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 of a busy city street to ride the bike safely. Suddenly, the siren of an ambulance rings out. This unpredictable sound can involuntarily capture your attention and compromise performance. Related to that 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 where participants responded as fast and as correct as possible whether a visual target appeared on the left or right. Each target was preceded by a task-irrelevant sound, usually the same (i.e. standard) animal sound. Rarely, it was a novel (i.e. deviant) environmental sound. Crucially, 50% of the deviants occurred at the same and the other 50% at the opposite side as the target. As expected, responses were slower to targets that followed a task-distracting deviant vs. standard. Crucially, responses were faster when targets followed deviants at the same vs. different side, suggesting a *spatial* shift of attention. Corroborating support comes from our magnetoencephalographic data. Left-hemispheric visual alpha power increased in response to the left deviant, indicating that visual areas processing information outside the locus of involuntary attention are disengaged. 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 indicates an involuntary shift of spatial attention. They further suggest that involuntary attention has a similar impact on target processing as voluntary attention, thus, challenging previous reports claiming otherwise.

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

Highlights

- Lateralized, task-distracting deviant sounds capture involuntary spatial attention.
- Responding is faster when a target follows a deviant at 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 behaviour break through attention filters in order 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 bike on a busy city street. While filtering out street noises helps focusing on the traffic to bike 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 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. The 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). In a task where participants attend and respond to a target, behavioral distraction is defined as the slowing down of responses following the presentation of the task-distracting event. This is caused by an involuntary (stimulus driven, bottom-up or exogenous) shift of attention from the task towards the deviant, actually reflecting the time penalties due to the shift of attention to the deviant and back to the task (Parmentier et al., 2008; Schröger, 1996).

The present study aims to tackle two questions concerning the cognitive and neural underpinnings of deviant distraction in a crossmodal scenario such as the one described above: 1) The first question addresses the nature of the shift of attention. Especially in scenarios where 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 will outline how we will address these questions 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 where 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 few reports on that topic that could either not 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 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 a visual target either at the same or opposite side. Importantly, the location of the sound did neither predict the location nor the type of the upcoming visual target. Results showed that if the visual target appeared at 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 when these events occurred at 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 during the exogenous spatial cueing paradigm. They showed 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 whether oscillatory alpha activity reflects an involuntary shift of spatial attention has been motivated by studies on voluntary (goal driven, top-down or endogenous) spatial attention where 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). That 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 an auditory target, sustained oscillatory alpha power appeared to be lateralized especially over parieto-occipital areas. It was higher in the ipsilateral than in the contralateral hemisphere relative to the attended target location. Often, the lateralization has been driven by an ipsilateral increase and/or a contralateral decrease in alpha power relative to the attended side, reflecting the inhibition of brain regions processing task-irrelevant information at unattended locations or facilitated 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 that topic is sparse and there is only one study so far focusing especially 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, the deviant was a novel environmental sound. All sounds were presented binaurally. The deviant induced low alpha power in the pretarget time window as compared to standards with sources in the occipital, parietal and supratemporal cortices that correlated with response speed for the deviants only. While this study provides first indices that alpha power can reflect involuntary attention shifts it still needs to be tested whether it can do so for involuntary *spatial* attention.

Initial support for the latter comes from two electroencephalographic (EEG) studies employing an exogenous spatial cueing task. They 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 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 preferrably in different conceptual frameworks to either strengthen or reject this view. Moreover, the changes in alpha power 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 or two dissociable cognitive mechanisms (Feng et al., 2017; Störmer et al., 2016).

Current approach

To tackle the two questions within the framework of deviant distraction we employ 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 as correctly as possible 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 at the same side as the target. That condition is referred to as the Congruent condition. The other 50% of the deviants occurred at the opposite side as the target. That condition is called the Incongruent condition.

On the behavioral level we intend to reproduce a distraction effect, indicated by longer reaction times to the visual target that follows a deviant vs. 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 hypothesize a *spatial* shift of attention, that should be indicated by shorter reaction times in the Congruent vs. Incongruent condition, i.e. when the visual target follows the auditory deviant at the same vs. different side.

