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Research report

Parietal but not temporoparietal alpha-tACS modulates endogenous visuospatial attention

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ABSTRACT

Visuospatial attention can either be voluntarily directed (endogenous/top-down attention) or automatically triggered (exogenous/bottom-up attention). Recent research showed that dorsal parietal transcranial alternating current stimulation (tACS) at alpha frequency modulates the spatial attentional bias in an endogenous but not in an exogenous visuospatial attention task. Yet, the reason for this task-specificity remains unexplored. Here, we tested whether this dissociation relates to the proposed differential role of the dorsal attention network (DAN) and ventral attention network (VAN) in endogenous and exogenous attention processes respectively. To that aim, we targeted the left and right dorsal parietal node of the DAN, as well as the left and right ventral temporoparietal node of the VAN using tACS at the individual alpha frequency. Every participant completed all four stimulation conditions and a sham condition in five separate sessions. During tACS, we assessed the behavioral visuospatial attention bias via an endogenous and exogenous visuospatial attention task. Additionally, we measured offline alpha power immediately before and after tACS using electroencephalography (EEG). The behavioral data revealed an effect of tACS on the endogenous but not exogenous attention bias, with a greater leftward bias during (sham-corrected) left than right hemispheric stimulation. In line with our hypothesis, this effect was brain area-specific, i.e., present for dorsal parietal but not ventral temporoparietal tACS. However, contrary to our expectations, there was no effect of ventral temporoparietal tACS on the exogenous visuospatial attention bias. Hence, no double dissociation between the two targeted attention networks. There was no effect of either tACS condition on offline alpha power. Our behavioral data reveal that dorsal parietal but not ventral temporoparietal alpha oscillations steer endogenous visuospatial attention. This brain-area specific tACS effect matches the previously proposed

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dissociation between the DAN and VAN and, by showing that the spatial attention bias effect does not generalize to any lateral posterior tACS montage, renders lateral cutaneous and retinal effects for the spatial attention bias in the dorsal parietal condition unlikely. Yet the absence of tACS effects on the exogenous attention task suggests that ventral temporoparietal alpha oscillations are not functionally relevant for exogenous visuospatial attention. We discuss the potential implications of this finding in the context of an emerging theory on the role of the ventral temporoparietal node.

1. Introduction

A common visual scene consists of a large number of stimuli, which cannot all be recognized simultaneously. Visuospatial attention enables one to preferentially process relevant stimuli while ignoring irrelevant stimuli based on their location in space and thereby helps us to cope with this bottleneck (Posner, 1980a, 1980b; Posner, Snyder, & Davidson, 1980). Visuospatial attention can be categorized into endogenous and exogenous attention (Connor, Egeth, & Yantis, 2004; Corbetta & Shulman, 2002a; Itti & Koch, 2001). Exogenous attention, also known as stimulus-driven or bottom-up attention, describes attentional processing that is automatic and driven by salient inherent properties of the stimulus itself, such as location, brightness, color or motion. Endogenous or top-down attention/goal-driven attention, in contrast, refers to the voluntary direction of attention based on prior knowledge or current goals. Endogenous and exogenous spatial attention can be assessed with variants of the Posner cueing task (Müller & Rabbitt, 1989; Posner, 1980b; Posner et al., 1980), which measure the participants' ability to react to lateralized target stimuli in either hemifield after presentation of endogenous (central, symbolic) or exogenous (peripheral, salient) spatial cues indicating the potential location where the target may appear.

It has been proposed that endogenous versus exogenous attention are regulated by two separate but interacting attention networks (Chica, Bartolomeo, & Lupiáñez, 2013): the dorsal attention network (DAN), which consists of the intraparietal sulcus (IPS) and frontal eye field (FEF), and the ventral attention network (VAN), which comprises the temporoparietal junction (TPJ) and the ventral frontal cortex (VFC) respectively. According to Chica et al. (2013), the VAN detects salient, unexpected events and interrupts the ongoing attention deployment to enable exogenous attention shifts. The DAN, on the other hand, maintains the attentional locus according to the current goals and initiates endogenous as well as exogenous attention shifts in case of relevant events (for alternative views see Macaluso & Doricchi, 2013 and Vossel, Geng, & Fink, 2014). The functional role of the two attention networks has been extensively investigated using functional magnetic resonance imaging (fMRI) (Corbetta, Kincade, & Shulman, 2002; Corbetta & Shulman, 2002b; Doricchi, Macci, Silvetti, & Macaluso, 2010; Hahn, Ross, & Stein, 2006; J. B. Hopfinger, Buonocore, & Mangun, 2000; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; Kincade, 2005; Mayrhofer, Duecker, van de Ven, Jacobs, & Sack, 2019). However, it remains unclear how alpha oscillations, which are strongly related to visuospatial attention performance, relate to the functioning of these two separate attention networks.

Electroencephalography (EEG) studies have demonstrated that attentional shifts are associated with a modulation of alpha power over parietal and occipital areas, i.e., alpha power increases in the ipsilateral relative to the contralateral hemisphere (Gould, Rushworth, & Nobre, 2011; Händel, Haarmeier, & Jensen, 2011; Sauseng et al., 2005b). This power modulation can be observed after presentation of a central spatial cue but before the lateralized target stimulus is shown, which suggests that the occipitoparietal alpha power changes represent an endogenous attention related response rather than a stimulus-driven response. While various EEG studies investigated the association between alpha power and endogenous attention shifts (Gould et al., 2011; Händel et al., 2011; Sauseng et al., 2005b), we are not aware of any experiment that looked into alpha power modulations related to exogenous attention shifts. This may be brought about by the transitory nature of exogenous attention (Müller & Rabbitt, 1989), which hampers the analysis as well as the interpretation of the associated oscillatory responses due to the simultaneously occurring event-related potentials (ERPs) triggered by exogenous cues (Yordanova, Kolev, & Polich, 2001). Hence, neuroimaging techniques such as EEG do not easily allow for a proper investigation of the oscillatory responses during exogenous attention shifts. As an elegant alternative, neuromodulatory techniques may be used to address the functional relevance of alpha oscillations in exogenous attention. Transcranial alternating current stimulation (tACS) is a non-invasive neuromodulatory technique, which delivers alternating current via two or more electrodes attached to the participant's scalp. TACS at alpha frequency has previously shown to enhance the power of alpha oscillations at or near the stimulation site (Kasten, Dowsett, & Herrmann, 2016; Neuling, Rach, & Herrmann, 2013; Witkowski et al., 2016; Zaehle, Rach, & Herrmann, 2010) and various previous studies have reported an effect of tACS on visual or auditory attention performance (Deng, Reinhart, Choi, & Shinn-Cunningham, 2019; Joseph B. Hopfinger, Parsons, & Fröhlich, 2017b; Kasten, Wendeln, Stecher, & Herrmann, 2020; Kemmerer et al., 2020; Schuhmann et al., 2019; Wöstmann, Vosskuhl, Obleser, & Herrmann, 2018). Interestingly, recent research demonstrated that alpha-tACS over the left dorsal parietal cortex induces a visuospatial attention bias in an endogenous but

not in an exogenous attention task (Kasten et al., 2020; Schuhmann et al., 2019). These results suggest that dorsal parietal alpha oscillations are functionally relevant for endogenous but not for exogenous attention performance. It could be argued that these findings are in line with the functional dichotomy between a dorsal and ventral attention system as proposed by Chica et al. (2013). However, research into the effects of alpha-tACS targeting the VAN on visual exogenous attention is still lacking. At the same time, it is also still unclear whether the effect of tACS on endogenous visuospatial attention is specific to stimulation of the dorsal parietal cortex.

To test for a potential double dissociation regarding the functional role of alpha oscillations in the DAN versus VAN for endogenous versus exogenous visuospatial attention, we here applied alpha-tACS to the dorsal parietal and temporoparietal cortices, targeting the IPS and the TPJ respectively (Fig. 1A) while measuring endogenous and exogenous attention performance. Each participant completed five stimulation conditions in separate sessions and randomized order: left parietal, right parietal, left temporoparietal and right temporoparietal alpha-tACS as well as sham/placebo stimulation. The behavioral visuospatial attention bias was measured with an endogenous and exogenous attention task, two variants of the Posner cueing task (Johnson, Posner, & Rothbart, 1991; Posner, 1980b) (Fig. 1B and C). Before and directly after tACS, we collected 3 min of resting state EEG data to assess the offline tACS effect on alpha power lateralization (Fig. 1B). In general, we hypothesized that left and right hemispheric tACS would have opposing effects on the visuospatial attention bias and alpha power lateralization, i.e., induce an attention bias and alpha power lateralization towards the ipsilateral side. Because of the functional role of the IPS as part of the DAN and the functional role of occipitoparietal alpha power in the allocation of voluntary attention seen in EEG, magnetoencephalography (MEG) as well as in recent tACS research (Kasten et al., 2020; Kemmerer et al., 2020; Schuhmann et al., 2019), we expected that IPS alpha-tACS would specifically modulate the endogenous but not the exogenous attention bias. Stimulation of the TPJ, on the other hand, might affect the exogenous attention bias given the proposed functional role of the TPJ in exogenous attention or detection of salient, unexpected events (Chica et al., 2013; Corbetta, Patel, & Shulman, 2008). All in all, this might result in a double dissociation, i.e., an effect of parietal tACS and temporoparietal tACS on endogenous versus exogenous attention performance respectively. As the VAN is supposedly lateralized towards the right hemisphere (Corbetta & Shulman, 2002b; Thiebaut de Schotten et al., 2011), we expected to find a stronger stimulation effect for right as compared to left temporoparietal tACS, whereas no clear hemispheric lateralization effects were anticipated for the parietal tACS conditions.

