Increases in parieto-occipital alpha-band power reflect involuntary spatial attention due to a task-distracting deviant sound

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Abstract

Imagine you are focusing on the traffic on a busy city street to ride a bike safely. Suddenly, the siren of an ambulance rings out. This unpredictable sound can involuntarily capture your attention and compromise performance. Related to this, the present study addresses two questions: 1) Does a shift of *spatial* attention contribute to this type of distraction?; and 2) Does oscillatory alpha activity reflect involuntary spatial attention? We harnessed a crossmodal paradigm in which participants responded as fast and as accurately as possible to the location of a visual target (left or right of fixation). Each target was preceded by a task-irrelevant sound, usually the same (i.e. standard) animal sound. Rarely, it was replaced by a novel (i.e., deviant) environmental sound. Fifty percent of the deviants occurred on the same side as the target, and 50% occurred on the opposite side of the target. As expected, responses were slower to targets that followed a task-distracting deviant compared to a standard. Crucially, responses were faster when targets followed deviants on the same versus different side, suggesting a *spatial* shift of attention. Magnetoencephalographic data provided corroborating support for this effect: left-hemispheric visual alpha power increased in response to the left deviant, indicating a disengagement of visual areas when visual information is outside the locus of involuntary attention. Upon the occurrence of the right deviant, right-hemispheric alpha power increased in regions functionally linked to auditory processing and attentional reorienting. Overall, our findings strengthen the view that alpha power is modulated with an involuntary shift of spatial attention. They further suggest that involuntary attention has a similar impact on sensory processing as voluntary attention, thus challenging currently held claims to the contrary.

Keywords: alpha oscillations, deviant distraction, involuntary attention, magnetoencephalography, spatial attention

Highlights

- Lateralized, task-distracting deviant sounds capture spatial attention.
- Responding is faster when a target follows a deviant on the same side.
- Deviant sounds alter visual oscillatory alpha power in a spatially selective manner.
- Those changes are driven by alpha power increases for the ipsilateral deviant.
- Thus, visual areas that process deviant-unrelated information are disengaged.

Introduction

Efficient cognitive functioning requires not only the ability to filter out task-irrelevant events to better engage in the task at hand, but also to let changes in the soundscape that are potentially relevant for behavior break through attention filters to adequately adapt or react to them. While such a trade-off can be advantageous, it may also come at a cost. To exemplify this, imagine the following scenario: you are riding a bicycle on a busy city street. While filtering out street noises helps you focus on the traffic to ride safely, some of the task-irrelevant events may still involuntarily catch your attention. Those may be behaviorally relevant and require further action, such as the siren of an ambulance, or they may be completely unimportant, such as someone nearby yelling at another person across the street. In any case, the task-irrelevant events may distract you from your current task (Parmentier, 2014).

Task-distracting events occur unexpectedly in the soundscape. In an experimental setting, these so-called deviants usually violate predictions by deviating from an otherwise (more or less) regular sound sequence consisting of so-called standards. Distraction due to auditory deviants has been extensively studied via event-related potentials and behavioral measures (e.g. Bendixen et al., 2007; Schröger and Wolff, 1998; Wetzel et al., 2012). It is well known that deviant distraction is accompanied by distinct event-related markers (not focused on here; for reviews, see Escera et al., 2000; Parmentier, 2014) and a behavioral effect (referred to as behavioral distraction hereafter) observed when expected sounds violate sensory predictions (e.g., Bendixen et al., 2008; Parmentier et al., 2011), even when our actions are predictable (Parmentier & Gallego, 2020). In a task in which participants attend and respond to a target, behavioral distraction is defined as the slowing of responses following the presentation of a task-distracting event. This is caused by an involuntary (stimulus driven, bottom-up, or exogenous) shift of attention from the task towards the deviant, which is thought to reflect a time penalty due to attention shifting to the deviant and then back to the task (Parmentier et al., 2008; Schröger, 1996) and appears related to a transient inhibition of actions (Dutra et al, 2018; Vasilev et al., 2019; Wessel and Aron, 2017).

The present study has two goals for investigating the cognitive and neural underpinnings of deviant distraction in a crossmodal scenario, such as the one described above. The first goal is to address the nature of the shift of attention. Especially in scenarios in which the auditory deviant and the visual target occur at different locations, there are several types of attention shifts - not necessarily mutually exclusive - that may contribute to behavioral distraction (Parmentier et al., 2008; Parmentier, 2014). The attention shift of interest in the current study is the spatial shift from the location of the target to the location of the deviating sound. The second goal is to probe whether neural oscillatory alpha activity reflects a shift of involuntary spatial attention due to a deviant, which has been widely overlooked, to date. Before we outline how we will address these goals in detail, we will briefly review the state-of-the-art on those topics.

1) Does a shift of *spatial* attention contribute to behavioral distraction?

In the field of deviant distraction, the nature of the involuntary shift of attention in scenarios in which the deviant and target occur in close temporal succession, but at different locations, is still relatively poorly understood (for a review, see Parmentier, 2014). One might assume that a deviant sound can capture spatial attention originally allocated to the upcoming task-relevant event, and that this process is reversed as soon as the target appears. Given that such spatial shifts require time to complete (Cheal and Gregory, 1997; Luck et al., 1996; Shiu and Pashler, 1994), they might actually contribute to behavioral distraction (Parmentier, 2014).

Still, strong evidence for the hypothesis of a *spatial shift of involuntary attention* is lacking. There are only a few reports on this topic that were not able to exclude alternative (though not mutually exclusive) interpretations (Parmentier et al., 2008), or that found ambiguous results (Corral and Escera, 2008). However, support for a *spatial shift of involuntary attention* comes from behavioral data outside of the deviant distraction research field. Those studies applied an exogenous spatial cueing paradigm, in which a task-irrelevant sound, such as a noise burst, appeared lateralized (left or right) briefly before the presentation of a visual target either on the same or opposite side. Importantly, the location of the sound neither predicted the location, or the type, of the upcoming

visual target. Results showed that if the visual target appeared on the same side as the cue, perceptual processing (Spence and Driver, 1997) and response time improved (Dufour, 1999; Feng et al., 2014; McDonald et al., 2000), compared to a situation in which these events occurred on opposite sides. This pattern of results indicated that the cues were effective in generating an involuntary shift of spatial attention.

Further support comes from event-related potentials (e.g. Feng et al., 2014; Matusz et al., 2016; McDonald et al. 2013) and neural oscillatory activity (Feng et al., 2017; Störmer et al., 2016) collected in the exogenous spatial cueing paradigm. These measures have shown that an auditory cue can bias neural activity localized to the visual cortex in the hemisphere contralateral to the location of the sound. The magnitude of these lateralized activations over parieto-occipital areas were informative about the perception of a subsequent visual target (Feng et al., 2014; Feng et al., 2017; Störmer et al., 2019).

2) Does oscillatory alpha activity reflect an involuntary shift of spatial attention?

The question concerning whether oscillatory alpha activity reflects an involuntary shift of spatial attention has been motivated by studies of voluntary (goal driven, top-down, or endogenous) spatial attention in which alpha power has already been well-characterized and used as a neural marker (e.g. Banerjee et al., 2011; Deng et al., 2019; Rihs et al., 2009; Sauseng et al., 2005; Thut et al., 2006; Worden et al., 2000; Wöstmann et al., 2016). This research made use of endogenous spatial cueing tasks, allowing attention to be modulated in a goal-driven manner via cues that guided participants' attention to certain target locations (left or right). Irrespective of whether spatial attention was directed to a visual or auditory target, sustained oscillatory alpha power appeared to be lateralized, especially over parieto-occipital areas. It was also higher in the ipsilateral hemisphere, compared to the contralateral hemisphere, relative to the attended target location. This lateralization is often driven by an ipsilateral increase and/or a contralateral decrease in alpha power relative to the attended side, thought to reflect the inhibition of brain regions that process task-irrelevant information at unattended

locations, or facilitate processing of task-relevant information at attended locations, respectively (for reviews, see Hanslmayr, 2011; Klimesch, 2012; for a controversial view see Palva and Palva, 2007).