Besides 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 expect 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 predict neural sources of this alpha power modulation to 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), as well as 3) areas linked to the ventro-frontoparietal attention system, comprising the

temporoparietal junction and the ventral frontal cortex, that have functionally been linked to attentional 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 was conducted following the code of Ethics of the World Medical Association (Declaration of Helsinki).

Participants

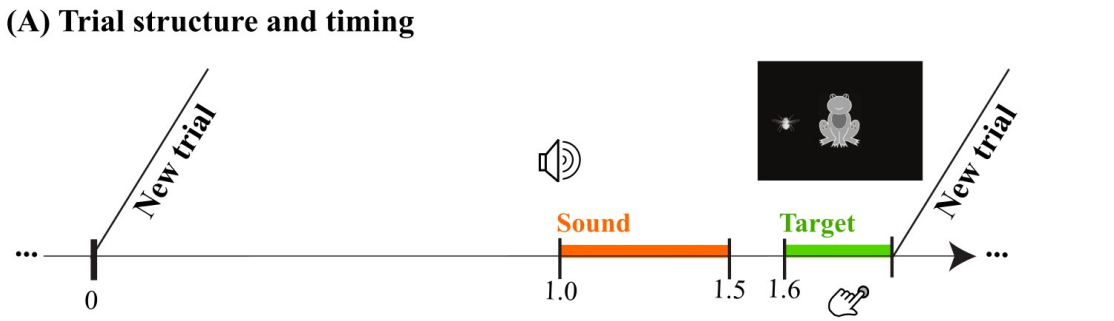
30 healthy young adults participated in the MEG experiment (12 males, mean age ± STD: 27 ± 6 yrs, 4 left-handed, 1 ambidexter). Volunteers gave written informed consent prior to their participation. All participants reported normal hearing, normal or corrected-to-normal vision, and none reported a history of neurological or psychiatric diseases. Volunteers received 10€/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). Stimulus presentation and exact timing was ensured by 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.

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 on at all times. Every trial a visual target in the shape of a fly was presented on the screen next to the frog. In 50% of the trials the target appeared on the left side of the frog. In the other 50% of the trials it appeared on the right side. The participants' task was to respond via their left or right thumb and distinct buttons where the fly had been presented. The mapping between the response buttons and the target location was counterbalanced across participants. Both, the target presentation and the response window, was maximal 1 s in duration following the onset of the visual target or ended as soon as the participant responded.



(B) Sound sequence

Left S S D S S S D S S S

Right S S S S S S S D S

Legend

D Deviant (10% left, 10% right)

S Standard (80%, binaural)

(C) Locations of deviant and target in different conditions

	Congruent Location		Incongruent Location	
Left	Deviant Target		Deviant	Target
Right		Deviant Target	Target	Deviant

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 (indicated as an orange bar) preceded the task-relevant visual stimulus (indicated as a blue bar). Participants had to respond whether the target occurred at the left or right next to the fixation frog. (B) Exemplary sound sequence. The task-irrelevant sounds were presented in an oddball paradigm: Standards were presented binaural on 80% of the trials, deviants were presented left (10%) or right (10%). (C) Listing of the two different conditions (Congruent Location, Incongruent location) and the corresponding locations (left, right) of deviant and corresponding target presentation.

Additionally, on each trial a sound of 0.5 s duration (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 out of 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 reaction time).

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 at the same side, i.e. both appeared on the left or right. In the Incongruent condition, the deviant and target occurred at opposite sides. That is, while the deviant occurred e.g. on the left the visual target occurred on the right or vice versa. Noteworthy, each deviant could occur only once within a block and once every three blocks while it could appear four times in total (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]) with respect to the whole experimental stimulation.