2. Methods

2.1. Data statement and pre-registration

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study. No part of the study procedures or analyses was pre-registered in a time-stamped, institutional registry prior to the research being conducted. The data and experimental scripts are openly accessibly (https://doi.org/10.34894/OUVYI5).

2.2. Participants

25 healthy, right-handed participants (19 female, mean age (SD) = 21.48(2.56) years, age range = 18−28 years) with normal or corrected to normal vision completed this experiment. The sample size for this experiment was estimated based on the effect size of our previous tACS studies on visuospatial attention (Schuhmann et al., 2019). According to a power calculation (one-tailed paired t-test; effect size dz = .44; α error probability = .05; Power 1-β error prob), 33 participants were required to show a significant difference in visuospatial attention bias between the left parietal alpha-tACS condition and sham. Yet in contrast to our previous experiment in which we stimulated with a fixed frequency of 10 Hz, we here tuned the stimulation frequency to the individual alpha frequency (IAF). Because of this individually tailored stimulation protocol, we expected stronger stimulation effects as compared to our previous study and hence a lower required sample size to reach a significant effect. Data collection was ultimately stopped due to lab closure related to COVID-19. However, based on the above considerations, we believe that the sample size of 25 (at which we were forced to stop data collection due to COVID-19) provided enough power for the planned analysis. No participant was excluded from the analysis. At the beginning of each session, participants filled in an informed consent form and a tACS safety screening form scanning for e.g., neurological disorder, skin diseases and medication, following the recommended procedures of Antal and colleagues (Antal et al., 2017). This experiment was carried out in accordance with the Declaration of Helsinki and was approved by the local Ethics Review Committee Psychology and Neuroscience (ERCPN) (ERCPN number: 177). As compensation for taking part in the experiment, participants received vouchers.

2.3. Procedure

The experiment consisted of five stimulation conditions: left and right parietal tACS, left and right temporoparietal tACS (Fig. 1A) as well as sham/placebo tACS to one of the four stimulation sites that was randomly selected. Each participant underwent all five stimulation conditions in separate sessions and in randomized order. In the first session, we acquired 3 min of eyes-closed resting state EEG data and subsequently determined the individual alpha frequency (IAF) by calculating the frequency with the highest power in the alpha frequency range. This estimate served as stimulation frequency for all stimulation conditions. In each session, we initially recorded 3 min of eyes-closed resting state EEG data to determine the baseline lateralization of alpha power lateralization. Then, participants received tACS of successively increasing intensity for approximately 3 min to get used to the skin sensation. During this test stimulation, participants
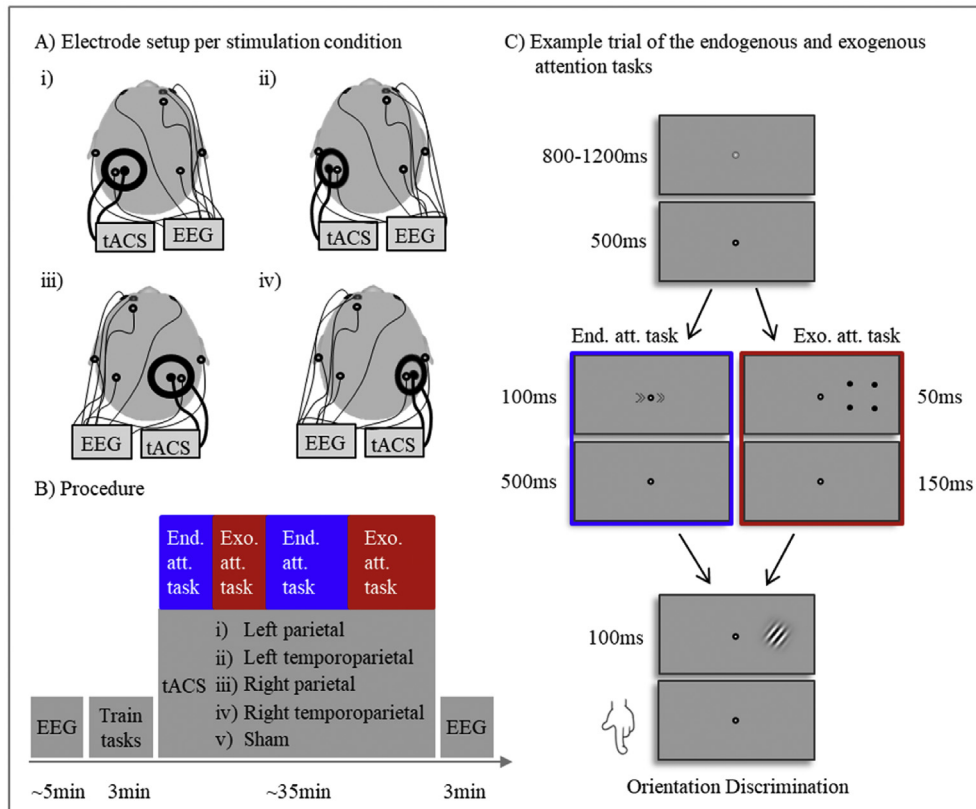
Fig. 1 — Electrode setup per stimulation condition, procedure and example trial of the endogenous and exogenous attention tasks. (A) tACS and EEG electrode configuration. The small tACS disk electrode was placed on the i) left parietal ii) left temporoparietal cortex iii) right parietal or iv) right temporoparietal cortex and the large ring electrode was centered on it. By mounting the tACS electrodes over the parietal or temporoparietal cortex, we targeted the intraparietal sulcus (IPS) of the dorsal attention network (DAN) or the temporoparietal junction (TPJ) of the ventral attention network (VAN) respectively. In between the disk and the ring electrode, we mounted one single EEG electrodes and mirrored to it also one single EEG electrodes in the contralateral hemisphere. (B) Procedure. At the beginning of each session, we measured resting state EEG data. Then, participants completed a shortened practice version of the attention tasks while receiving tACS of increasing intensity in order to adapt to the skin sensation. Subsequently, we applied alpha-tACS (or sham tACS) to one of the target sites while the participants performed both attention tasks in two alternating blocks. Here, the initial task (and thereby also the logically following task blocks) was randomized between participants. As soon as the participant completed all task blocks, the tACS device was switched off and resting state EEG data were measured again. Each participant underwent all five stimulation conditions in separate sessions and randomized order. (C) Example trial of the endogenous and exogenous attention task. In both tasks, a given trial started with a fixation period followed by an endogenous (in the endogenous attention task) or an exogenous cue (in the exogenous attention task). The endogenous cue consisted of central arrow heads pointing to the left, right or both sides whereas the exogenous cue consisted of four laterally placed dots, which surrounded the potential target location. This was followed by a fixation interval and subsequently a sinusoidal grating rotated by 45° either clock- or counterclockwise, was presented either in the left or right hemifield. The participants were instructed to discriminate the grating's orientation as fast and accurately as possible (valid trial in this example).

practiced the two attention tasks. Subsequently, alpha-tACS (or sham/placebo tACS) was applied for 35–40 min over one of the four stimulation sites while participants performed the endogenous and exogenous attention task. The attention tasks were administered in two alternating blocks and the initial as well as the corresponding following task blocks were randomized between participants. During the tasks, we acquired electrooculogram (EOG) data, which was subsequently used in the offline analysis to identify and subsequently delete trials confounded with eye artifacts. After completion of the tasks, tACS was switched off and 3 min of eyes-closed resting

state EEG data was acquired again (Fig. 1B). To verify whether participants were able to differentiate between real and sham tACS, we administered a questionnaire at the end of each session, which prompted the participants to guess the stimulation condition based on the subjective experience.

2.4.   Task description

We administered two variants of the classical Posner task, an endogenous and an exogenous attention task, to assess the efficiency, the speed and accuracy, in discriminating target

stimuli in either hemifield after endogenous or exogenous cues triggered attention shifts to either hemifield (Fig. 1C). Similar to our previous alpha tACS study (Kemmerer et al., 2020), we used the inverse efficiency score (reaction time (RT)/accuracy) as dependent variable, accounting for the trade-off between accuracy and RTs. The visuospatial attention bias score was calculated by subtracting the inverse efficiency score for right target location trials from the inverse efficiency score for left target location trials.