Evidence is slowly accumulating that alpha power is not only an indicator of voluntary, but also involuntary, (spatial) attention (Feng et al., 2017; Störmer et al., 2016; Weise et al., 2016). Still, to date, research on this topic is sparse, and there is only one study so far that has particularly focused on deviant distraction (Weise et al., 2016). That magnetoencephalography (MEG) study used a crossmodal distraction paradigm wherein, on each trial, a visual target followed a task-irrelevant sound. Across trials, sounds were presented in an oddball paradigm. The standard was an animal noise, and the deviant was a novel environmental sound. All sounds were presented binaurally. The deviant induced low alpha power in the pretarget time window compared to standards with sources in the occipital, parietal, and supratemporal cortices, which correlated with response speed for the deviants only. While this study provides the first evidence that alpha power can reflect involuntary attention shifts, it is still unknown whether alpha power can also reflect shifts in involuntary *spatial* attention.

Initial support for the latter comes from two electroencephalographic (EEG) studies employing an exogenous spatial cueing task. These studies found a bilateral decrease in occipital alpha power, while the alpha power decrease contralateral to the cue was more pronounced. The alpha power modulation built up rapidly (starting around 200 to 300 milliseconds (ms) after cue onset), and was rather short-lived, thus resembling the properties of involuntary attention (Feng et al., 2017; Störmer et al., 2016). Also, the authors proposed that involuntary attention to the sound has a “purely facilitatory influence on processing targets on the cued side, with no inhibitory influence on targets on the opposite side. This lack of an early inhibitory influence may represent a fundamental difference between involuntary and voluntary attention” (Feng et al., 2017). No doubt, such a strong assumption based on two very similar tasks clearly asks for more research exploiting variants of exogenous spatial cueing paradigms, preferably using different conceptual frameworks, to either strengthen or question this view. Moreover, the observed changes in alpha power in these studies were accompanied by evoked

activity - the so-called auditory-evoked contralateral occipital positivity - that is known for its link to involuntary spatial attention (McDonald et al., 2013; Feng et al., 214; Störmer et al., 2019). Critically, both alpha power and evoked activity shared similarities in the time course, scalp topography, and source estimation, making it difficult to interpret whether they reflect the same cognitive mechanism or two dissociable mechanisms (Feng et al., 2017; Störmer et al., 2016).

Current approach

To tackle the two questions within the framework of deviant distraction, we employed a unique crossmodal paradigm that combines a distraction task (Escera et al., 1998; Ruhnau et al., 2013) with an exogenous spatial cueing task (e.g. Feng et al., 2017; Störmer et al., 2016). Participants were instructed to respond as fast and accurately as possible, as to whether a visual target appeared on the left or right. Each target followed a task-irrelevant sound. Similar to the distraction task, 80% of the sounds were standards, while 20% of the sounds were deviants. Similar to the exogenous spatial cueing task, the deviant was non-informative about the spatial position of the upcoming target. That is, 50% of the deviants occurred on the same side as the target (Congruent condition) and the other 50% of the deviants occurred on the opposite side of the target (Incongruent condition).

At the behavioral level, we intended to reproduce a distraction effect operationalized by longer reaction times (RTs) to visual targets following a deviant compared to a standard (Escera et al., 1998; Parmentier et al., 2008; Ruhnau et al., 2013). This behavioral distraction effect can be taken as a sign of an involuntary shift of attention from the task towards the deviant sound (Parmentier, 2014). Crucially, we hypothesized a *spatial* shift of attention, which should be indicated by shorter RTs in the Congruent versus Incongruent condition (i.e., when the visual target follows the auditory deviant on the same versus different side).

In addition to collecting behavioral data, we recorded MEG to shed light on neural oscillatory activity, with an emphasis on alpha power and its link to involuntary spatial attention. We expected the deviant to induce a lateralized, short-lived alpha power modulation over parieto-occipital sensors that builds up rapidly after stimulus onset (Feng et al., 2017; Störmer et al., 2016; Weise et al., 2016), thereby

matching the characteristics of involuntary spatial attention (for a review, see Corbetta and Shulman, 2002). We predicted that neural sources of this alpha power modulation would be located in 1) parieto-occipital areas, known for their role in spatial attention, even in purely auditory tasks (Deng et al., 2019; Deng et al., 2020; Feng et al., 2017; Störmer et al., 2016); 2) auditory areas, due to the processing of the attention-capturing sound (ElShafei et al., 2018; Frey et al., 2014; Weisz et al., 2014; Wöstmann et al., 2016); and 3) areas linked to the ventro-frontoparietal attention system, comprising the temporoparietal junction and the ventral frontal cortex, which have been functionally linked to attention reorienting (for reviews, see Corbetta et al., 2008; Vossel et al., 2014).

Method

The study was approved by the local ethics committee of the Paris Lodron Universität Salzburg and adhered to the code of ethics of the World Medical Association (Declaration of Helsinki).

Participants

30 healthy young adults participated in the MEG experiment (12 males, mean age ± STD: 27 ± 6 yrs, 4 left-handed, 1 ambidextrous). Volunteers gave written, informed consent prior to their participation. All participants reported normal hearing and normal or corrected-to-normal vision, and none reported a history of neurological or psychiatric diseases. Volunteers received 10€/hour (h) or 1 credit point/h as compensation for their participation.

Stimuli and Procedure

The experiment was programmed in MATLAB 9.1 (The MathWorks, Natick, Massachusetts, U.S.A) using the open source Psychophysics Toolbox (Brainard 1997; Kleiner et al. 2007) and o_ptb, an additional class-based abstraction layer on top of the Psychophysics Toolbox (https://gitlab.com/thht/o_ptb). Stimuli were presented with precise timing using the VPixx System (DATAPixx2 display driver, PROPixx DLP LED Projector, TOUCHPixx response box by VPixx Technologies, Canada). The Blackbox2 Toolkit (The Black Box ToolKit Ltd, Sheffield, UK) was used to measure and correct

for timing inaccuracies between triggers and the visual and auditory stimulation. Note that the tubes of the MEG-proof sound system caused a time-delay between sound and trigger of 16.5 ms that was corrected within the stimulation protocol.