The experiment consisted of seven blocks in total, each lasting ∼5 min and consisting of 160 trials (128 standards, 16 deviants presented to the left, 16 deviants presented to the right). Thus, the stimulation without any breaks lasted maximally ~35 min in total and resulted overall in 112 left and 112 right deviants while half of them occurred in the Congruent condition and the other half in the Incongruent one. The auditory stimuli were presented at 50 dB above sensation level. The auditory stimulation was delivered via MEG compatible pneumatic in-ear headphones (SOUNDPixx, VPixx

technologies, Canada). The visual stimuli were presented inside 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 the individual sensation level was determined using a 200-ms 1000 Hz tone presented via a staircase threshold measurement procedure separately for the right and left ear. Thereafter, the participant practiced the task with a fewer number of trials to get familiar with the experiment. Deviants were chosen randomly from the pool of environmental sounds (N=56). They 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 at 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.

During data recording participants were in a seated position. 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 1) to automatically remove and interpolate the data of bad channels, and 2) to 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). 3) It also allowed to 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. 1) Preprocessing of the data was optimized for applying independent component analysis (ICA). Therefore, MEG data were offline filtered 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. 2) The second preprocessing pipeline was optimized for further data analysis. In more detail, cleaned MEG data were offline filtered 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 2 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 where deviants occurred on the left or right are referred to as Deviant Left or Deviant Right, respectively, hereafter. Only those deviant trials entered the analysis for which participants responded once, correctly and within the predefined response window (100 to 800 ms following the target). This resulted on average in 106.53/112 (SD = 3.38) Deviant Left trials and 106.93/112 (SD = 2.89) Deviant Right trials.

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, trials that included more than one button press. Individual reaction times (RTs) and hit rates were calculated.

Statistical analyses. For the statistical analyses of behavioral data we used jamovi (version 1.2.22.0, https://www.jamovi.org/). 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 analyses of variance (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). As an effect size measure we report the generalized eta-squared (η^2_G; Bakeman, 2005). 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 separately for each participant and condition. 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 separately for Deviant Left and Deviant Right.

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 on the direction of the lateralized alpha power modulations expected in each hemisphere, we applied paired-sample one-tailed Student's t-tests separately for the left-hemispheric channels and the right-hemispheric channels. 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 thereon clusters were formed of 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 cluster-level statistic. The cluster with the maximum sum was subsequently used as a 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 are considered to be significantly different from each other if not more than 5% of the sum-t-values of all of the 10,000-permuted data are 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 the preceding step that phase-locked activity, i.e. the evoked signal averaged across trials of the respective condition, was subtracted from every single trial in order 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 tested what caused 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). The ROIs consisted each 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 mm 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 146400 points covering the grey 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 to 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

Task performance in terms of accuracy was in general 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 outcome of 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 nor a significant interaction. This result may be linked to an increase in nonspecific arousal upon the occurrence of a deviant (Näätänen, 1992) that facilitates task performance. Hit rates did not differ when deviant and target occurred at 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 nor a significant interaction.

As depicted in Figure 2A, reaction times (RTs) are prolonged when targets follow a deviant vs. 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 nor a significant interaction. Overall, these results point to a behavioral distraction effect due to an attentional shift towards the task-distracting deviant. As depicted in Figure 2B, RTs are shorter when deviant and target occurred at the congruent vs. 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 nor a significant interaction. Overall, these results point to a *spatial* shift of attention towards the task-distracting deviant sound.