In both tasks, participants were instructed to consistently fixate on a central fixation point. At the beginning of each trial, this fixation point consisted of a white circle, surrounded by a black or grey annulus, which was circumscribed by a black circle. After a jittered interval of 800−1200 msec, the grey area turned black for 500 msec. Subsequently, a spatial cue was presented for 100 msec, which triggered spatial attention shift to either the left or right hemifield. In the exogenous attention task, the cue consisted of four black dots surrounding either the left or right potential target location and predicted the correct target location with chance accuracy (50% valid trials, 50% invalid trials). This salient, lateralized cue automatically triggers exogenous attention shifts. In the endogenous attention task, the cue surrounded the central fixation point and consisted of arrowheads pointing to the left (<<•<<) or right (>>•>>) side. For half of the participants (twelve participants), the cue predicted the correct target location with 62% accuracy (62% valid trials, 38% invalid trials). The other half of the participants (thirteen participants) were presented with cues that predicted the correct target location with only chance accuracy (50% valid trials, 50% invalid trials) and to ensure a cueing effect, we explicitly told the participants to initiate voluntary attention shifts according to the cue, independent of its validity. This between-subject factor cue validity was included in our design to rule out a potential confounder and to allow for controlled comparisons between cue and task conditions. In contrast to exogenous cues, the commonly employed endogenous cues are predictive, which implies a higher number of valid than invalid trials and means that invalid targets are scarce and therefore violate the participant's expectations. Hence, any behavioral differences between valid and invalid cue type trials and generally the endogenous and exogenous attention tasks cannot be unambiguously attributed to the respective attention processes but might be caused by differences in violations of expectations instead. By including the between-subject factor cue validity in this experimental design and testing for interactions with it, we are able to investigate whether violations of expectations represent a confounder, and if so, limit the analyses to the non-predictive condition of the endogenous attention task. The endogenous or exogenous cues were followed by a target stimulus after an interval of 500 msec and 150 msec for the endogenous and exogenous attention task respectively. This target stimulus was presented in the left or right hemifield at 7° (endogenous attention task) or 14° (exogenous attention task) eccentricity from the fixation point. The target stimulus consisted of a sinusoidal grating (spatial frequency = 1.5 cycles per degree, envelope standard deviation = .75°) with a Gaussian envelope, which was rotated by 45° in either clockwise or counter-clockwise direction. Participants were instructed to discriminate the orientation of the target stimulus as accurately and quickly as possible,

pressing the numerical buttons 1 or 2 for counter-clockwise and clockwise rotated stimuli respectively. Trials with a delayed (>1000 msec) or hasty (<120 msec) response were repeated. The endogenous and exogenous attention task were administered in two alternating blocks, in which the first two blocks consisted of 120 trials each and the last two blocks of 180 trials each. While the exogenous attention task and the 50% cue validity condition of the endogenous attention task comprised 150 valid and invalid trials respectively, the 62% validity condition of the endogenous attention task included 186 valid and 114 invalid trials. In total, each task consisted of 300 trials and took 35−40 min.

2.5.   tACS and electric field simulation

We used a small high-density concentric ring electrode montage (NeuroConn, Ilmenau, Germany) over the left or right parietal or temporoparietal cortex respectively. This montage results in a focal and confined electrical field with high current density in the brain area directly under the disc electrode and diffuse current flowing towards the ring electrode (Datta, Elwassif, Battaglia, & Bikson, 2008b) (Fig. 1A). Hence, the stimulation effect is greatest at the center of the ring electrode montage, which approximately corresponds to the IPS and TPJ for the parietal and temporoparietal ring electrode configuration respectively. First, we marked the electrode positions on the participant's head according to the international 10−20 EEG system. Then, the small circular electrode (Diameter: 2.1 cm; Thickness, 2 mm) was positioned over either the left parietal cortex (between P1 and P3), right parietal cortex (between P2 and P4), left temporoparietal cortex (between P5, P7, CP5 and TP7) or right temporoparietal cortex (between P6, P8, CP6 and TP8) and the large ring electrode (Outer diameter: 10 cm; Inner diameter: 7.5 cm; Thickness: 2 mm) was centered on it. The location of the respective montage was a priori determined based on current simulations on ten freely available individual models of healthy brains, aiming at an electric field that encompasses the IPS and the TPJ for the parietal and temporoparietal montage respectively. tACS was applied via a DC-stimulator plus (NeuroConn, Ilmenau, Germany) at the IAF and a stimulation intensity of 1.5 mA peak to peak. In all the active tACS conditions, we ramped the stimulation up for 100 cycles and subsequently stimulated for 35−40 min at the IAF. The stimulator was switched off after completion of all tasks but never exceeded 40 min. For the sham stimulation, we ramped the stimulation up over 100 cycles, maintained stimulation for 300 cycles, and then ramped back down, over 100 cycles. This stimulation protocol mimics the skin sensations of real tACS while minimizing neuronal stimulation effects. We used conductive gel (Ten20 paste, Weaver and Company, Aurora, CO, USA) to attach the electrodes on the skin and to keep impedances below 10 kΩ.

To visualize the expected norm electric field, we performed an electric current simulation (Fig. 2) using a custom-written MATLAB script (Heise, Monteiro, Leunissen, Mantini, & Swinnen, 2019), which interfaces with the software SimNIBS (Saturnino, Puonti, et al., 2019; Saturnino, Thielscher, Madsen, Knösche, & Weise, 2019). For this, we used a freely available head mesh of a healthy brain (Boayue, Csifcsák, Puonti, Thielscher, & Mittner, 2018). The electrode parameters were
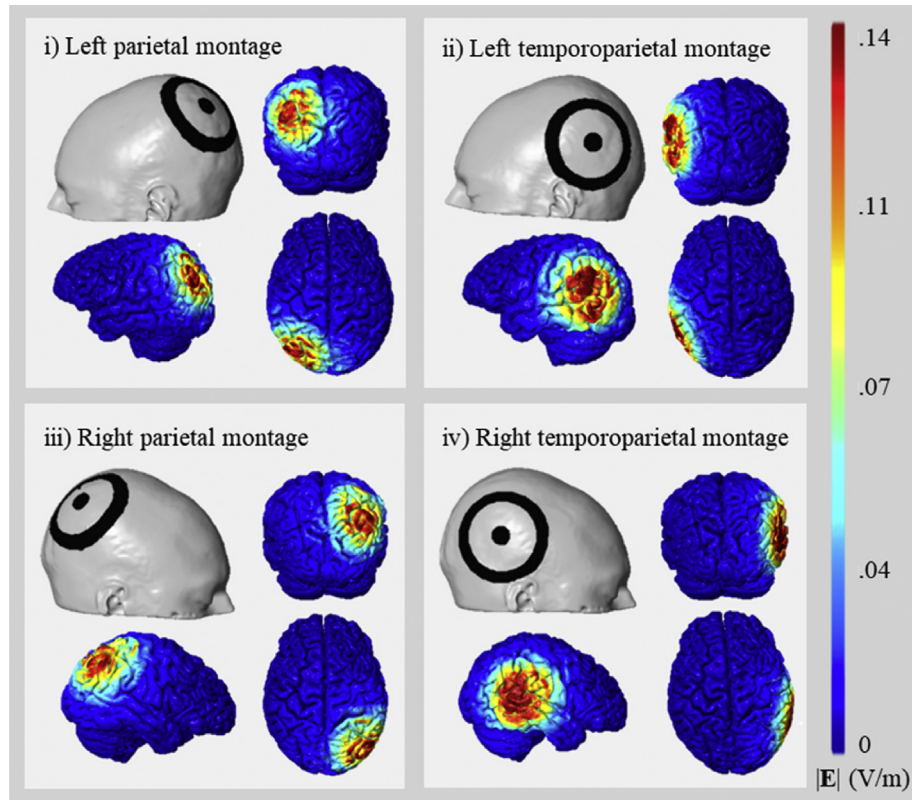
Fig. 2 — **Current simulation results for the i) left parietal ii) left temporoparietal iii) right parietal and iv) right temporoparietal stimulation condition. Depicted is the norm electric field (V/m) on an example brain from a coronal, transverse and left or right sagittal view. The software SimNIBS was used to run the simulations.**

set to a random connector location and a conductance paste conductivity of 8 S/m (estimation is based on the concentration of CI- in the gel (Saturnino, Antunes, & Thielscher, 2015)) (Fig. 2).

2.6. EEG apparatus and data acquisition

At the beginning of the first session, we mounted a single EEG electrode at Pz, one reference electrode at each mastoid and a ground electrode on the forehead, to determine the IAF, which was subsequently used as a stimulation frequency. For all the subsequent EEG measurements, a single EEG electrode was mounted in between the small disk and concentric ring tACS electrode and another one mirrored to this electrode in the contralateral hemisphere. For the parietal and temporoparietal electrode montage, we placed the EEG electrode on the lateral and medial side of the small disk tACS electrode respectively, resulting in similar cortical EEG electrode locations within one hemisphere. Additionally, we placed electrooculogram (EOG) electrodes above and below the right eye and at the outer canthus of each eye to measure vertical and horizontal eye movements during the tasks. The ground electrode was placed on the forehead and two reference electrodes were mounted on either mastoid. The recordings were online referenced to the left and offline re-referenced to both mastoids. For the EEG measurement, we used Ag–AgCl electrodes (BrainProducts GmBh, Munich, Germany) and a BrainAmp DC amplifier (BrainProducts, GmbH, Gilching,

Germany) employing a sampling rate of 500 Hz and an online bandpass filter of .1–200 Hz. The impedance for all electrodes was kept below 10 kΩ for the cortical and EOG electrodes and below 5 kΩ for the reference and ground electrodes.