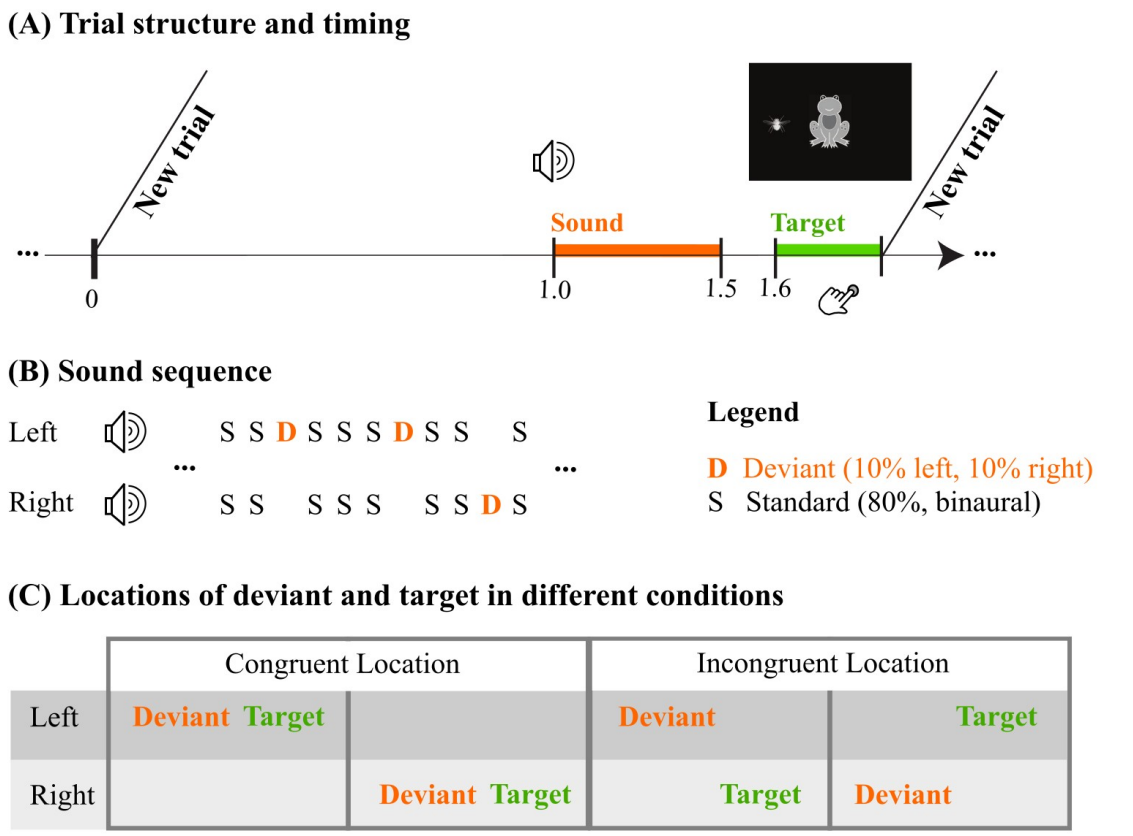

Figure 1: Cross-modal paradigm combining a distraction task with an exogenous spatial cueing task. (A) Trial structure and timing. During each trial, the to-be-ignored sound (illustrated as an orange bar) preceded the task-relevant visual stimulus (illustrated as a blue bar). Participants had to respond whether the target occurred to the left or right of the fixation frog. (B) Exemplary sound sequence. The task-irrelevant sounds were presented in an oddball paradigm: standards were presented binaural on 80% of trials, deviants were presented left (10%) or right (10%). (C) A visual representation of the two conditions (Congruent location, Incongruent location) and the corresponding locations (left, right) of deviants and targets.

We employed a cross-modal paradigm combining a distraction task with an exogenous spatial cueing task. Participants performed a visual-spatial two-alternative forced choice task (see Figure 1). Throughout the stimulation, a frog was presented at the center of the screen that participants were asked to fixate at all times. Every trial, a visual target in the shape of a fly was presented on the screen next to the frog. On 50% of trials, the target appeared on the left side of the frog. On the other 50% of trials, it appeared on the right side. Participants held their left thumb over a left-side button, and their right thumb over a right-side button. The participants' task was to indicate on which side the fly had been presented, by pressing the left or right button. The mapping between the response buttons and the target location was counterbalanced across participants. The target appeared for maximally 1 second (s); otherwise, a response terminated the trial.

Additionally, on each trial, a sound of 0.5 s duration (with, additionally, 10 ms rise and fall times) was presented that had to be ignored. This sound always appeared after a 0.8 s silent interval and preceded the visual target by 0.6 s. That is, a silent interval of 0.1 s separated both the auditory and visual event. The sound was either a binaurally presented standard (buzzing mosquito, $p = 0.8$) or a monaurally presented deviant. Deviants were chosen from a pool of 56 different environmental sounds (e.g., speech, animal voices, tool noise, etc.; $p = 0.2$) selected from a commercial CD (1,111 Geräusche, Döbeler Cooperations, Hamburg, Germany). All sounds were equalized for overall intensity (RMS). The trial order within the whole stimulation was pseudorandomized such that a deviant was preceded by at least two standards. One auditory-visual trial lasted maximally 2.6 s, but was usually shorter (due to the relatively fast RT).

Within one experimental block, we presented two different conditions as a function of where the deviant sound and the visual target appeared. In the Congruent condition, both the deviant and target occurred on the same side (i.e., both appeared on the left or right). In the Incongruent condition, the deviant and target occurred on opposite sides. For example, if the deviant occurred on the left, the visual target occurred on the right. Note, each deviant could occur only once within a block, and only

once every three blocks, for a total of four times in the whole experiment -- twice on the left (once in the Incongruent and once in the Congruent condition) and twice on the right (once in the Incongruent and once in the Congruent condition).

The experiment consisted of seven blocks in total, each lasting ~5 minutes (min) and consisting of 160 trials (128 standards, 16 deviants presented on the left, 16 deviants presented on the right). Thus, the stimulation (without any breaks) lasted maximally ~35 min and resulted in a total of 112 left and 112 right deviants, half Congruent and half Incongruent. The auditory stimuli were presented at 50 dB above sensation threshold level. The auditory stimulation was delivered via MEG-compatible pneumatic in-ear headphones (SOUNDPixx, VPixx technologies, Canada). The visual stimuli were presented inside of the magnetically shielded room using a projector (PROPixx DLP LED Projector), via a back projection screen and a mirror system.

Before the start of the experiment, individual sensation threshold was determined using a 200-ms 1000 Hertz (Hz) tone presented via a staircased threshold procedure, measured separately for the right and left ear. Thereafter, participants practiced the task with fewer trials to familiarize themselves with the experiment. Deviants were chosen randomly from the pool of environmental sounds (N=56). These were played backwards so that participants did not become familiar with those sounds.

MEG recording and preprocessing

Before MEG recording, five head position indicator (HPI) coils were placed on the left and right mastoid, on the upper right and lower right forehead, and on the left middle forehead. Anatomical landmarks (nasion and left/right preauricular points), the HPI locations, and at least 300 headshape points were sampled using a Polhemus FASTTRAK digitizer. Six pre-gelled and self-adhesive Ag/AgCl electrodes (Ambu Neuroline 720) were attached to record the vertical and horizontal electrooculogram (EOG) and the electrocardiogram (ECG). One additional electrode - placed at the right shoulder - served as ground.

Participants were in a seated position during data recording. A chin rest was used to avoid head movements during and across different blocks of recording. The eye, heart, and magnetic signals of the brain were recorded at 1000 Hz (hardware filters: 0.03 - 330 Hz) in a standard passive magnetically shielded room (AK3b, Vacuumschmelze, Germany) using a whole-head MEG (Elekta Neuromag Triux, Elekta Oy, Finland). Signals were captured by 102 magnetometers and 204 orthogonally placed planar gradiometers at 102 different positions.

MEG data were preprocessed and analyzed offline using Fieldtrip (Oostenveld et al., 2011), an open source toolbox for Matlab (www.mathworks.com), and custom-written functions. Maxfilter (version 2.2.15, Elekta Neuromag, Finland) was applied to the continuous MEG raw data using a signal space separation algorithm (Taulu and Kajola, 2005; Taulu and Simola, 2006) provided by the MEG manufacturer. This allowed us to 1) automatically remove and interpolate the data of bad channels; 2) remove artifacts from the MEG signal (50 Hz line-noise and its harmonics, 16.7 Hz train noise, and muscle activity with origins beyond the head); and 3) compensate, offline, for different head positions across blocks by realigning the data to a common standard head position (-trans default Maxfilter parameter) based on the head position measured at the beginning of each block. Thereafter, continuous data were visually inspected and sample points of extensive artifacts were stored separately for each block and participant.

Two different pipelines served for further preprocessing of the MEG data. First, preprocessing of the data was optimized for independent component analysis (ICA). Therefore, MEG data were filtered offline using a 100 Hz lowpass filter (sinc FIR, kaiser window, order 3624, cutoff (-6 dB) 100 Hz) and a 1-Hz highpass filter (sinc FIR, kaiser window, order 908, cutoff (-6 dB) 1 Hz). After rejecting sample points covering extensive artifacts, runica ICA was applied in order to identify components originating from eye movements and heartbeat. The second preprocessing pipeline was optimized for further data analysis. Specifically, cleaned MEG data were filtered offline using a 35 Hz lowpass filter

(sinc FIR, kaiser window, order 3624, cutoff (-6 dB) 35 Hz). Data were downsampled to 256 Hz. Thereafter, a 0.1 Hz highpass filter was applied (sinc FIR, kaiser window, order 9056, cutoff (-6 dB) 0.1 Hz).

