

Oscillatory Alpha Modulations in Right Auditory Regions Reflect the Validity of Acoustic Cues in an Auditory Spatial Attention Task

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Anticipation of targets in the left or right hemifield leads to alpha modulations in posterior brain areas. Recently using magnetoencephalography, we showed increased right auditory alpha activity when attention was cued ipsilaterally. Here, we investigated the issue how cue validity itself influences oscillatory alpha activity. Acoustic cues were presented either to the right or left ear, followed by a compound dichotically presented target plus distractor. The preceding cue was either informative (75% validity) or uninformative (50%) about the location of the upcoming target. Cue validity × side-related alpha modulations were identified in pre- and posttarget periods in a right lateralized network, comprising auditory and non-auditory regions. This replicates and extends our previous finding of the right hemispheric dominance of auditory attentional modulations. Importantly, effective connectivity analysis showed that, in the pre-target period, this effect is accompanied by a pronounced and time-varying connectivity pattern of the right auditory cortex to the right intraparietal sulcus (IPS), with influence of IPS on superior temporal gyrus dominating at earlier intervals of the cue–target period. Our study underlines the assumption that alpha oscillations may play a similar functional role in auditory cortical regions as reported in other sensory modalities and suggests that these effects may be mediated via IPS.

Keywords: alpha oscillations, auditory cortex, intraparietal sulcus, magnetoencephalography, spatial attention

Introduction

Since brain oscillations in the alpha frequency range are an omnipresent (Jasper and Penfield 1949) and dominant feature of “resting” electroencephalography (EEG)/magnetoencephalography (MEG), which becomes greatly reduced (event related desynchronization) with sensory stimulation, alpha activity has traditionally been conceptualized as “idling” activity of the brain (Pfurtscheller et al. 1996). This notion of alpha activity being an idle mode of brain function is rapidly changing, and alpha oscillations have been ascribed a crucial role in diverse cognitive processes such as attention (e.g. Worden et al. 2000; Thut et al. 2006), perception (van Dijk et al. 2008; Obleser and Weisz 2011), and working memory (e.g. Jokisch and Jensen 2007; Obleser et al. 2012). The common theme between these diverse reports appears to be that the level of alpha reflects the level of excitability in respective sensory regions that can be modulated in a top down manner. In particular, an increase in alpha activity has been interpreted to reflect an active disengagement of affected task irrelevant brain regions (Jensen and Mazaheri 2010) and based on behaviorally conforming data has been also described as representing “functional inhibitory states.” Besides of this behavioral

description, the notion of alpha to represent inhibitory states has recently received strong support by an invasive study (Haegens, Händel, et al. 2011; Haegens, Nächer, et al. 2011), showing striking relationships between overall alpha power and phases of alpha with the firing rate in monkey sensorimotor regions (alpha phase has also been shown to have differential effects on behavior; however, a detailed treatment of this topic is beyond the scope of this article; for review see, e.g. Vanrullen et al. 2011).

Two of the most intriguing aspects about alpha oscillations is that they can be (1) purely top down driven (e.g. Thut et al. 2006; Müller and Weisz 2011), and that (2) these top down modulations can be regionally very circumscribed (e.g. Rihs et al. 2007). The largest body of evidence supporting these claims have been derived from attention research, which has shown marked pretarget alpha power changes in posterior cortical regions following a (also nonvisual; see e.g. Thut et al. 2006) cue. A consistent finding has been a pretarget decrease of alpha in visual areas processing to be attended features (usually hemifield) and an increase of alpha in regions processing to be ignored features (Worden et al. 2000; Thut et al. 2006; Rihs et al. 2007; Siegel et al. 2008). A study using combined EEG/transcranial magnetic stimulation (TMS) indicates that, in particular, the right frontal eye field (FEF) as well as intraparietal sulcus (IPS) play a central role in regulating posterior alpha modulations related to visuospatial attention (Capotosto et al. 2009). Outside of the visual system, similar alpha (μ) activity patterns have also recently been reported in the somatosensory modality (Jones et al. 2010). Even though alpha like oscillations between 6.5 and 9 Hz (labeled as tau rhythm by the authors) have also been described in the auditory modality (Lehtelä et al. 1997; see also data on evoked alpha recorded in the auditory cortex of cats, Schürmann et al., 1998), their involvement in cognitive operations has been rarely investigated so far (see Weisz, Hartmann, et al. 2011 for a review). Even more, despite the acknowledgement of a temporal lobe alpha rhythm (labeled “third rhythm” by Niedermeyer 1999), its relationship to auditory functions, as well as its measurability using noninvasive methods, has been some times doubted (see Niedermeyer 1999, p. 178: “Personal data [...] do not provide good evidence for a relationship to auditory function. [...] It seems that the function of this rhythm is still debatable.”).