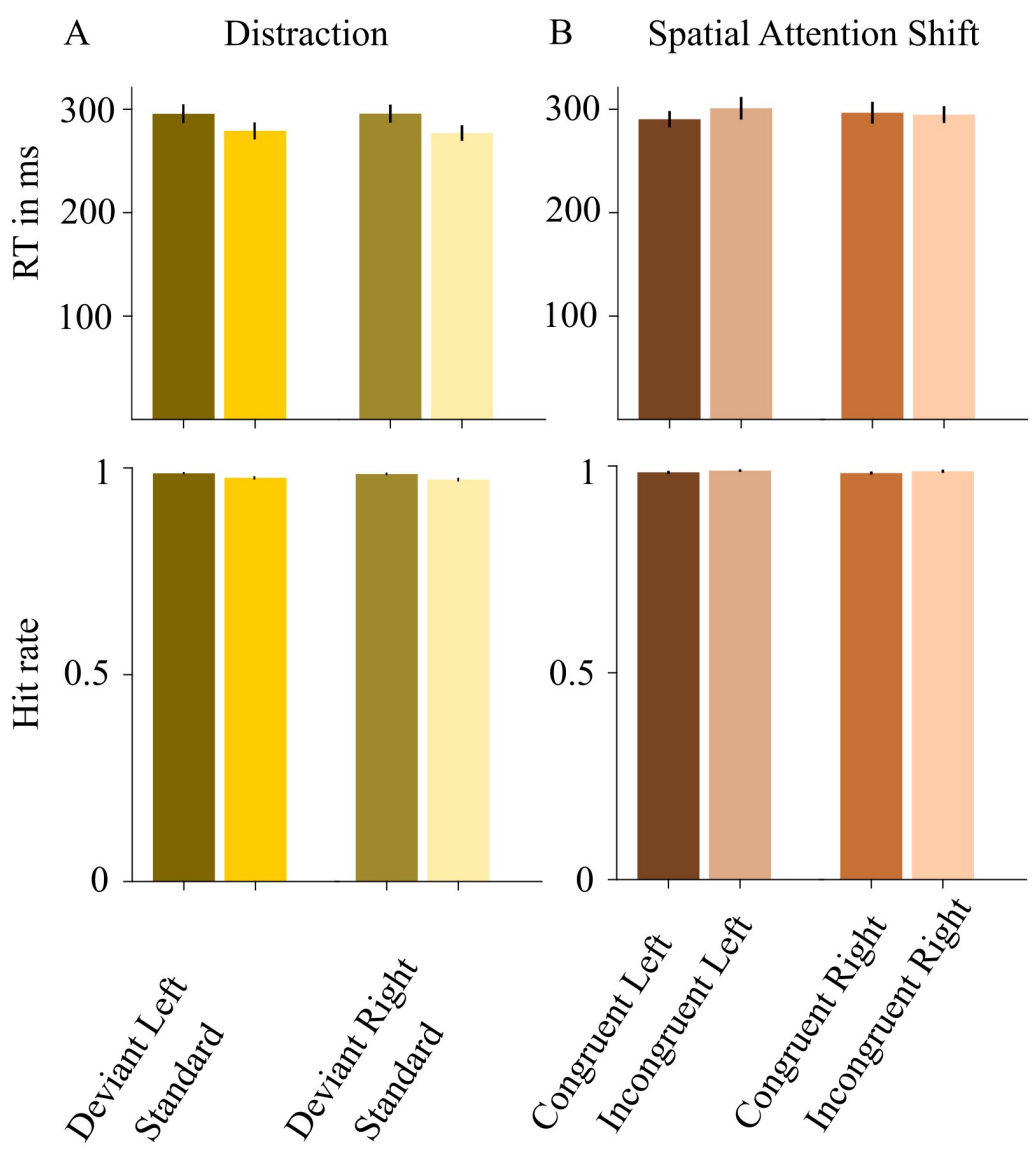


Figure 2: Bar plots of reaction times and hit rates in response to visual targets to determine a distraction effect (A) or a shift of spatial attention (B) caused by the deviant. (A) Prolonged RTs and higher hit rates for targets following deviants presented at the left or right side vs. standard before deviant. (B) Shortened RTs for targets following deviants at the same vs. different side in the Incongruent and Congruent condition, respectively. Data were analysed with respect to the deviant side (left, right). Hit rates did not differ between conditions. SEMs are indicated.

Alpha power analysis

To probe whether attentional reorienting towards the location of the deviant sound, as indexed via the current RT data, is also reflected in neural oscillatory activity we analyzed alpha-band (8 - 14 Hz) power. We followed the methodological approach used for studying 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 vs. attend right). Accordingly, we here 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 on 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 separately for the left-hemispheric and the right-hemispheric channels. Overall, the results clearly show that alpha power to lateralized deviants is modulated in a spatially selective manner (Figure 3).

In more detail, 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 to 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 to 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).