Filtered continuous data (originating from the second preprocessing pipeline) were cleaned from the ICs (on average two per participant). Data were segmented into 3-s epochs (-1.5 s to 1.5 s time-locked to the onset of the sound) and cleaned from artifacts that were identified via visual inspection (see above). For further analysis, we used deviant trials only. Trials in which deviants occurred on the left or right are, hereafter, referred to as Deviant Left or Deviant Right, respectively. Only those deviant trials for which participants responded once, correctly, and within the predefined response window (100 to 800 ms following the target), entered the analysis. This resulted in 106.53/112 (SD = 3.38) Deviant Left trials and 106.93/112 (SD = 2.89) Deviant Right trials, on average.

Data analyses

Behavioral Analysis

The following trials were excluded from the analysis of behavioral data: trials without responses, trials including responses faster than 100 ms or slower than 800 ms after target onset, and trials that included more than one button press. Individual RTs and hit rates were calculated.

Statistical analyses. We used jamovi (version 1.2.22.0, https://www.jamovi.org/) for the statistical analyses of behavioral data. To determine the behavioral distraction effect on RTs and hit rates, we applied two-way repeated-measures analyses of variance (ANOVAs) using the factors sound type (deviant, standard) and deviant location (left, right). Note that we used standards before the corresponding deviants for the analyses. To determine the behavioral effect of the spatial shift of attention on RTs and hit rates, we applied two-way repeated-measures ANOVAs using the factors congruence type (congruent, incongruent) and deviant side (left, right). Note that for statistical purposes, hit rates were transformed to rationalized arcsine units (rau) to account for non-normality of

proportion data (Studebaker, 1985). We reported the generalized eta-squared (η^2_G; Bakeman, 2005) as a measure of effect size. Where appropriate, we reported mean values (M) and the standard error of the mean (SEM) in the format M ± SEM.

MEG Data Analyses

For the analyses of MEG data in sensor and source space, we solely used the signal recorded at the gradiometers. Data were detrended to remove slow frequency shifts.

Sensor space analyses.

Time-frequency analysis. Time-frequency analysis was performed on the preprocessed single trial data between 1 and 30 Hz (1 Hz steps) using Morlet wavelets with a width of 5 cycles, for each participant and condition, separately. The analysis time window was shifted in steps of 50 ms between -1.5 to 1.5 s relative to deviant onset. Note that power was first computed for each individual gradiometer. In a second step, the power for each gradiometer pair was summed in order to yield an orientation independent estimate. Thereafter, single trial spectral power was log transformed with a base of 10. For each participant, trials were averaged for Deviant Left and Deviant Right, separately.

In order to statistically examine alpha power modulations in dependence of the deviant side (Deviant Left, Deviant Right) in both hemispheres, we performed non-parametric, cluster-based dependent-samples t-tests, with Monte-Carlo randomization (Maris and Oostenveld, 2007). The tests were restricted to the alpha frequency range (8 – 14 Hz) and the time window ranging from 0.2 to 0.6 s following the deviant sound and preceding the target (cf. Feng et al., 2017; Störmer et al., 2016; Weise et al., 2016). Since we had a priori hypotheses concerning the direction of the lateralized alpha power modulations expected in each hemisphere, we applied paired-sample, one-tailed Student's t-tests for the left-hemispheric channels and the right-hemispheric channels, separately. The Student's t-tests were applied for each sensor-time-frequency bin separately for each hemisphere by testing the alpha power values of Deviant Left against the alpha power values of Deviant Right. Based on this, clusters were formed among neighboring sensors of the respective hemisphere and corresponding

time-frequency bins that exceeded an a priori chosen threshold (p = 0.05). The sum of the t-values within the respective cluster was used as the cluster-level statistic. The cluster with the maximum sum was subsequently used as the test statistic. By permuting the data between the two conditions and recalculating the test statistic 10,000 times, we obtained a reference distribution of maximum cluster t-values to evaluate the significance of the to-be-tested contrast. The power distributions between the two conditions were considered to be significantly different from each other if no more than 5% of the sum-t-values of all of the 10,000-permuted data were larger than the sum-t-value of the to-be-tested cluster.

In addition, we ran the time frequency analysis a second time using the same parameter as described above, but with a preceding step that phase-locked activity; that is, the evoked signal averaged across trials of the respective condition was subtracted from every single trial, to increase sensitivity to non-phase locked signals, and to reduce contamination by phase-locked signals. The results are comparable to those obtained via the time frequency analysis of phase-locked activity, and can be found in the supplementary material.

We further investigated the cause of the alpha power modulation observed in the data (Figure 3). Therefore, we analyzed the time courses of ipsi- and contralateral alpha power for the right centro-temporal and the left parieto-occipital region of interest (ROI), respectively, that had been identified via the preceding cluster-based permutation analysis (see above). Each ROI consisted of three channels that showed prominent deviant-related effects in the deviant–target interval. Data were pooled within each ROI and across frequencies (right centro-temporal ROI: 8 – 14 Hz, left parieto-occipital ROI: 9-13 Hz; see results). Alpha power was submitted to non-parametric, cluster-based, dependent-samples t-tests with Monte-Carlo randomization (n = 10,000; Maris and Oostenveld, 2007), contrasting the data at each sample point in the deviant-target interval (0.2 to 0.6 s following the deviant) with the mean alpha power of the baseline period (-0.4 to -0.2 s; Feng et al., 2017). Since

we had no a priori hypotheses on the direction of the alpha power modulations expected in the respective ROI, we applied paired-sample, two-tailed Student's t-tests.

Source space analyses.

Source projection of time series data. For each participant, realistically shaped, single-shell head models (Nolte, 2003) were computed by co-registering the participants' head shapes either with their structural MRI (18 participants) or—when no individual MRI was available (12 participants)—with a standard brain from the Montreal Neurological Institute (MNI, Montreal, Canada), warped to the individual head shape. A grid with 3-millimeter resolution based on an MNI template brain was morphed to fit the brain volume of each participant. The leadfield was calculated for each grid point and the forward model was computed for gradiometers only.

To project the preprocessed single-trial sensor data into source space (i.e., to the points of the grid), we applied the linearly constrained minimum variance (LCMV) spatial filter (Van Veen et al., 1997). We followed a procedure described for single virtual sensors (http://www.fieldtriptoolbox.org/tutorial/virtual_sensors/) and extended it to 146,400 points covering the gray matter of the brain. The covariance matrix across all trials (including Deviant Left and Deviant Right conditions) was calculated and used to obtain a LCMV beamformer spatial filter for each of the grid points (for a similar approach, see Neuling et al., 2015; Ruhnau et al., 2016). The covariance window for the calculation of the beamformer filter was based on a 2-s time window centered at deviant onset. To optimize the analysis in source space (i.e., increase spatial resolution using a high-definition grid and at the same time compensate for computation time), we divided the individual brain into 333 parcels (Gordon et al., 2016; http://www.nil.wustl.edu/labs/petersen/Resources.html) based on the 'Anatomical Automatic Labeling' [AAL] atlas (Tzourio-Mazoyer et al., 2002; provided by the fieldtrip toolbox). That is, for each anatomical area, the spatial filters of the corresponding grid points were averaged to obtain one spatial filter per parcel. The resulting 'averaged filter' was then

multiplied with the sensor level data to obtain time series data for each of the 333 parcels. A regularization parameter (lambda = 5%) was applied.

Time-frequency analysis. For each participant, time-frequency analysis was performed on the single trial data in source space between 1 and 30 Hz (1 Hz steps) using Morlet wavelets with a width of 5 cycles. The analysis time window was shifted in steps of 50 ms between -1.5 to 1.5 s relative to deviant onset. For each participant, trials were averaged separately for Deviant Left and Deviant Right.