In a previous study, we were able to show stronger alpha desynchronizations in the auditory cortex during a physically “invariant” sound, when this sound was expected to be followed by a salient stimulus (noise individually matched to discomfort threshold; Hartmann et al. 2012), thereby demonstrating auditory alpha to be sensitive to expectations. In another study,

more similar to the aforementioned ones in the visual domain, using a “visual” cue indicating which ear to attend, we could furthermore demonstrate significant enhancements of right auditory cortical alpha activity in the pretarget phase when the cue instructed the participant to monitor the right (i.e. ipsilateral) ear (Müller and Weisz 2011). Following the disengagement idea outlined above (Jensen and Mazaheri 2010), this result argues for an active inhibition of the ipsilateral auditory cortex when attention is focused to the right ear. Analysis of phase synchrony in this cue target interval furthermore suggested that the alpha power increase was paralleled by an increased connectivity between the right auditory cortex and the FEF, a region frequently implicated in mediating covert spatial attention (e.g. Corbetta and Shulman 2002) and thus strengthening the interpretation that relevant alpha modulations were top down driven. Attention related “relative” alpha power enhancements in an intersensory attention task (i.e. resulting from the contrast which modality auditory or visual was attended) have recently also been shown in the right auditory cortex using electrocorticography (ECoG) by Gomez Ramirez et al. (2011), thus underscoring our earlier claim of the relevance of auditory cortical alpha modulations. This important ECoG evidence thus underscores the validity of earlier noninvasive works reporting auditory cortical alpha modulations (auditory working memory: van Dijk et al. 2010; auditory spatial attention: Müller and Weisz 2011; for a comprehensive review on auditory alpha see Weisz, Hartmann, et al. 2011; Weisz, Lecaignard, et al. 2011).

While the overall data base is scarce, the 2 aforementioned studies reporting attentionally related auditory cortical alpha enhancements interestingly both in the right hemisphere have employed experimental settings in which participants were always validly cued to the target bearing ear (using arrows; Müller and Weisz 2011) or modality (blockwise via instructions; Gomez Ramirez et al. 2011). It should be added, however, that Gomez Ramirez et al. (2011) collected data solely from right hemispheric grids thereby in contrast to Müller and Weisz (2011) precluding statements about the lateralization of auditory attentional effects. In the present study, we were interested to what extent auditory cortical alpha modulations depend on the validity of the cue (for work in the visual domain see Gould et al. 2011; Händel et al. 2011; for somatosensory work see Haegens, Händel, et al. 2011; Haegens, Nächer, et al. 2011), with the general notion that “top down” attentional modulation of auditory cortical alpha activity being more pronounced following an informative cue (in the following when speaking to attention/attentional modulation/etc. refers to the top down variant). For this purpose, we reanalyzed data from a published study (Weisz, Hartmann, et al. 2011; Weisz, Lecaignard, et al. 2011), which contained informative (75% validity) and uninformative (50% validity) acoustic cues, showing that target related auditory steady state responses (aSSRs) were significantly reduced in the right primary auditory cortex when participants attended the right ear following an informative cue. In this study, we hypothesized that this effect may be preceded and accompanied by alpha increases in the right auditory cortex. We therefore scrutinized alpha band dynamics in both the pre and posttarget periods and are able to show a right lateralized distributed set of regions, including the right superior temporal gyrus (rSTG) as well as the right IPS, that exhibit differential alpha activity patterns depending on cue validity as well as laterality. In

particular conforming with our hypothesis, rSTG decreases of alpha power were observed when attention was directed to the left ear via the informative cue and vice versa when the cue was presented to the right ear. Exceeding the mere local synchronization effect, using an effective connectivity analysis, we also studied the directional interaction between the right IPS (Capotosto et al. 2009) and rSTG. This analysis indicates that the right IPS may be a crucial hub in regulating attentional effects on auditory cortical activity.

Materials and Methods

Participants

Eleven healthy right handed volunteers (6 females; age range: 24–38 years) participated in this experiment. They reported normal hearing and no history of previous neurological or psychiatric disorders. Participants were introduced to the MEG and the basic experimental procedure before the beginning of the experiment. Written informed consent was collected from all participants, and the procedures of the experiment were approved by the local Ethical Committee.

Procedure and Materials

The participants’ task was to indicate on which ear a certain target sound was presented, defined by an amplitude modulation (AM) frequency of 42 Hz. Simultaneously, a distractor sound with 19 Hz AM was presented on the opposite ear. To aid the perceptual segregation of sounds, the carrier frequencies (CFs) were chosen to be 500 or 1300 Hz. Each AM frequency was combined with each CF to yield overall 4 compound sounds (800 ms duration; 10 ms linear fading at on and offset): [left ear: 42 Hz AM, 1300 Hz CF; right ear: 19 Hz AM, 500 Hz CF], [left ear: 42 Hz AM, 500 Hz CF; right ear: 19 Hz AM, 1300 Hz CF], [left ear: 19 Hz AM, 1300 Hz CF; right ear: 42 Hz AM, 500 Hz CF], and [left ear: 19 Hz AM, 500 Hz CF; right ear: 42 Hz AM, 1300 Hz CF]. The 4 possible sounds were created in Matlab, and the sequence of presentation within a block was predetermined via lists generated in R (<http://www.r-project.org/>). The sequence was pseudorandomized in a sense that each sound occurred equally often within a block (i.e. 28 times; see below); however, apart from this restriction the sequence was randomized. This means that, within 1 block, the CF presented to 1 ear altered in a pseudorandom fashion in order to avoid that potential attentional effects on a behavioral as well as neurophysiological level are confounded by a rigid relationship between ear and CF. Before creating the compound sounds, each separate sound (e.g. left ear: 42 Hz AM, 500 Hz CF) was matched to equal subjective loudness to a 1000 Hz calibration sound, which was previously set to 50 dB SL. Sounds were delivered via air conducting tubes with ear inserts (Ety motic Research, IL, USA) in the MEG shielded room.