3. Preprocessing

3.1. Behavioral data

Prior to the analysis of the behavioral data, we first identified, and subsequently excluded trials contaminated with eye movements based on the trial-by-trial electrooculogram (EOG) data that was acquired during the attention tasks. Separately for the endogenous and exogenous attention task, we analyzed the cue target interval and used the function ft_artifact_eog.m to detect and reject trials with a z-score above 6. This resulted in a similar number of rejected trials for the behavioral data of the endogenous and exogenous attention task as in our previous comparable projects (Kemmerer et al., 2020; Schuhmann et al., 2019), which included eye tracker recordings (3% of all trials). For the sham condition, a more liberal z-score threshold of 9 was chosen to account for the absence of tACS artifacts and to achieve a similar number of rejected trials for all stimulation conditions. Subsequently, we analyzed the RT scores per attention task and excluded trials with an incorrect or missing response (5% of all trials). Furthermore, per stimulation condition and trial type (valid,

invalid), we excluded trials with deviating RT scores, falling outside the median $\pm$ 1.5*interquartile range (IQR) (3% of all trials). Just like in our previous tACS attention study (Kemmerer et al., 2020), we subsequently calculated the visuospatial attention bias score by subtracting the inverse efficiency score (RT/accuracy) of right from left target location trials per participant and condition.

3.2. EEG data

EEG data was analyzed offline using the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) for MATLAB (MathWorks). First, we segmented the data into 4-s epochs and excluded trials with an amplitude over time variance deviating by more than 2 standard deviations from the mean. Then, we performed a Fourier analysis using Hanning tapers per electrode and participant and averaged the frequency power spectrum over the 3 min resting state EEG recording. The IAF was defined by determining the frequency with the highest power in the frequency range between 7 and 13 Hz. For the analysis of the neuronal stimulation effect, we first determined the individual alpha power in the frequency interval IAF-1Hz to IAF+1 Hz. Then we calculated the alpha lateralization index (ALI), the proportion increase in individual alpha power (PIA) from the pre-to the post-measurement (PIA: (alpha$_{\text{post-measurement}}$ $-$ alpha$_{\text{pre-measurement}}$)/alpha$_{\text{pre-measurement}}$ *100) in the left relative to the right hemisphere (ALI: PIA$_{\text{left hemisphere}}$ $-$ PIA$_{\text{right hemisphere}}$). Similarly to our previous tACS experiment (Kemmerer et al., 2020), we only analyzed the first minute of the post-measurement, in which the greatest after-effects are expected.

4. Statistical analysis

4.1. Behavioral data

First, we analyzed the cueing effect in the endogenous and exogenous attention task using the RT data of the sham condition averaged over both target location trials. Then we performed a repeated measures ANOVA on the inverse efficiency score using cue type as factor. For the endogenous attention task, cue validity (50%, 62%) was additionally included as between-subject factor to account for potential differences caused by the validity with which the cue predicted the correct target location.

For the analysis of the behavioral tACS effect, we followed an a priori determined analysis pipeline. First, we subtracted the visuospatial attention bias score of the sham condition from the data of the active stimulation conditions per condition and participant. This sham-corrected visuospatial attention bias score was used as dependent variable for all subsequent analyses. We ran a repeated measures ANOVA on this sham-corrected visuospatial attention bias score including stimulated area (parietal, temporoparietal), stimulated hemisphere (left, right) and type of cue (valid, invalid) as factors. For the endogenous attention task, we also included cue validity as between-subject factor. Furthermore, we tested whether there are significant differential tACS effects on the two tasks by performing an analysis on the z-score transformed bias score.

For this, we first calculated the mean and standard deviation over all conditions per participant and subsequently used these estimates for the calculation of the z-score (score - mean/standard deviation) per stimulated area, stimulated hemisphere and type of cue.

4.2. EEG data

We first verified the test-retest reliability of the IAF estimates. For this, we determined the IAF per participant and session using the pre-stimulation EEG recording. Then we analyzed the intraclass correlation for the IAF estimates of the five testing sessions.

For the analysis of the tACS effect on alpha power, we first calculated the proportion increase in alpha power (PIA) from the pre-to the post-measurement per hemisphere, stimulation condition and participant. We subsequently computed ALI by subtracting PIA of the right from PIA of the left hemisphere and sham-corrected it by subtracting the ALI score of the sham condition from the active stimulation conditions per condition and participant. Then, we ran a repeated measures ANOVA with stimulation condition (left parietal, right parietal, left temporoparietal, right temporoparietal) as factor and sham-corrected ALI score as dependent variable.

4.3. Blinding success

To verify blinding success, we fitted generalized estimating equations on the indicated stimulation conditions ('real tACS', 'sham tACS', 'I do not know') including the actual stimulation condition with five levels (left/right dorsal parietal tACS, left/right ventral temporoparietal tACS, sham) as factors. We statistically tested whether the actual stimulation condition affected the indicated stimulation condition using generalized estimating equations. Note that because of time constraints during testing, the post-questionnaire was not completed in 11 out of 131 sessions.

5. Results

5.1. Behavioral data

5.1.1. Spatial cues modulate task performance
The average accuracy in the endogenous attention task was 95% and ranged between 67% and 100% whereas in the exogenous attention task, the average accuracy was 94% and ranged between 54% and 100% over participants and conditions.

Similarly to our previous experiments (Kemmerer et al., 2020; Schuhmann et al., 2019), we first validated the attention tasks before analyzing the effect of the brain stimulation on task performance. For this, we used the data of the sham session, which is expected to be unaffected by the brain stimulation and compared the inverse efficiency score between valid and invalid cue trials. For the endogenous attention task, we performed a repeated measures ANOVA on the sham-corrected inverse efficiency score including cue type (valid, invalid) and cue validity (50%, 62%) as independent variables. For the exogenous attention task, we compared the

sham-corrected inverse efficiency score between valid and invalid cue type trials using a paired-samples *t*-test. In the endogenous attention task, there was a significant effect of cue type ($F(1,23) = 14.31$, $P = .001$) with a lower inverse efficiency score for valid ($M = 472.70$, $SE = 12.18$) as compared to invalid cue trials ($M = 495.47$, $SE = 13.48$) (Fig. 3). The interaction effect with cue validity ($F(1,23) = 1.34$, $P = .258$) was not significant (see Fig. 3-figure supplement 1 for a visualization of the cueing effect per cue validity condition). Also in the exogenous attention task, there was a significant difference between valid and invalid cue trials ($t(24) = -9.49$, $p < .001$) with a lower inverse efficiency score in valid ($M = 442.80$, $SE = 7.93$) as compared to invalid cue trials (498.87, $SE = 10.84$) (Fig. 3).

This means that the endogenous as well as exogenous cues modulated task performance by increasing the response efficiency for targets in the cued as compared to the uncued hemifield. This effect was independent of the endogenous cue validity, i.e., not significantly different for cues that predict the correct target location with 50% or 62% validity.

5.1.2. Area-specific effect of tACS on the visuospatial attention bias

We first verified whether there is a differential effect of parietal and temporoparietal tACS on the endogenous and exogenous attention task by running the full model, that is a repeated measures ANOVA on the z-transformed visuospatial attention bias score including task (endogenous, exogenous),
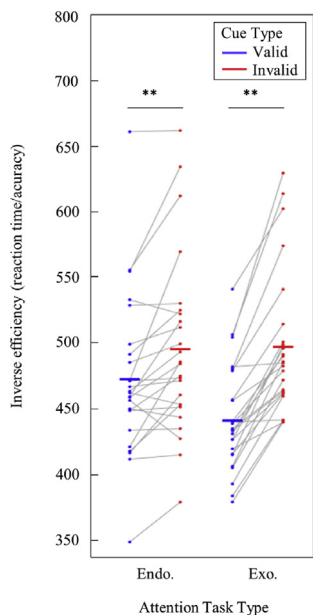

Fig. 3 – Cueing effect in the endogenous and exogenous attention task. The bar graph depicts the inverse efficiency score (reaction time/accuracy) per cue type (valid, invalid) for the sham condition. The colored dots, the colored thick horizontal lines and the thin grey lines depict the data of individual participants, the group mean and the connection between data points of individual participants respectively. Error bars visualize the standard error of the mean across participants and the double asterisk depicts significant differences with P-values ≤ .001.

stimulated area (parietal, temporoparietal), stimulated hemisphere (left, right) and cue type (valid, invalid) as factors. We found a three-way interaction between stimulated area, stimulated hemisphere and cue type ($F(1,24) = 6.55$, $P = .017$) as well as a four-way interaction effect between task, stimulated area, stimulated hemisphere and cue type ($F(1,24) = 5.55$, $P = .027$). All other main and interaction effects were not significant (stimulated area: $F(1,24) = .75$, $P = 395$; stimulated hemisphere: $F(1,24) = .04$, $P = .838$; cue type: $F(1,24) = .99$, $P = .329$; task x stimulated area: $F(1,24) = .32$, $P = .577$; task x stimulated hemisphere: $F(1,24) = .59$, $P = .449$; stimulated area x stimulated hemisphere: $F(1,24) = .02$, $P = .894$; stimulated area x cue type: $F(1,24) = .24$, $P = .630$; stimulated hemisphere x cue type: $F(1,24) = 1.90$, $P = .181$; task x cue type: $F(1,24) = 1.49$, $P = .235$; task x stimulated area x stimulated hemisphere: $F(1,24) = 4.10$, $P = .054$; task x stimulated area x cue type: $F(1,24) = 1.77$, $P = .196$; task x stimulated hemisphere x cue type: $F(1,24) = .07$, $P = .799$) (Fig. 4, see also Fig. 4 supplement 2 for a visualization of all five stimulation conditions including sham).