To localize the deviant induced sensor level effects in source space, data were restricted to the time-frequency ranges covering the alpha power effect (right centro-temporal ROI: 8 – 14 Hz and 0.3 - 0.5 s, left posterior ROI: 9 - 13 Hz and 0.2 - 0.6 s). Alpha power was averaged over frequency and time. T values were calculated via a paired-sample, one-tailed Student's t-test for each of the parcels and the corresponding time-frequency bin, contrasting the alpha power values between Deviant Left and Deviant Right. The respective labels of localized brain regions were identified with an anatomical brain atlas (AAL atlas; Tzourio-Mazoyer et al., 2002) and a network parcellation atlas (Gordon et al., 2016).

Results

Behavioral data

In terms of accuracy, task performance was generally very good, as indicated by the high hit rate (>0.97) for targets, regardless of whether they were preceded by deviants or standards (Figure 2A). The two-way repeated measures ANOVA on hit rates shows a significant main effect for factor stimulus type ($F(1, 29) = 18.51$, $p < .001$, $\eta^2_G = .087$), with higher hit rates for deviant trials (0.99 ± 0.003) than standard trials (0.97 ± 0.004). There was neither a significant main effect for factor deviant side, or a significant interaction. This result may be linked to an increase in nonspecific arousal upon the occurrence of a deviant (Näätänen, 1992), which nevertheless facilitates task

performance. Hit rates did not differ when deviant and target occurred on the congruent vs. incongruent side (Figure 2B), as indicated by the two-way repeated-measures ANOVA yielding neither significant main effects for the factors congruence type and deviant side, or a significant interaction.

As depicted in Figure 2A, RTs were prolonged when targets followed a deviant versus a standard. This is substantiated by the two-way repeated measures ANOVA on RTs, yielding a significant main effect for stimulus type ($F(1, 29) = 39.68$, $p < .001$ $\eta^2_G = .037$; deviants: 296 ± 9 ms; standards: 278 ± 8 ms). There was neither a significant main effect for factor deviant side, or a significant interaction. Overall, these results point to a behavioral distraction effect due to an attention shift towards the task-distracting deviant. As depicted in Figure 2B, RTs were shorter when deviant and target occurred on the congruent versus incongruent side. This is substantiated by the two-way repeated measures ANOVA on RTs, yielding a significant main effect for congruence type ($F(1, 29) = 4.59$, $p < .041$ $\eta^2_G = .002$; congruent: 293 ± 9 ms; incongruent: 298 ± 10 ms). There was neither a significant main effect for factor deviant side, or a significant interaction. Overall, these results point to a *spatial* shift of attention towards the task-distracting deviant sound.

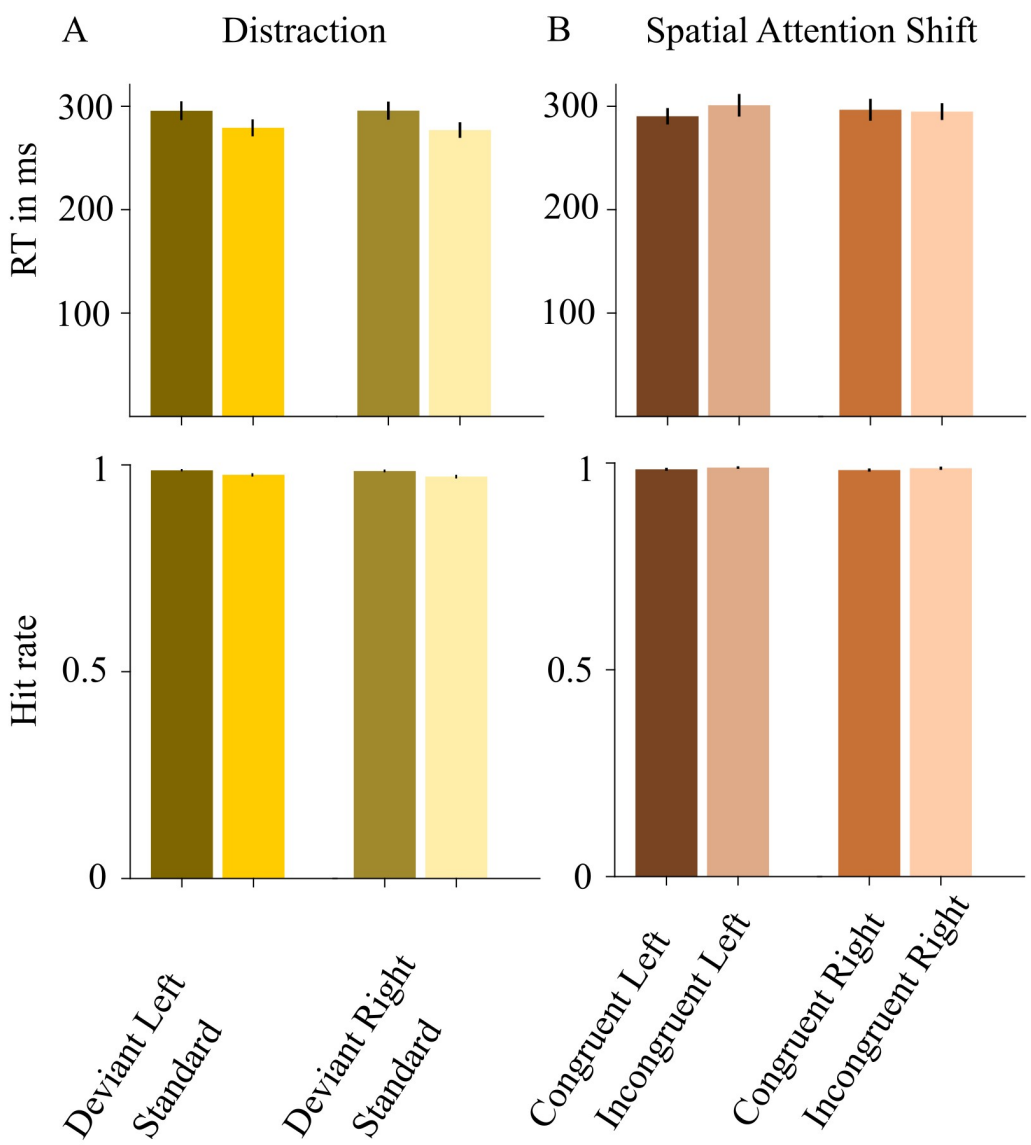

Figure 2: Bar plots of RTs and hit rates in response to visual targets to determine a distraction effect (A) or a shift of spatial attention (B) caused by the deviant. (A) Prolonged RTs and higher hit rates for targets following deviants presented on the left or right side versus standard before deviant. (B) Shortened RTs for targets following deviants on the same versus different side in the Incongruent and Congruent conditions. Data were analyzed with respect to the deviant side (left, right). Hit rates did not differ between conditions. Error bars represent SEM.

Alpha power analysis

We analyzed alpha-band (8 - 14 Hz) power to probe whether attentional reorienting towards the location of the deviant sound is also reflected in neural oscillatory activity, as indexed via the current RT data. We followed a methodological approach used to measure voluntary attention (Banerjee et al., 2011; Deng et al., 2020; Haegens et al., 2011; Wöstmann et al., 2016) and contrasted alpha power for the cued / attended target positions (attend left versus attend right). Accordingly, we contrasted alpha power for the left and right attention-capturing, task-distracting deviants (Deviant Left condition vs. Deviant Right condition). Since we had a priori hypotheses concerning the direction of the lateralized alpha power modulations expected in each hemisphere, we applied the corresponding, non-parametric, cluster-based permutation statistics (using paired-sample, one-tailed Student's t-tests) on the left-hemispheric and the right-hemispheric channels, separately. Overall, the results clearly show that alpha power to lateralized deviants is modulated in a spatially selective manner (Figure 3).

Specifically, the results for the left hemispheric channels show that alpha power is significantly higher ipsilateral to the deviant location in the time window from about 0.2 s to 0.6 s following the auditory deviant and preceding the visual target (see Fig. 3 A). It mainly covers the frequencies from 9 - 13 Hz. This effect is most pronounced over left parieto-occipital sensors ($p = .023$), as highlighted via the scalp distribution of the alpha power modulation for the frequency range 9 - 13 Hz and the time range 0.2 to 0.6 s following the deviant (see Fig. 3 C). The main generators of this sensor level effect are estimated in occipital regions, including primary and secondary visual cortex (see Fig. 3 E).