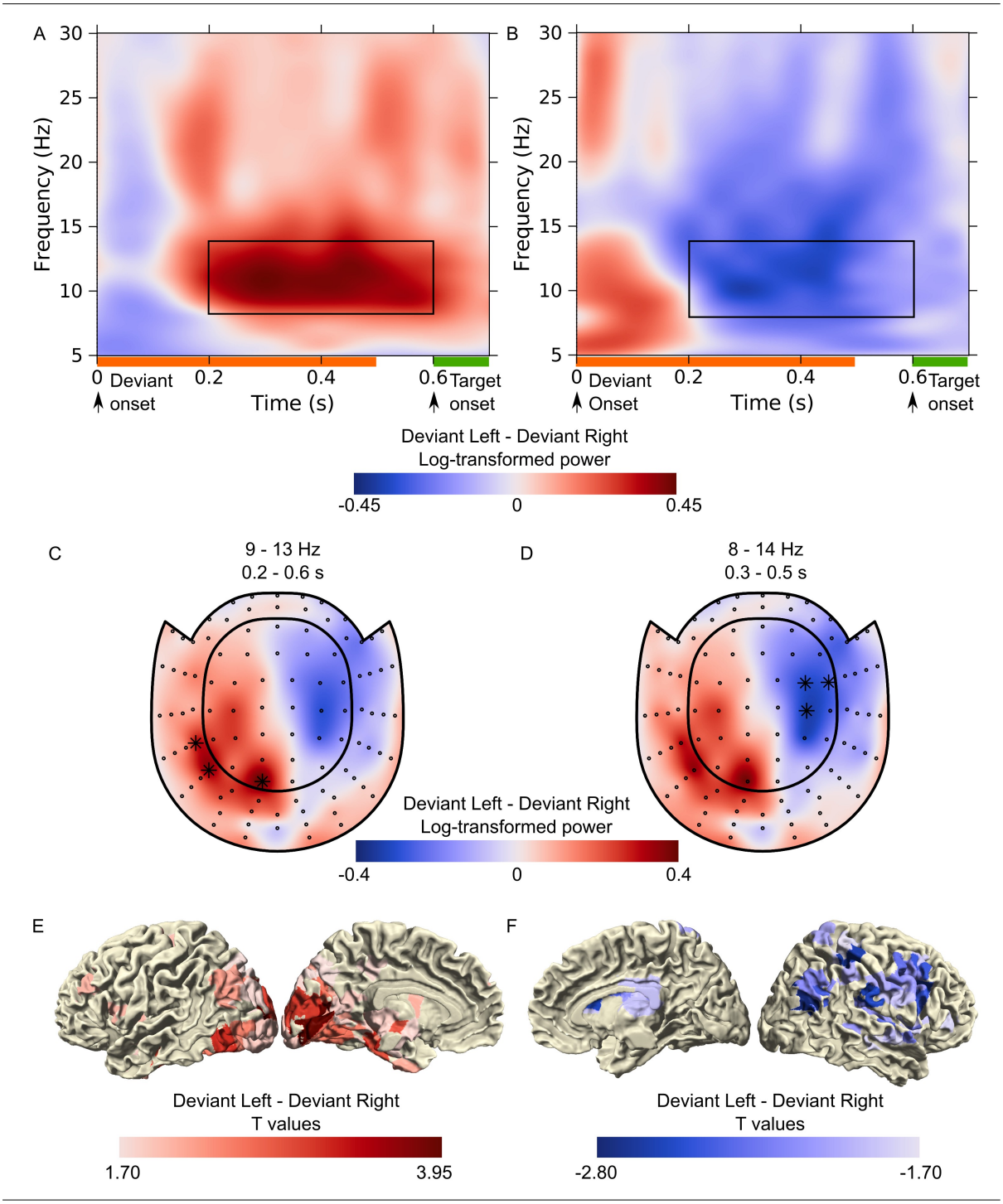


Figure 3: Log10-transformed alpha power modulation to lateralized deviants based on group-

averaged data 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 where the statistical effect was prominent. (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 current alpha lateralization (see Fig. 3) is driven by a decrease or increase in alpha-band power, we analyzed the time courses of alpha power separately for the right hemispheric centro-temporal and the left hemispheric parieto-occipital region of interest 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 causes 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). Further, we find that the left/ipsilateral deviant results in 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). Also, the right/contralateral deviant results in 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)