Following up on the four-way interaction, we subsequently tested whether parietal and temporoparietal tACS induced a visuospatial attention bias in the endogenous attention task. To that aim, we performed a repeated measures ANOVA with the visuospatial attention bias score as dependent variable and stimulated area (parietal, temporoparietal), stimulated hemisphere (left, right) and cue type (valid, invalid) as factors. Additionally, we added cue validity (50%, 62%) as between subject factor. There was a significant three-way interaction effect between stimulated area, simulated hemisphere and cue type ($F(1,23) = 17.82$, $p < .001$) (Fig. 4). All other main and interaction effects were not significant (stimulated area: $F(1,23) = .06$, $P = .817$; stimulated hemisphere: $F(1,23) = .01$, $P = .937$; cue type: $F(1,23) = .12$, $P = .734$; stimulated area x stimulated hemisphere: $F(1,23) = .27$, $P = .607$; stimulated area x cue type: $F(1,23) = 2.53$, $P = .126$; stimulated hemisphere x cue type: $F(1,23) = 1.15$, $P = .295$; stimulated area x cue validity: $F(1,23) = 2.07$, $P = .164$; stimulated area x cue validity: $F(1,23) = .04$, $P = .844$; cue type x cue validity: $F(1,23) = 2.41$, $P = .134$; stimulated area xx stimulated hemisphere x cue validity: $F(1,23) = .93$, $P = .345$; stimulated area x cue type x cue validity: $F(1,23) = .621$, $P = .439$; stimulated hemisphere x cue type x cue validity: $F(1,23) = 1.16$, $P = 293$; stimulated area x stimulated hemisphere x cue type x cue validity: $F(1,23) = .798$, $P = .381$). We also tested whether α-tACS modulated the exogenous visuospatial attention bias by running a repeated measures (ANOVA) on the visuospatial attention bias score as measured with the exogenous attention task including stimulated area (parietal, temporoparietal), stimulated hemisphere (left, right) and cue type (valid, invalid) as factors. There were no significant main or interaction effects (stimulated area: $F(1,24) = .36$, $P = .556$; stimulated hemisphere: $F(1,24) = .09$, $P = .771$; cue type: $F(1,24) = 2.62$, $P = .119$; stimulated area x stimulated hemisphere: $F(1,24) = 3.99$, $P = .057$; stimulated area 'cue type: $F(1,24) = .29$, $P = 595$; stimulated hemisphere x cue type: $F(1,24) = .82$, $P = .375$; stimulated area x stimulated hemisphere x cue type: $F(1,24) = .69$, $P = .413$) (Fig. 4).

To break down the significant three-way interaction between stimulated area, stimulated hemisphere and cue type for the endogenous attention task, we subsequently
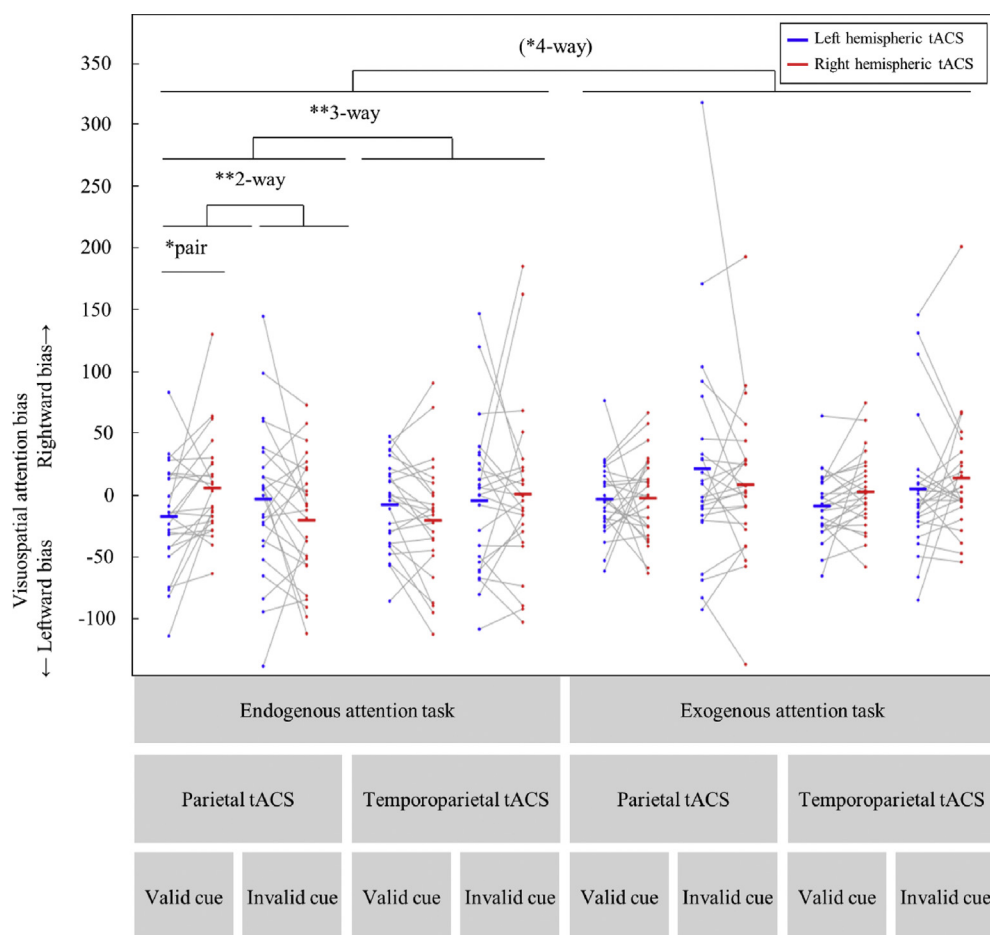
Fig. 4 — Stimulation site-, cue- and task-specific tACS effect on the sham-corrected visuospatial attention bias. Depicted is the visuospatial attention bias per stimulated hemisphere (left tACS in dark blue, right tACS in light blue), task condition (endogenous versus exogenous attention task), stimulated area (parietal, temporoparietal), and cue type (valid, invalid). As the data is visualized relative to sham, zero represents the individual baseline visuospatial attention bias as assessed during the sham session, whereas positive and negative values represent a tACS-induced leftward and rightward biases respectively. The visuospatial attention bias is the lateralization of the inverse efficiency score (RT/accuracy$_{left\ target\ trials}$ − RT/accuracy$_{right\ target\ trials}$) and a positive or negative value represents a rightward or leftward bias respectively. To account for absolute and relative differences in the visuospatial attention bias score between the endogenous and exogenous attention task, the 4-way interaction effect (symbolized in brackets) was tested using z-scores. The colored dots, the colored thick horizontal lines and the thin grey lines depict the data of individual participants, the group mean and the connection between data points of individual participants respectively. The asterisk and double asterisk symbolize significant differences with P-values ≤ .05 and ≤.001 respectively. 4-way: four-way interaction effect, 3-way: three-way interaction effect, 2-way: two-way interaction effect, pair: pair-samples t-test, single: one-sample t-test that tests for significant differences from zero.

performed follow-up analyses per stimulated area. For the parietal stimulated area, there was a significant two-way interaction between stimulated hemisphere and cue type ($F(1,23) = 13.80$, $P = .001$) (Fig. 4). All other main and inter-action effects were not significant (stimulated hemisphere: $F(1,23) = .09$, $P = .769$; cue type: $F(1,23) = .179$, $P = .676$; stimulated hemisphere x cue validity: $F(1,23) = .615$; $P = .441$; cue type x cue validity: $F(1,23) = .90$, $P = .353$; stimulated hemisphere x cue type x cue validity: $F(1,23) = .17$, $P = .683$). For the temporoparietal stimulated area, there were no sig-nificant main or interaction effects (stimulated hemisphere: $F(1,23) = .20$, $P = .660$; cue type: $F(1,23) = 1.24$, $P = .277$; stimulated hemisphere x cue type: $F(1,23) = 1.97$, $P = .174$;

stimulated hemisphere x cue validity: $F(1,23) = .32$, $P = .576$; cue type x cue validity: $F(1,23) = 3.39$, $P = .078$; stimulated hemisphere x cue type x cue validity: $F(1,23) = 1.60$, $P = .218$).

We subsequently broke down the two-way interaction by performing follow-up analyses per cue type. For the valid cue type, there was a significant difference between the left and right stimulated hemisphere ($t(24) = -2.60$, $P = .016$), with a lower visuospatial attention bias score for the left ($M = −15.82$, $SE = 8.61$) as compared to the right stimulated hemisphere ($M = 6.98$, $SE = 8.05$) (Fig. 4, also see Fig. 4-figure supplement 1 for a visualization of the stimulation effect per stimulation condition and target location and Table 1 for a summary of all median RTs, accuracy and inverse efficiency scores per

Table 1 — Median reaction times (RT), accuracy and inverse efficiency score per condition for the endogenous orienting task. The table shows the average values per stimulation condition (left parietal, right parietal, left temporoparietal, right temporoparietal, sham), target location (left, right) as well as cue type (valid, invalid). The standard error of the mean across participants is indicated in brackets.