The results for the right hemispheric channels show that alpha power, including the frequencies 8 - 14 Hz, is significantly lower contralateral to the deviant location in the time window from about 0.3 s to 0.5 s following the auditory deviant and preceding the visual target (see Fig. 3 B). This effect is most pronounced over right centro-temporal sensors ($p = .012$), as highlighted via the scalp distribution of the alpha power modulation for the frequency range 8 - 14 Hz and the time range 0.3 to 0.5 s following the deviant (see Fig. 3 D). The main generators of the sensor level effect are estimated in

parieto-occipital, auditory, and somatosensory regions, as well as in regions belonging to the ventral attention system (see Fig. 3 F).

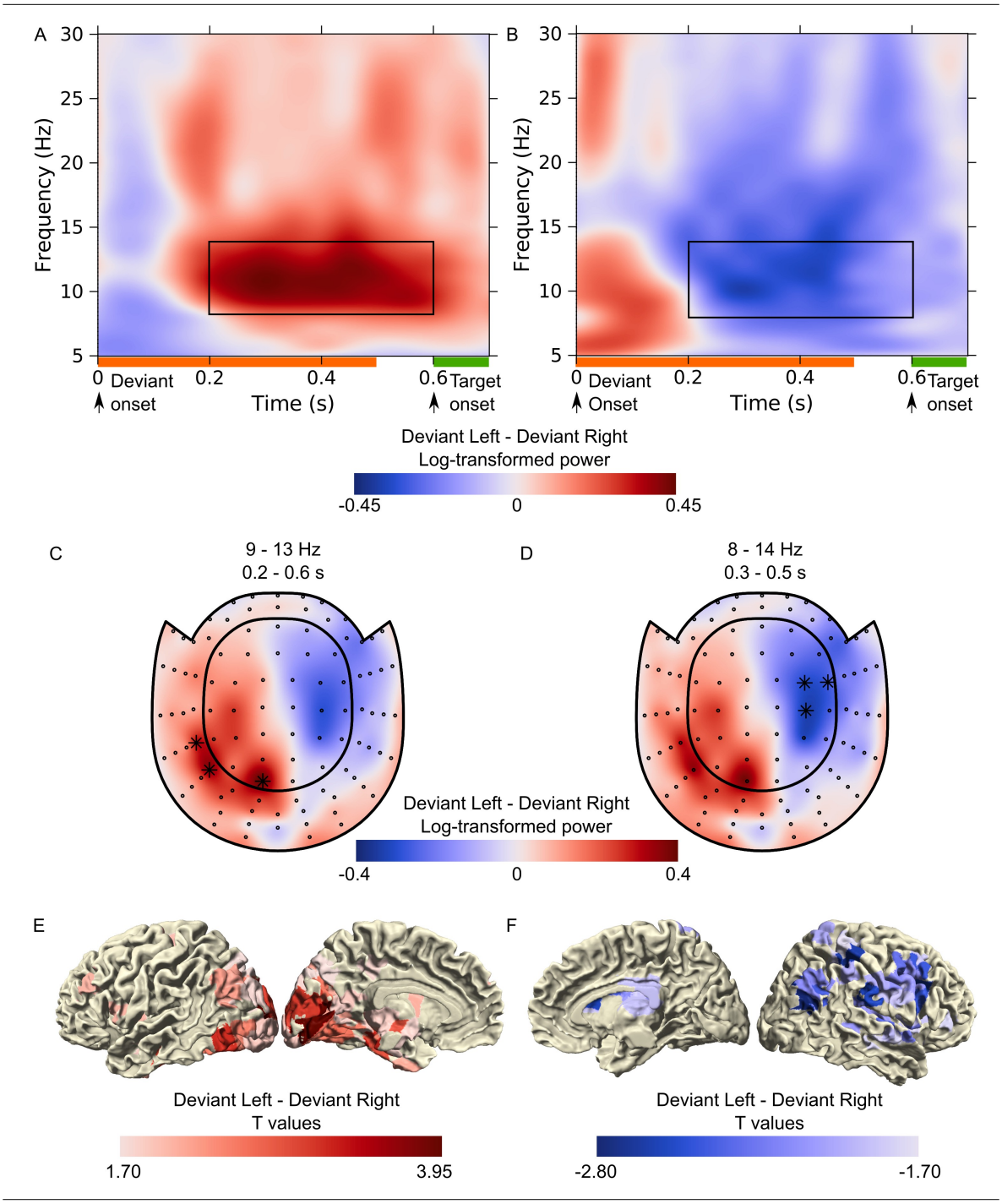

Figure 3: Log10-transformed alpha power modulation to lateralized deviants based on group-averaged data for Deviant Left minus Deviant Right, with a focus on the left hemispheric parieto-

occipital effect (left column) and the right hemispheric centro-temporal effect (right column). (A and B) Time frequency representations highlighting (A) high alpha power ipsilateral to the deviant location at left-hemispheric posterior gradiometers (average across three channels showing a prominent effect, marked in C with a star), and (B) low alpha power contralateral to the deviant location at right-hemispheric centro-temporal gradiometer (average across three channels showing a prominent effect, marked in D with a star). The black box marks the time-frequency range (time: 0.2 - 0.6 s, frequency: 8 - 14 Hz) used for the statistical cluster analysis. (C and D) Topoplot of the alpha power distribution (C: 9 -13 Hz, D: 8-14 Hz) in the time window showing a significant alpha power modulation (C: 0.2 - 0.6 s, D: 0.3 - 0.5 s). Stars indicate channels on which there was a prominent statistical effect. (E and F) Source estimation of the (E) left hemispheric parieto-occipital alpha power effect and (F) the right hemispheric centro-temporal alpha power effect.

To test whether the observed alpha lateralization (see Fig. 3) was driven by a decrease or increase in alpha-band power, we analyzed the time courses of alpha power for the right hemispheric centro-temporal ROI and the left hemispheric parieto-occipital ROI, separately, and the corresponding ipsi- and contralateral deviant. We contrasted the alpha power following the deviant with the mean alpha power of the baseline period, via a non-parametric cluster-based permutation statistic. Since we had no a priori hypotheses on the direction of the alpha power modulations, we applied paired-sample, two-tailed Student's t-tests. The results show that the right/ipsilateral deviant caused a significant increase in alpha power in the right-hemispheric centro-temporal ROI, in the time range 0.2 to 0.4 s after sound onset ($p = .017$, see Fig. 4 A). Furthermore, for the left/ipsilateral deviant, we found a significant increase in alpha power in the left-hemispheric parieto-occipital ROI, in the time range 0.2 to 0.3 s after sound onset ($p = .044$, see Fig. 4 B). Additionally, the right/contralateral deviant caused a significant decrease in alpha power in the left-hemispheric parieto-occipital ROI, in the time range 0.5 to 0.6 s after sound onset ($p = .044$, see Fig. 4 B).