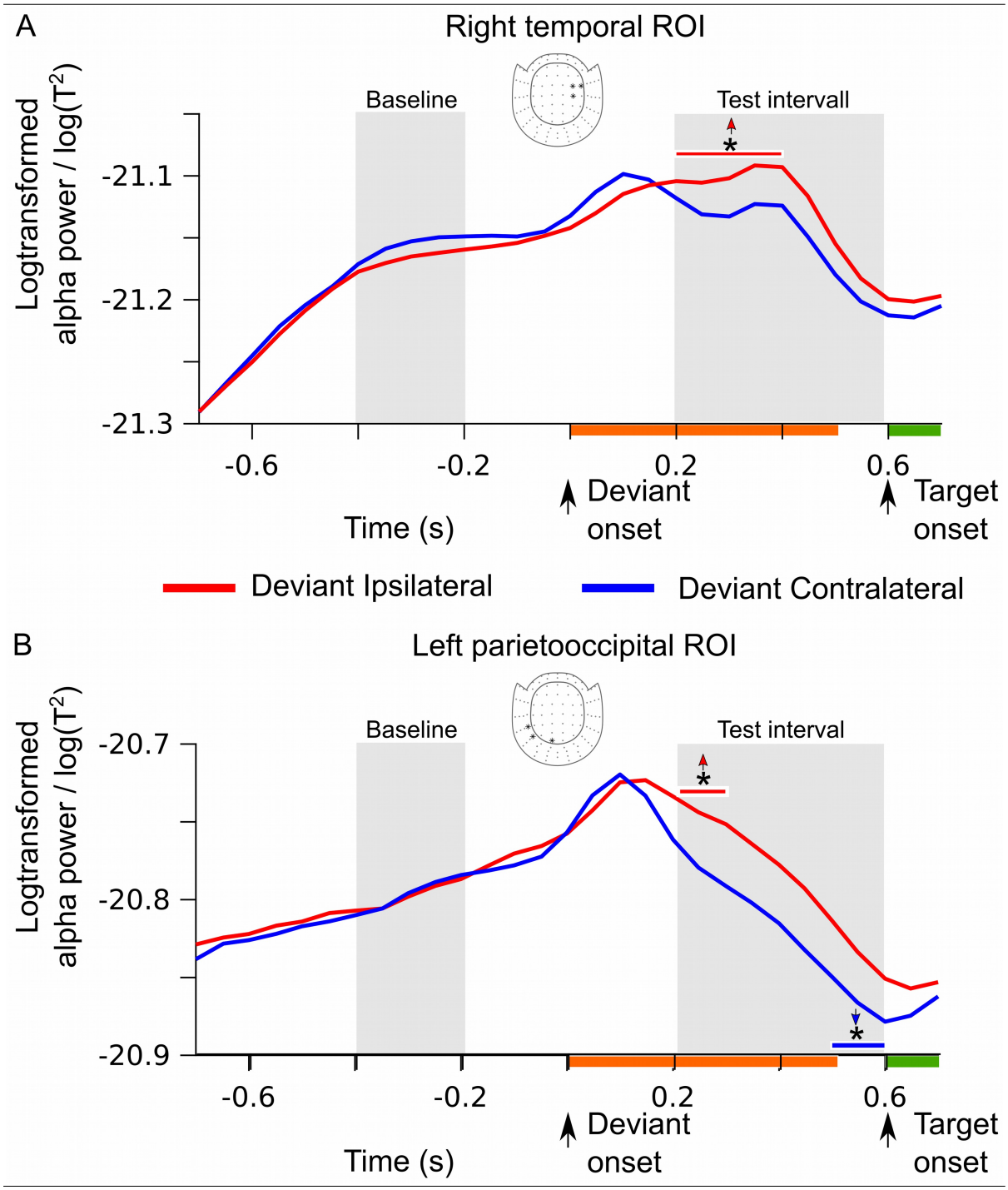


Figure 4: What drives the alpha power modulations? The ipsilateral deviant conditions lead to a significant increase of alpha power compared with the baseline. Deviant-locked time courses of contra- and ipsilateral log10-transformed and group-averaged alpha power for (A) the right centro-temporal ROI (8 - 14 Hz) and (B) the left parieto-occipital ROI (9 -13 Hz). Red traces show deviant