Stim. condition	Left parietal				Right parietal				Left temporoparietal				Right temporoparietal				Sham			
Target location	Left		Right		Left		Right		Left		Right		Left		Right		Left		Right	
Cue type	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid
Median RT	458 (8.65)	481 (11)	456 (13	461 (13)	464 (12)	482 (12)	445 (9)	461 (11)	451 (7)	479 (10)	440 (8)	454 (9)	457 (9)	477 (12)	453 (11)	461 (13)	460 (9)	477 (11)	446 (10)	458 (10)
Accuracy	97% (1)	94% (1)	97% (1)	95% (1)	94% (1)	97% (1)	95% (1)	95% (1)	95% (1)	95% (1)	96% (1)	95% (1)	96% (1)	93% (2)	95% (1)	95% (1)	96% (1)	94% (1)	96% (1)	96% (1)
Inverse efficiency	475 (11)	515 (17)	473 (14)	487 (16)	495 (18)	501 (17)	469 (13)	490 (17)	474 (9)	507 (15)	462 (11)	481 (13)	479 (12)	523 (23)	480 (16)	491 (19)	482 (12)	510 (14)	464 (13)	481 (14)

condition). A descriptive analysis of the stimulation effect (visuospatial attention bias$_{\text{left parietal tacs}}$ − visuospatial attention bias$_{\text{right parietal tACS}}$) per participant in the valid trials of the endogenous attention task revealed that 17 out of 25 participants showed an effect in the hypothesized direction (Fig. 5). In the invalid cue type condition, there was no difference between the left and right hemispheric stimulation condition (t(24) = 1.50, P = .146).

Following up on the significant difference between sham-corrected left and right parietal tACS, we subsequently performed one-sample t-tests to verify in which of the two conditions (hemispheres), the visuospatial attention bias significantly differed from zero. While previous analyses directly assessed differences between hemispheres, this post-hoc analysis should reveal separately for the left hemisphere and/or the right hemisphere whether parietal tACS affected the endogenous attention task. We found a significant effect for the left (t(24) = −1.84; p = .039, one-sided) but not for the right parietal stimulation condition (t(24) = .867, p = .197, one-sided), in line with our previous studies showing that left parietal tACS affects endogenous attention but not finding the same statistical support for the right hemisphere (see Tables 1 and 2 for an overview of median RTs, accuracy and inverse efficiency scores per condition for the endogenous and exogenous attention task respectively).

Hence, the effect of tACS on the visuospatial attention bias is area-specific, i.e., present in the parietal but not in the temporoparietal stimulation condition as well as cue- and task-specific, i.e., evident in the valid (but not invalid) trials of the endogenous but not in the exogenous attention task. The visuospatial attention bias effect was marked by a lower visuospatial attention bias score (leftward bias) in the left as compared to the right parietal stimulation condition (rightward bias), in line with our hypothesis. Follow-up tests revealed that the visuospatial attention bias of the sham-corrected left but not sham-corrected right parietal tACS differed from zero.

5.1.3. EEG data

We first examined the within- and between-subject variability of the IAF to verify its reliability. The average IAF was 10.02 Hz and varied between 7.25 Hz and 12.25 Hz amongst participants. For the analysis of the within-subject variability we calculated the intraclass correlation coefficient (ICC) over the five IAF estimates of the pre-measurements of each session. The test-retest reliability of the IAF was very high as shown by an intraclass correlation coefficient (ICC) of .95 (F(24,96) = 21.82, p < .001). This means that the IAF was a stable trait marker with little variation over the five sessions.

To test whether tACS induced an alpha power lateralization towards the ipsilateral side, we performed a repeated measures ANOVA on the sham-corrected alpha power lateralization index (ALI) including stimulated area (parietal, temporoparietal) and stimulated hemisphere (left, right) as factors. There were no significant main or interaction effects (stimulated area: F(1,24) = .861, P = .363, stimulated hemisphere: F(1,24) = .95, P = .339, stimulated area x stimulated hemisphere: F(1,24) = .05, P = .824) (left dorsal parietal: M = −3.35, SE = 7.88, right dorsal parietal: M = −8.23, SE = 8.72, left ventral temporoparietal: M = 5.31, SE = 9.10, right ventral
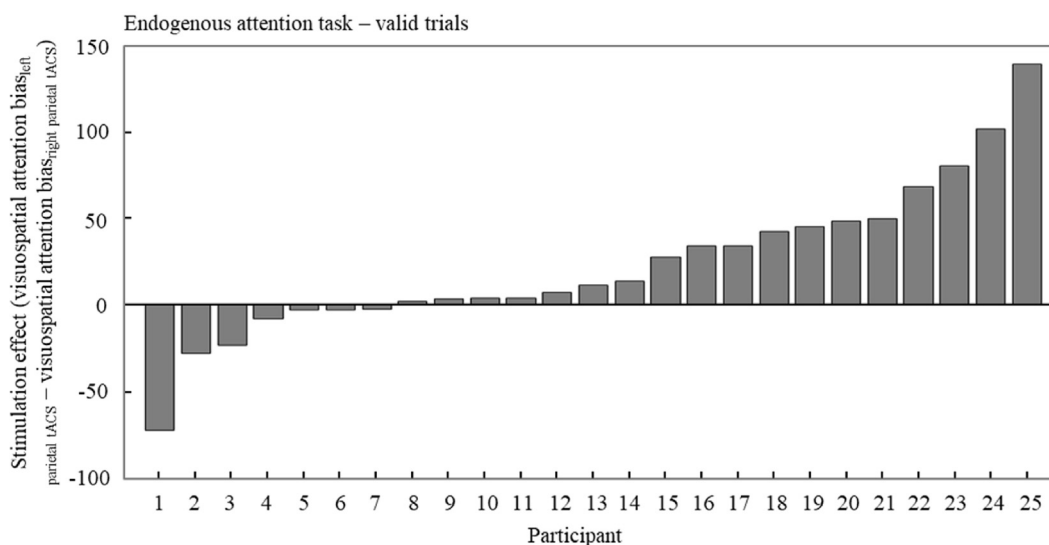
Fig. 5 – Stimulation effect (visuospatial attention bias$_{\text{left parietal tacs}}$ – visuospatial attention bias$_{\text{right parietal tACS}}$) per participant for the valid trials of the endogenous attention task. A positive score means that tACS induced the expected behavioral stimulation effect, i.e., a greater visuospatial attentional leftward bias in the left relative to the right hemispheric stimulation condition.

temporoparietal: M = −3.73, SE = 11.04). This means that, even though the direction of effect partly matches our hypotheses, we found no evidence for an offline tACS effect in the EEG data.

5.1.4.   Blinding success

To verify whether participants were able to differentiate between the Stimulation Conditions, we performed a generalized estimating equation analysis (Liu & Zhang, 2006). Actual Stimulation Condition with five levels (left/right dorsal parietal, left/right ventral temporoparietal, sham) was included as factor and Indicated Stimulation Condition with three levels ('real stimulation', 'sham stimulation', 'I do not know') was used as dependent variable. The Wald chi square test indicated that the actual Stimulation Condition did not affect the Indicated Stimulation Condition ($X^2(4, N = 118) = 7.19$, $P = .126$), which means that blinding was successfully maintained.

6.   Discussion

In this experiment, we tested the effect of left and right parietal versus temporoparietal alpha-tACS on the endogenous versus exogenous visuospatial attention bias. By stimulating the parietal and temporoparietal cortex we targeted the DAN and the VAN respectively, two networks that have previously been associated with endogenous and exogenous attentional control respectively (Chica et al., 2013). Each participant completed five stimulation conditions in separate sessions and randomized order: left parietal, right parietal, left temporoparietal and right temporoparietal alpha-tACS as well as placebo/sham stimulation. During stimulation, we measured the visuospatial attention bias with an endogenous and an exogenous attention task and immediately before and after tACS, we acquired 3 min of resting-state EEG data to assess the

offline tACS effect on alpha power lateralization. We hypothesized that left and right hemispheric alpha-tACS induces a leftward and rightward visuospatial attention bias and alpha power lateralization respectively. Our data show a differential effect of sham-corrected left and right parietal alpha-tACS on the endogenous visuospatial attention bias. This effect was driven by a greater visuospatial attentional leftward bias for left parietal tACS as compared to sham. The effect of dorsal parietal tACS on endogenous attention matches previous fMRI experiments about the functional role of the IPS (Corbetta et al., 2002; Corbetta & Shulman, 2002b; Doricchi et al., 2010; Hahn et al., 2006; J. B.; Hopfinger et al., 2000; Kastner et al., 1999; Kincade, 2005) as well as EEG experiments about the functional role of parietooccipital alpha power in endogenous visuospatial attention (Gallotto et al., 2020; Gould et al., 2011; Händel et al., 2011; Lasaponara, Pinto, Aiello, Tomaiuolo, & Doricchi, 2019; Newman, O'Connell, & Bellgrove, 2013; Sauseng et al., 2005a; Thut, 2006). Ventral temporoparietal tACS, on the other hand, did not modulate the visuospatial attention bias in either task, which suggests that temporoparietal alpha oscillations might not be functionally relevant for exogenous or endogenous visual attentional control. We found no tACS effect on the alpha power lateralization score (see section limitations below for possible explanations).