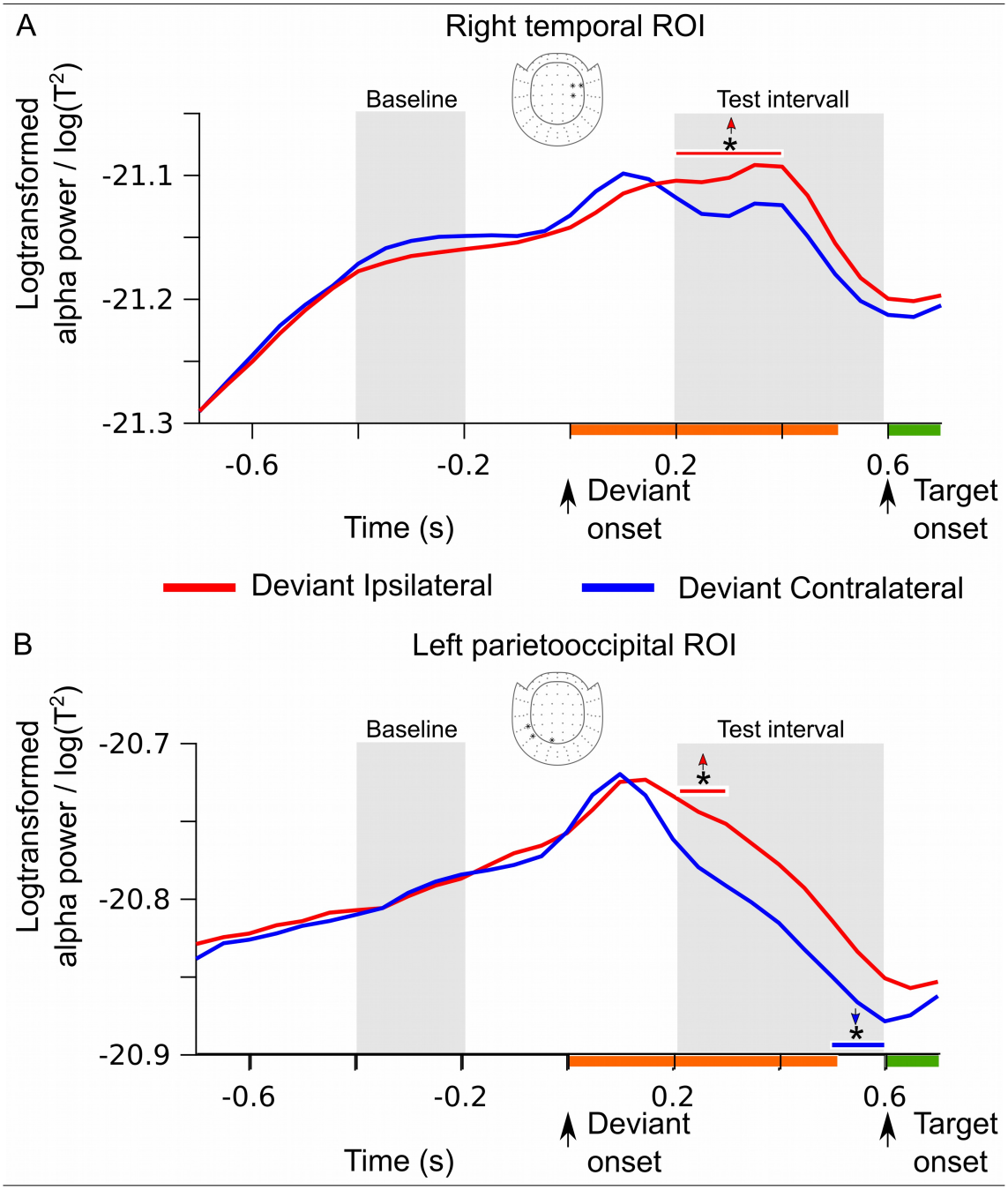

Figure 4: What drives the alpha power modulations? The ipsilateral deviant conditions caused a significant increase in alpha power compared to baseline. Deviant-locked time courses of contra- and ipsilateral log10-transformed and group-averaged alpha power for (A) the right centro-temporal ROI (8 - 14 Hz) and (B) the left parieto-occipital ROI (9 -13 Hz). Red traces indicate deviant ipsilateral and blue traces indicate deviant contralateral. Channels belonging to the ROI are marked with stars in the corresponding channel layout. Significant time samples are illustrated by the horizontal red and

blue traces (*p < .05). Upward directed arrows indicate an alpha power increase, and the downward directed arrow indicates an alpha power decrease. Gray areas indicate the baseline interval (-0.4 to -0.2 s) and the test interval (0.2 to 0.6 s). The orange and green bar indicate the presentation time of deviant and target, respectively.

Discussion

Our MEG study aimed to answer two questions concerning the cognitive and neural underpinnings of behavioral distraction: 1) Does a shift of *spatial* attention, due to a lateralized deviant sound, contribute to behavioral distraction? 2) Does neural oscillatory alpha activity reflect this involuntary *spatial* attention shift? Our RT and neural oscillatory MEG data provide a positive answer to each of these questions, which we will discuss in more detail in the following paragraphs.

1) The shift of involuntary *spatial* attention contributes to behavioral distraction

As expected, our behavioral distraction effect - that is, the longer RTs to targets that followed a deviant versus a standard - shows that the deviant captured attention involuntarily. This strengthens previous findings that have been obtained via a roughly comparable behavioral distraction task numerous times before (Bendixen et al., 2007; Parmentier et al., 2008; Schröger and Wolff, 1998; Wetzel et al., 2012).

Importantly, we observed an advantage in response speed when deviants and targets occurred on the same versus opposite side. This clearly speaks in favor of a *spatial* shift of attention, which has been proposed, though not directly tested, earlier (Parmentier et al., 2008; Weise et al., 2016). That is, when the deviant and target occur on the same side, the time penalty due to the spatial shift is lower compared to when both events occur on opposite sides. This finding is in line with behavioral data obtained via the exogenous cueing paradigm (McDonald et al., 2000), and receives further support from our MEG data, as will be discussed below.

Note that we do not claim that the spatial component of the attention shift fully accounts for the overall behavioral distraction effect; in fact, several cognitive determinants may contribute to it. A second potential determinant that could be at play in a crossmodal situation, is the involuntary shift of attention across sensory modalities (i.e., from vision to audition). In this case, the time penalty accumulated by a shift of attention from the visual to the auditory channel (i.e., upon the onset of the deviant), and its re-orientation towards the visual channel (i.e., upon the onset of the target), would contribute to behavioral distraction (Parmentier, 2014). This idea receives support from behavioral studies showing that RTs are slower for a target in an unexpected modality compared to a target in an expected modality (Boulter, 1977; Spence et al., 2001).

At first glance, the RT data seem to be at odds with the hit rates. While the RTs indicate a decrease in performance for targets following a deviant versus a standard, the hit rates rather reflect an increase. However, this apparent contradiction can be reconciled by linking the RTs to the costs of the attention shift towards the deviant (Schröger and Wolff, 1998; Parmentier et al., 2008; for a review, see Parmentier 2014), and by linking the hit rates to an increase in nonspecific arousal that improves cognitive functioning (Näätänen, 1992). The current findings are well in line with previous research on deviant distraction, showing both costs and benefits (SanMiguel et al., 2010; Wetzel et al., 2012, Wetzel et al, 2019).

2) Oscillatory alpha power reflects an involuntary shift of spatial attention

Our study is the first to show that a lateralized deviant sound modulates alpha power in a spatially selective way, which cannot be attributed to stimulus-driven evoked activity (Figure 3). Similarly to recent EEG data collected during an exogenous spatial cueing paradigm (Feng et al., 2017; Störmer et al., 2016), we observed a lateralized alpha power modulation over parieto-occipital sensors that occurred relatively early and was rather short-lived, thereby closely matching the characteristics of involuntary attention both in timing and in the build-up phase (Corbetta and Shulman, 2002). Our whole-brain analyses estimated that the main sources of this modulation occurred in the alpha band in

the visual cortex, thus confirming and extending earlier EEG data (Feng et al., 2017; Störmer et al., 2016) using a MEG approach.