ipsilateral, blue traces show deviant contralateral. Channels belonging to the ROI are marked with stars in the corresponding channel layout. Significant time samples are indicated by the horizontal red and blue traces (*p < .05). Upward directed arrows indicate an alpha power increase, 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? And 2) Does neural oscillatory alpha activity reflect this involuntary *spatial* attention shift? Our reaction time and neural oscillatory MEG data provide a positive answer to each of these questions that we will discuss in more detail in the following.

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

As expected, our behavioral distraction effect - i.e. the longer reaction times to targets that followed a deviant vs. a standard - shows that the deviant captured attention involuntarily from the task. This strengthens previous findings that have been obtained via a more or less 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 at the same vs. opposite side. This clearly speaks in favor for a *spatial* shift of attention that has been proposed though not directly tested earlier (Parmentier et al., 2008; Weise et al., 2016). That is, when deviant and target occur at the same side the time penalties due to the spatial shift is lower as when both events occur at 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. If this holds, the time penalty accumulated by the attentional shift 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). The claim receives support from behavioral studies showing that reaction times are slower for a target in an unexpected modality as opposed to a target in an expected modality (Boulter, 1977; Spence et al., 2001).

The reaction time data seem to be at odds with the hit rates at a first glance. While the former indicate a decrease in performance for targets following a deviant vs. standard, the latter rather reflect an increase. However, this apparent contradiction can be reconciled when linking the response times to the costs of the attentional shift towards the deviant (Schröger and Wolff, 1998; Parmentier et al., 2008; for a review, see Parmentier 2014) and 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 not only costs but also 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 in a narrow time window that 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 in timing and build-up phase (Corbetta and Shulman,

2002). Our whole-brain analyses approach estimated the main sources of the change in the alpha band in the visual cortex, thus, confirming and extending earlier EEG data (Feng et al., 2017; Störmer et al., 2016) via an MEG approach.

Of utmost importance, we found a left-hemispheric alpha power modulation over parieto-occipital sensors that was higher ipsilateral vs. 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 where 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 and/or an alpha power increase in the hemisphere contralateral and/or ipsilateral to the attended side, respectively (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). What pattern is actually observed, reflecting mechanisms of suppression or enhancement at play in attentional biasing, probably relies on divergent task demands of the respective study (Kelly et al., 2006; Thut et al., 2006). Anyway, based on those studies, it has been widely acknowledged that brain regions showing decreased alpha power reflect the processing of task-relevant information in the voluntarily attended space. Brain regions with increased alpha power indicate 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 i.e. where deviant-induced involuntary spatial attention is *not* captured. This active inhibition of visual brain areas could free up resources for the corresponding counterpart contralateral to the deviant site processing relevant information (Jensen and Mazaheri, 2010; Meeuwissen et al., 2011) related to the attentional reorienting towards the

deviant location. This interpretation receives support from the current behavioral data, showing that deviants capture spatial attention (Figure 2B). Further, it is in line with findings suggesting that a sound can engage visual processing associated with its 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. Those earlier studies, which used exogenous spatial cueing paradigms, showed 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 the processing of targets on the cued side while the processing of targets 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 data - the increase of parieto-occipital alpha power - challenges that conclusion as well as the prevalent notion that the "lack of an early inhibitory influence may represent a fundamental difference between involuntary and voluntary attention" (Feng et al., 2017). The difference between the current and previous findings might be due to the fact that the current study did not only apply an exogenous spatial cueing task but in addition to that 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. Likewise 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 the inhibition of the underlying brain regions, namely the parieto-occipital, auditory and somatosensory