All in all, dorsal parietal but not ventral temporoparietal alpha-tACS induced an endogenous visuospatial attention bias towards the ipsilateral side, in line with our hypothesis. There was no effect of ventral temporoparietal (or dorsal parietal) alpha-tACS on the exogenous attention, i.e., no double dissociation, contrary to our original hypothesis. Although the absence of evidence in the temporoparietal stimulation condition is no evidence of absence, the laterality of the montage and the proximity to the parietal stimulation site make the ventral temporoparietal stimulation condition a well-suited

Table 2 – Median reaction times (RT), accuracy and inverse efficiency score per condition for the exogenous orienting task. Same legend as in Table 1.

Stim. condition	Left parietal				Right parietal				Left temporoparietal				Right temporoparietal				Sham			
Target location	Left		Right		Left		Right		Left		Right		Left		Right		Left		Right	
Cue type	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid	Valid	Invalid
Median RT	435 (7)	473 (9)	428 (7)	455 (9)	435 (9)	470 (11)	429 (8)	455 (9)	419 (6)	457 (8)	419 (6)	448 (8)	433 (8)	474 (12)	426 (8)	455 (10)	428 (7)	460 (9)	421 (7)	448 (9)
Accuracy	96% (1)	92% (2)	97% (1)	95% (1)	95% (1)	90% (2)	96% (1)	92% (1)	96% (1)	91% (1)	96% (1)	94% (1)	95% (1)	91% (1)	96% (1)	93% (1)	95% (1)	91% (1)	97% (1)	92% (1)
Inverse efficiency	454 (8)	520 (14)	444 (7)	480 (10)	460 (11)	526 (15)	449 (12)	498 (15)	439 (8)	502 (11)	435 (7)	478 (11)	459 (11)	528 (18)	443 (10)	495 (14)	449 (8)	508 (10)	437 (8)	490 (14)

active control for the dorsal parietal stimulation condition. Hence, the fact that the ventral temporoparietal stimulation did not modulate visuospatial attention renders alternative explanations such as lateral cutaneous or retinal stimulation effects for the visuospatial attention bias in the dorsal parietal tACS condition unlikely.

6.1. Brain area- and task-specific tACS effect

Our current findings are in accordance with our previous experiments (Kemmerer et al., 2020; Schuhmann et al., 2019) and those of Kasten and colleagues (Kasten et al., 2020), which all revealed behavioral effects of left parietal tACS on the endogenous visuospatial attention bias. Even though right dorsal parietal tACS seemed to induce a behavioral effect in the expected direction, which is a visuospatial attentional rightward bias, this effect failed to reach significance. It could be argued that this might be caused by a lack of statistical power. Yet, the absence of effects in this condition matches previous research, which showed no or inconsistent spatial attention effects for right hemispheric alpha-tACS (Joseph B. Hopfinger, Parsons, & Fröhlich, 2017a; Kasten et al., 2020; Veniero, Benwell, Ahrens, & Thut, 2017). In fact, various previous EEG studies have found stronger alpha power dynamics for the left hemisphere (Okazaki, De Weerd, Haegens, & Jensen, 2014; Sauseng et al., 2005b; Wöstmann, Herrmann, Maess, & Obleser, 2016). Furthermore, an fMRI study revealed that during rest, the functional connectivity is tonically higher in the right hemisphere whereas the left hemisphere seems to be more specifically recruited during high attentional demands (Meyer, Du, Parks, & Hopfinger, 2018). It could therefore be argued that the left parietal cortex occupies a dominant role in the dynamic modulation of alpha power and attentional control. However, systematic tests, which rule out confounding factors such as handedness, are needed to verify these hemispheric asymmetries.

Our behavioral data show no double dissociation between the dorsal parietal and temporoparietal cortex for endogenous versus exogeneous visuospatial attention. However, we found a brain-area and task-specific effect of dorsal parietal on endogenous attention performance, which is in line with previous alpha-tACS research (Kasten et al., 2020; Schuhmann et al., 2019), the functional role of the DAN (Corbetta & Shulman, 2002a; Doricchi et al., 2010; J. B.; Hopfinger et al., 2000) as well as with the functional role of occipitoparietal alpha oscillations in endogenous attention performance (Gallotto et al., 2020; Gould et al., 2011; Händel et al., 2011; Lasaponara et al., 2019; Newman et al., 2013; Sauseng et al., 2005a; Thut, 2006). For the chosen attention tasks and tACS setup, stimulation of the ventral temporoparietal cortex, one the other hand, did not affect the spatial distribution in either task. One could argue that this absence of effects indicates that temporoparietal alpha oscillations in general are not functionally relevant for visual attention performance. As Wöstmann et al. (2018) recently demonstrated that left temporoparietal alpha-tACS impairs the recall of contralateral targets in a dichotic listening task, temporoparietal alpha oscillations might be functionally relevant for auditory rather than visual spatial attention. Alternatively, the absence of effects of temporoparietal tACS could be interpreted in the

framework of an emerging theory about the functional role of the TPJ (Macaluso & Doricchi, 2013). This theory questions the functional role of the temporoparietal node of the VAN in exogenous visuospatial attention performance, pointing out a confounder in previous studies that seemingly supported such a function. Various fMRI studies have demonstrated that the TPJ displays greater activation in invalid as compared to valid cue type trials of endogenous attention tasks (Arrington, Carr, Mayer, & Rao, 2000; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000). As invalid cue type trials, in contrast to valid cue type trials, involve a shift of reflexive attention towards the target at the unexpected location, this differential activation has been attributed to exogenous attention. However, there is an alternative interpretation for the activation of the VAN in this scenario, which is related to the unequal valid/invalid trial ratio. In a typical endogenous attention ask, valid cue type trials are more frequent than invalid cue type trials to motivate the participant to initiate voluntary attention shifts towards the cued direction. This unequal valid/invalid trial ratio implies that invalid targets are scarce and therefore violate expectations. Hence, previously reported differential temporoparietal activation in valid and invalid trials can be attributed to either exogenous attention shifts or to a violation of expectations in less frequent and thus deviating invalid cue type trials. Macaluso and Doricchi (2013) proposed the latter and suggested that the TPJ performs match/mismatch operations or prediction updates in case of unexpected invalid cue type trials. This alternative theoretical framework might account for the absence of stimulation effects on exogenous attention performance in the temporoparietal stimulation condition. According to this line of reasoning, one would also expect temporoparietal tACS to modulate the validity effect in the endogenous attention task. Yet contrary to these expectations, our results revealed no interaction effects with the between-subject factor cue validity or a modulation of the cueing effect through temporoparietal tACS, speaking against a functional role of the TPJ in match/mismatch operations or prediction updates. However, further research is needed to verify the role of the TPJ during attention tasks.

6.2. Cue-specific effect

The effect of dorsal parietal alpha-tACS on the valid cue trials in the endogenous attention task is in line with the functional role of the DAN (Corbetta & Shulman, 2002a; Doricchi et al., 2010; J. B. Hopfinger et al., 2000) and parietooccipital alpha oscillations (Gould et al., 2011; Händel et al., 2011; Lasaponara et al., 2019; Newman et al., 2013; Sauseng et al., 2005a; Thut, 2006) in endogenous attention. Kasten et al. (2020) recently reported a similar effect of (occipito)parietal alpha-tACS on the visuospatial attention bias exclusively in the invalid trials of an endogenous but not in an exogenous attention task. Although the task-specificity and the direction of effects match our results, the effect in the invalid cue type trials stands in contrast to our effect in the valid cue type trials. This divergent effect could be explained by the differences in the tACS electrode montages between our study and that of Kasten et al. (2020). Current simulations suggest that the parietal high-density (HD) ring electrode montage in our

experiment created a focal electrical field around the IPS (Fig. 2). Kasten et al. (2020), on the other hand, used two small circular electrodes placed on the parietal and occipital cortex of each hemisphere respectively. This is expected to result in a diffuse electrical field between the two electrodes (Datta et al., 2008b), which might extend to the angular gyrus and TPJ. Research suggests that the angular gyrus is involved in attentional reorienting to unexpected stimuli (Chen, Weidner, Vossel, Weiss, & Fink, 2012; Kubit & Jack, 2013), which might account for Kasten and colleagues' (2020) effect in the invalid cue type trials.