Crucially, we found a left-hemispheric alpha power modulation over parieto-occipital sensors that was higher ipsilateral versus contralateral to the deviant location (Figure 3 A, C). This effect was driven by an alpha power increase (relative to baseline) due to the left deviant (Figure 4 B). The current finding is in line with that obtained in endogenous spatial cueing tasks, in which attention was voluntarily guided to the location of either a visual (Kelly et al., 2006; Rihs et al., 2009; Worden et al., 2000) or auditory target (Banerjee et al., 2011; ElShafei et al., 2018; Frey et al., 2014; Müller and Weisz, 2012). In those tasks, lateralized alpha power was larger over the ipsilateral than the contralateral hemisphere, relative to the attended target location. This alpha power modulation was driven by 1) an alpha power decrease in the contralateral hemisphere and/or an alpha power increase ipsilateral to the attended side (e.g. Haegens et al., 2011); 2) a bilateral alpha power decrease that was maximal over the hemisphere contralateral to the attended position (e.g. Thut et al., 2006); or 3) a bilateral alpha power increase that was maximal over the hemisphere ipsilateral to the attended side (e.g. Banerjee et al., 2011; Worden et al., 2000). The pattern that is actually observed, reflecting mechanisms of suppression or enhancement at play in attention biasing, probably relies on divergent task demands of the respective study (Kelly et al., 2006; Thut et al., 2006). In any case, based on those studies, it has been widely acknowledged that decreased alpha power reflects the processing of task-relevant information in the voluntarily attended space, and increased alpha power indicates the inhibition of processes associated with task irrelevant information in the unattended space (for a review, see Klimesch, 2012). In a similar vein, our left-hemispheric parieto-occipital alpha power increase due to the left deviant can be linked to the suppression of irrelevant information in the unattended space, in that deviant-induced involuntary spatial attention is *not* captured. This active inhibition of visual brain areas may free up resources for brain areas contralateral to the deviant site that process relevant information (Jensen and Mazaheri, 2010; Meeuwissen et al., 2011), which are also consequently involved in attention reorienting towards the deviant location. This interpretation

receives support from the current behavioral data, showing that deviants capture spatial attention (Figure 2B). Furthermore, it is in line with findings suggesting that a sound can engage visual processing at the same location (Feng et al., 2014; Feng et al., 2017; McDonald et al., 2013; Störmer et al., 2016).

Importantly, the current pattern of results contradicts the prevailing view on alpha power in the context of involuntary attention. Earlier studies used exogenous spatial cueing paradigms to demonstrate a bilateral alpha power decrease that was more prominent in the hemisphere contralateral to the task-irrelevant sound. Based thereon, the authors suggested that a shift in involuntary attention exclusively facilitates target processing on the cued side, whereas target processing on the opposite side is not negatively impacted (Feng et al., 2017; Störmer et al., 2016). This conclusion was substantiated by the characteristic pattern of alpha power modulation preceding correct and incorrect discriminations of valid and invalid targets (Feng et al., 2017). Our results - demonstrating an increase of parieto-occipital alpha power - challenge that conclusion, as well as the prevalent notion that the "lack of an early inhibitory influence may represent a fundamental difference between involuntary orienting and voluntarily directed attention" (Feng et al., 2017, page 326). The difference between the current and previous findings is that the current study did not only apply an exogenous spatial cueing task, but also a distraction task, thus resulting in different task demands (Kelly et al., 2006; Thut et al., 2006).

3) Oscillatory alpha power indicates deviant-related processes beyond involuntary spatial attention

In addition to the current evidence pointing to a spatial shift of attention, the current right-hemispheric alpha power modulation over centro-temporal sites (Figure 3 B, D) gives more insights into the processing of deviant-related information in a crossmodal scenario. Similar to the left hemispheric visual alpha power modulation, the right-hemispheric effect was driven by an increase in alpha power, relative to baseline, due to the right/ipsilateral deviant (Figure 4 A). This reflects inhibition of the

underlying brain regions, namely the parieto-occipital, auditory, and somatosensory areas, as well as the ventral attention network (Figure 3 F). This active inhibition leads to an increased allocation of resources to contralateral brain regions that are responsible for processing relevant deviant-related information (Jensen and Mazaheri, 2010; Meeuwissen et al., 2011). Specifically, the left auditory cortex should be engaged in processing the right deviant, and somatosensory cortex should be involved in processing the anticipated behavioral relevance of the right deviant. Based thereon, we can draw further conclusions about the nature of attention reorienting in crossmodal scenarios. The current modulation in auditory alpha power fits the notion that, in crossmodal scenarios, attention is not only shifted spatially, but also across modalities (i.e., from vision to audition; Parmentier, 2014; Weise et al., 2016). This interpretation supports the involvement of a resource-limited supramodal attention mechanism that operates independent of stimulus modality (Banerjee et al., 2011; Deng et al., 2020; Wöstmann et al., 2016). Therefore, when attention shifts from vision to audition, auditory processing is facilitated at the cost of diminished visual processing. This explanation accounts for our behavioral result showing longer RTs to visual targets that follow a deviant versus a standard (cf. Ruhnau et al., 2013; Weise et al., 2016), which cannot be attributed exclusively to the spatial shift of attention (see above).

The pattern of auditory alpha power modulation observed in the current study contributes to the growing number of findings highlighting distinct alpha generators in the auditory cortex. So far, this has mainly been shown using endogenous (spatial) cueing paradigms (Billig et al., 2019; Frey et al., 2014; ElShafei et al., 2018; Müller and Weisz, 2012; Weisz et al., 2014; Wöstmann et al., 2016). Our data importantly extend those results to the field of involuntary spatial attention.

The right-hemispheric alpha power modulation in regions related to somatosensory processing may point to the allocation of resources in contralateral brain regions in preparation for action. Though auditory deviants were not relevant to the task, the brain seems to classify those sounds as behaviorally relevant. This receives support from the engagement of the ventral attention network,

which is activated when behaviorally relevant events are detected (Corbetta et al., 2000). Note that the observed somatosensory alpha power modulation cannot be explained by preparatory processes related to the task for two reasons: 1) Participants responded to the left and right target with both hands, and the button-response assignment was counterbalanced across participants; 2) The alpha power modulation occurred in the pre-target interval, whereas the responding hand was only determined once the target stimulus appeared.

The observed right hemispheric alpha power modulation in areas linked to the ventral attention network fits to the right hemispheric bias of that network known mainly from fMRI studies (e.g. Downar et al., 2000; Corbetta et al., 2000; Vossel et al., 2012). Given that this fronto-parietal network has been functionally linked to stimulus-driven attention reorienting (for reviews, see Corbetta and Shulman, 2002; Corbetta et al., 2008), our MEG data establish a strong link between neural oscillatory activity in the alpha range and involuntary attention. One reason why the current MEG data showed sources in the fronto-parietal network, whereas previous EEG data did not, (Feng et al., 2017; Störmer et al., 2016) might be due to the different stimulus material that was used. Earlier studies used salient noise bursts, whereas we used environmental sounds that have real-world behavioral relevance (e.g., baby crying, telephone ringing, etc.). In fact, previous fMRI studies suggest that behaviorally relevant events activate the ventral attention network, whereas salient, but noninformative, events do not (Downar et al., 2001). Furthermore, the observed alpha power modulation in the ventral attention network fits the view that this neural network is particularly engaged whenever environmental events elicit a change in the current task, and especially when these events are rare, as in the current study (for a review, see Corbetta and Shulman, 2008). Even though only the visual targets were task-relevant, the auditory deviants produced a clear behavioral distraction effect, which can be regarded as a temporary change in the task.

4) Conclusion

Here, we show that lateralized deviant sounds cause a shift of involuntary spatial attention and contribute to behavioral distraction. This is evident in our reaction time data, which demonstrates that

responses are faster when the target follows an auditory deviant on the same side compared to the opposite sides. Additionally, our MEG data clearly show that oscillatory alpha power is shaped in a spatially selective manner. Most importantly, attention-capturing, task-distracting deviant sounds induced high visual alpha power in the left hemisphere. These attention-related changes were driven by alpha power increases due to the left deviant, suggesting disengagement of visual areas that process task-irrelevant information outside the locus of involuntary attention. Together with the behavioral data, our oscillatory data strengthen the view that alpha power reflects a shift of involuntary spatial attention. Critically, the current results challenge the prevailing view that involuntary attention capture only affects facilitatory mechanisms.

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Data and code availability

The preprocessed MEG and behavioral data used to generate the figures and calculate the statistics are available at the OSF public repository (https://osf.io/qt95u/). The corresponding data analysis code is available at the corresponding author's GitLab repository (https://gitlab.com/aweise/crossfrog-final-analysis). The original raw data are available, upon reasonable request, from the corresponding author.

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