.43, range 18–31) with normal hearing (as assessed by standard audiometry, mean hearing level ≤25 dB) participated in the experiments. Only male subjects were included in the study to avoid potential confounding effects of sex on the results, since a strong effect of sex on behavioral performance has been demonstrated in tasks as used here (Zündorf et al., 2011; Lewald and Hausmann, 2013) and there are also indications of sex differences in neural processing of sound location in a "cocktail-party" situation (Schlüter et al., 2014). All participants were right-handed, as assessed by the hand section of the Laterality Questionnaire of Siefer et al. (2003). Three groups of subjects were tested, according to three different scalp sites of bilateral bipolar-balanced tDCS: (1) superior temporal gyrus (STG; $n=24$), (2) inferior parietal lobule (IPL; $n=28$), and (3) somatosensory-motor cortex (SMC; $n=22$). There were no significant differences between groups in age ($F[2,71]=0.65$, $p=0.52$). Following a crossover design, each subject was tested with the two possible electrode configurations of bilateral bipolar-balanced tDCS (left anode/right cathode; right anode/left cathode) in two sessions on different days, with a minimum interval of one week between sessions. The sequence of the two electrode configurations was counterbalanced across subjects within each group. Subjects were either paid for participation or received course credits. 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).

2.2. Auditory task

The auditory task was a modification of that described in Lewald and Getzmann (2015), based on the original task of Zündorf et al. (2011). During experiments, subjects sat on a comfortable chair in a totally dark, anechoic and sound-proof room (for details, see Guski, 1990). Head position was kept constant by a chin rest. A semicircular array of 91 broad-band loudspeakers (SC 5.9, Visaton, Haan, Germany) was 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). Four loudspeakers, located at −48°, −16° (to the left), 16°, and 48° azimuth (to the

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