6.3. Limitations

One limitation of this experiment relates to the differences in employed target eccentricities for the endogenous and exogenous attention task, which was implemented to achieve comparable average accuracy scores (endogenous attention task: 95%; exogenous attention task: 94%). Yet, while doing so controls for the task difficulty level and thereby general required attentional resources, it could be argued that the mismatch in target eccentricity gave rise to the differential effect of dorsal parietal tACS on the endogenous and exogenous attention task. However, several arguments speak against this alternative explanation. First of all, as the lateralized brain stimulation intervention induces a bias in visuospatial attention, we would expect stronger stimulation effects for more lateralized target stimuli. Yet our data shows that dorsal parietal tACS modulates the visuospatial attention bias specifically in the endogenous attention task, which includes less lateralized target stimuli than the exogenous attention task. Furthermore, the tACS effect on the endogenous attention task was specifically found for valid but not invalid cue type trials, which employ the same target eccentricity but involve purely endogenous (voluntary orienting) and a mixture of endogenous and exogenous processes (voluntary orienting followed by reflexive reorienting) respectively. This further supports our conclusion that dorsal parietal tACS modulates endogenous but not exogenous visuospatial attention and yields target eccentricity as alternative explanation for the differential task effect unlikely.

To measure the effect of tACS on endogenous attention processes, we here administered a variant of the Posner task, which includes central arrows as cues. While these symbolic cues have frequently been used to investigate voluntary attention processes, arrows have also shown to trigger attention shifts when their validity varies around chance level (Hommel, Pratt, Colzato, & Godijn, 2001; Ristic, Landry, & Kingstone, 2012; Ristic & Kingstone, 2006). As there is no reason to initiate voluntary attention shifts if the cue is not predictive of the future target location, one could argue that these attention shifts are the result of extensive training throughout life, perhaps giving arrows an orienting effect with an efficiency and speed approaching that of exogenous cues. This would then question our choice to study endogenous attention using arrows as symbolic cues, as the observed effects might have been exogenous. Yet, while previous studies do show that arrows can induce automatic spatial attention shifts (Hommel et al., 2001; Ristic et al., 2012; Ristic &

Kingstone, 2006), these effects do differ from classical exogenous attention shifts. Specifically, the cueing effects in the attention task with arrow-cues used here were observed after 500 msec, which does not match the faster attentional shifts following exogenous cues (within 30 msec—300 msec) (Chica, Martín-Arévalo, Botta, & Lupiáñez, 2014; Johnson et al., 1991; Lupiáñez, Milán, Tornay, Madrid, & Tudela, 1997). In addition, exogenous cueing effects are usually followed by a reversal of the attentional advantage to the previously attended location (Chica et al., 2014; Johnson et al., 1991; Lupiáñez et al., 1997), which is in opposition to the effects observed in the Posner task with arrow-cues used here. For these reasons, we consider it unlikely that the effects of the arrow cues were of an exogenous nature. Nevertheless, we acknowledge that the observed shifts of attention after presentation of non-predictive arrow cues (Hommel et al., 2001; Ristic et al., 2012; Ristic & Kingstone, 2006) were most likely not entirely driven by the statistical target occurrence distribution imposed in the task as one would expect in the case of arbitrary symbolic cues. Instead, it is likely that the participants' attention shifts were in part guided by their life-long experiences that arrows point to a relevant direction. While this does not undermine our fundamental effect of parietal but not temporoparietal tACS inducing a visuospatial attention bias, future research should employ endogenous cues to which participants have not previously been exposed to in order to better isolate purely voluntary attention processes independent of learning.

Despite the tACS-induced modulations of endogenous visuospatial attention, which are in line with the functional role of alpha oscillations, we found no tACS effect on offline alpha power lateralization. This absence of effects might partly be caused by the technical difficulties that we experienced during the acquisition of EEG data following tACS. Our data show an EEG amplifier overload and associated signal loss of up to 35s in some post-tACS EEG measurements. As the effect of lateralized alpha-tACS on alpha power has previously been observed only in the first minute of the post-stimulation EEG measurement (Kemmerer et al., 2020), the loss of the initial EEG data of the post-measurement might have decreased the power to detect an offline alpha power lateralization effect. Problems with amplifier overload during tACS have previously been reported (Kasten et al., 2020). Here, we used a similar combined tCS-EEG set-up as in one of our previous experiments (Kemmerer et al., 2020), which consists of single EEG electrodes mounted in between the central disc and the outer ring tCS electrodes. However, for this experiment, we chose a smaller outer tCS ring electrode as compared to our previous experiment, in order to achieve a more focal electrical field in the parietal and temporoparietal cortex respectively. This smaller ring electrode offered less space for the single EEG electrode in between tCS electrodes and therefore heightened the chances of conductive gel leakage. Bridging of the tACS and EEG electrodes due to conductance gel leakage might increase the chances of an EEG amplifier overload during stimulation (Fehér & Morishima, 2016). It is important to note that in this experiment, the amplifier overload and associated signal loss was observed several seconds after manually switching of the tCS stimulator. Because of this

delay, the amplifier overload cannot be directly related to the alternating current stimulation but was potentially caused by a capacitor discharge happening a few seconds after pressing the power button to switch off the device. tCS after-effects are variable (Guerra, López-Alonso, Cheeran, & Suppa, 2020) and new implementations that allow for contamination-free EEG recordings during and after stimulation are still a central focus of ongoing tCS research (Guerra et al., 2020; Tashiro et al., 2020). To prevent that residual noise from the stimulator contaminates the EEG recording, previous research removed the cable connecting the inner tCS electrode with the stimulator (Tashiro et al., 2020). This method resulted in clean EEG signal and, if automated, can be implemented within 1 sec after stimulation. Hence, future research should follow a similar procedure to prevent that residual noise from the stimulator or capacitor discharges causes an amplifier overload or other artefacts.

6.4.   *Potential confounders*

A frequent concern is that tACS effects are caused by stimulation of the retina instead of a direct modulation of neuronal activity (Kanai, Chaieb, Antal, Walsh, & Paulus, 2008; Rohracher, 1935). Electrical stimulation of the retina can cause phosphenes, which are percepts of light in the absence of corresponding visual input. These phosphenes might entrain neural assemblies in the visual cortex via the retino-thalamic pathway (Karabanov, Saturnino, Thielscher, & Siebner, 2019) and thereby modulate behavioral outcomes. tACS applied via a distant bi-polar electrode montage has previously shown to induce phosphenes (Kar & Krekelberg, 2012; Schutter & Hortensius, 2010; Schwiedrzik, 2009). This represents an interpretational problem because the stimulation effects cannot unambiguously be attributed to direct neuronal modulations. However, in this experiment, we used a high-density (HD) ring electrode montage, which produces a focal electrical field at the stimulation site (Bortoletto, Rodella, Salvador, Miranda, & Miniussi, 2016; Datta et al., 2008a, 2009; Dmochowski, Datta, Bikson, Su, & Parra, 2011) and thereby minimizes the risk of volume conduction to the retina (Karabanov et al., 2019). Furthermore, potential retinal stimulation cannot explain the asymmetry of our effects on visuospatial attention as unilateral tACS is expected to modulate activity in the retina of the ipsilateral eye and should therefore equally affect the left and right optic tract, which in turn would modulate activity in the left as well as right hemisphere. This would lead to symmetric and not asymmetric visuospatial attention effects. It is therefore unlikely that our effects are caused by retinal stimulation.

Similarly, it has been argued that tACS indirectly modulates neuronal activity and behavioral outcomes via stimulation of peripheral sensory afferents (Asamoah, Khatoun, & Mc Laughlin, 2019). Accordingly, tACS rhythmically activates nerve fibers in the skin under the electrode, which in turn entrains neural assemblies in the sensory cortex and connected areas. However, recent research in monkeys shows that tACS modulates single—unit activity during tACS independently of whether somatosensory input is blocked through topical anesthetic (Vieira, Krause, & Pack, 2020).

Furthermore, we show that the tACS effect on the visuospatial attention bias is area specific, i.e., it can be found in a parietal but not in an even more lateralized temporoparietal stimulation condition. This renders peripheral sensory afferent stimulation as alternative explanation for our behavioral tACS effects unlikely.

7. Conclusion

We demonstrate that lateralized dorsal parietal alpha-tACS modulates endogenous but not exogenous visuospatial attention performance, i.e., there was a visuospatial attention bias towards the ipsilateral hemifield in the valid trials of an endogenous attention task but not in the invalid trials or exogenous attention task. While this effect suggests that the functional role of local alpha oscillations matches the previously proposed distinction between a dorsal and ventral attention network for endogenous and exogenous attention respectively (Chica et al., 2013), no effect could be found in the ventral temporoparietal tACS condition. We therefore suggest that temporoparietal alpha oscillations are not functionally relevant for visual exogenous attention performance. However, further research should verify whether similar results can be found for other exogenous attention tasks. Importantly, the brain area-specificity of the dorsal parietal (but not ventral temporoparietal) tACS effect on the endogenous attention bias renders potential confounders such as retinal or cutaneous stimulation effects unlikely.

Credit author statements

T.A. de Graaf: conceptualization, methodology, writing — review & editing, supervision, validation.

S. ten Oever: conceptualization, methodology, writing — review & editing, supervision, validation.

M. Erkens: conceptualization, methodology, writing — review & editing.

P. De Weerd: resources, funding acquisition, conceptualization, writing — review & editing, supervision.

A.T. Sack: resources, funding acquisition, conceptualization, writing — review & editing, supervision.

S. K. Kemmerer: conceptualization, methodology, software, formal analysis, investigation, data curation, writing — original draft, visualization.

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Declaration of competing interest

We have no known conflict of interest to disclose.

Supplementary data

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