areas as well as the ventral attention network (Figure 3 F). That active inhibition leads to increased allocation of resources to their respective contralateral counterparts, responsible for the processing of the relevant deviant-related information (Jensen and Mazaheri, 2010; Meeuwissen et al., 2011). Accordingly, the left auditory and somatosensory cortex should be engaged in the processing of the right deviant or in preparatory processes according to the anticipated behavioral relevance of the right deviant, respectively. Based thereon, we may draw further conclusions about the nature of the attentional reorienting in crossmodal scenarios. In that case, 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 line of argumentation receives support from data pointing to a supramodal attention mechanism that operates modality independent (Banerjee et al., 2011; Deng et al., 2020; Wöstmann et al., 2016). Taking this for granted, when attention is shifted from vision to audition, auditory processing may be facilitated while the processing of the visual target comes at a cost. The latter point fits to our behavioral findings showing longer reaction times when targets follow a deviant vs. a standard (cf. Ruhnau et al., 2013; Weise et al., 2016) that we do not exclusively attribute to the spatial shift of attention (see above).

Moreover, the current modulation of auditory alpha power contributes to the slowly increasing number of findings highlighting distinct alpha generators in the auditory cortex. So far, this has mainly been shown when endogenous (spatial) cueing paradigms were employed (Billig et al., 2019; Frey et al., 2014; ElShafei et al., 2018; Müller and Weisz, 2012; Weisz et al., 2014; Wöstmann et al., 2016). Importantly, our data 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 the contralateral counterpart to be ready for action if needed. Though auditory deviants were not important for performing the task, the brain seems to classify those sounds as potentially behavioral relevant. This receives support from the engagement of the ventral attention network that is activated when behaviorally relevant events are detected (Corbetta et

al., 2000). Note that the current somatosensory alpha power modulation cannot be explained by preparatory processes related to the task for two reasons. 1) Participants responded with both hands to the left and right target while the button-response assignment was counterbalanced across participants. 2) The alpha power modulation occurs in the pre-target interval while the responding hand was only determined as soon as the target stimulus appeared.

The fact that we observed a right hemispheric alpha power modulation in areas linked to the ventral attention network fits to the right hemispheric bias of that network known from mainly fMRI studies (e.g. Downar et al., 2000; Corbetta et al., 2000; Vossel et al., 2012). Given that this fronto-parietal network has functionally been linked to stimulus-driven attentional 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 show sources in the fronto-parietal network while previous EEG data didn't (Feng et al., 2017; Störmer et al., 2016) might be due to the different stimulus material being used. Those earlier studies utilized salient noise bursts, whereas we made use of rare and unpredictable environmental sounds (e.g. baby crying, telephone ringing, etc.) with a rule-violating character being potentially behaviorally relevant. In fact, the outcome of fMRI studies suggests that especially behaviorally relevant events activate the ventral attention network while salient but noninformative events don't (Downar et al., 2001). Further, the modulation of alpha power in the ventral attention network fits to the view that this neural network is particularly engaged whenever environmental events call for a change in the task and especially when these events appear rare as is the case in the current study (for a review, see Corbetta and Shulman, 2008). Even though the visual targets only but not the deviants were task-relevant, the deviants clearly put the task related to the targets temporarily on hold - as shown via the behavioral distraction effect - what can be regarded as a temporary change in the task.

4) Conclusion

We here show that lateralized deviant sounds cause a shift of involuntary spatial attention and contribute to behavioral distraction. This becomes evident 1) by reaction time data indicating that

responding is faster when the target follows the auditory deviant at the same side as compared to a situation when both deviant and target occur at different sides. 2) Our MEG data clearly show that oscillatory alpha power is shaped in a spatially selective manner. Most importantly, the 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 that visual areas that process non-relevant information outside the locus of involuntary attention are disengaged. Together with the behavioral data, our oscillatory data strengthen the view that alpha power reflects a shift of involuntary spatial attention. Further, they challenge the prevailing view that involuntary orienting to the location of the sound has - contrary to voluntary attention - a merely facilitatory impact.

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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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