The basic setup of each trial is shown in Figure 1. Each trial began with a brief (100 ms) visual warning stimulus that indicated the beginning of the trial. Thirty milliseconds after offset of the warning stimulus, a brief cue sound (50 ms; 750 Hz) was presented either to the left or the right ear. Following a variable interstimulus interval (700, 800, or 900 ms), the compound stimulus containing the target and distractor AM sound was presented. To be able to analyze the posttarget without artifacts caused by the button press, participants were requested to indicate the side on which they perceived the target AM following sound offset. The participants were not specifically instructed to pay attention to the preceding cue (i.e. they were told to focus on the ear on which they perceived the target sound), but were told prior to the beginning of the actual experiment that depending on the block (see below), the cue could either indicate the probable location of the target or be entirely unpredictable. They were also asked to blink in a 1.5 s interval after their response, so that relevant periods of the trial were generally not contaminated by blink artifacts. The entire experiment consisted of 6 blocks with 112 trials each. Each block belonged to 1 of the 2 conditions, presented in an alternating manner and counterbalanced across subjects: In 1 condition (“uninformative”), the location cue sound that preceded the target (Fig. 1) stood in random relation to the

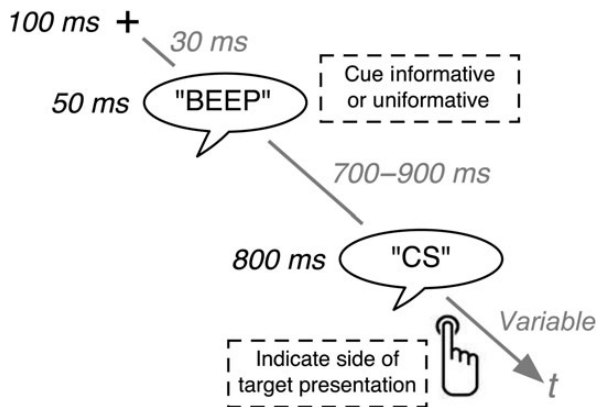


Figure 1. Sample trial outline. A brief cue presented to either the ear was followed by a compound sound (CS) in which differently amplitude modulated sounds were presented to the left and right ears, respectively. The task of the participant was to indicate on which ear the sound with the faster (42 vs. 19 Hz) amplitude modulation was presented via button press. Conditions differed with regard to the cue, which was valid in 75% in one (informative) condition and 50% in the other one (uninformative).

location of the target (50% on the same ear). Contrary to that, in another condition (“informative”), the ear at which the cue was presented was likely to be also the side of the target (75% correspondence). We deliberately chose not to use 100% valid cues in the informative condition for 2 reasons: First, we attempted to make the task more challenging for the participant forcing him/her to pay close attention to the compound sound. Secondly, next to showing a behavioral advantage for congruent cue/target pairs in the informative condition when compared with the uninformative condition, we also wanted to assess potential disadvantages induced by an invalid cue in the informative condition. At the beginning of each block, participants were informed about the condition via visual presentation of the word “informative” or “uninformative” on the screen. Conditions were presented in an alternating manner (i.e. A B A B A B), with the initial condition switching between each successive participant (i.e. ~half of the participants started with the “informative” condition). Before the beginning of the experiment in the MEG, each participant practiced approximately 10 min with a reduced version of the experiment, that is, without cue but with a visual feedback about the correctness of their response. This was to ensure that participants were well capable of differentiating the sounds and to detect the targets. The entire experimental procedure was controlled using Psyscope X, an open source software to design and run psychological experiments (Cohen et al. 1993; <http://psy.ck.sissa.it/>).

Data Acquisition and Analysis

Magnetoencephalographic data (480 Hz sampling rate) were recorded continuously using a 275 sensor whole head axial gradiometer system (CTF Omega, VSM MedTech, Canada) kept in a magnetically shielded room. Head positions of the individuals relative to the MEG sensors were controlled continuously within a block using 3 coils placed at 3 fiducial points (nasion, left and right preauricular points). Head movements did not exceed 1.5 cm within and between blocks.

Epochs of 2 s pre- and 2 s poststimulus were extracted from the continuous data stream around the acoustic cues and compound sounds. To remove direct current offset, data were detrended by subtracting the mean amplitude of each epoch from all sampling points within the epoch. Due to the reduced number of epochs in which target and cue locations were incongruent during the informative condition, only epochs were considered where target and cue sides were congruent. Epochs were visually inspected for artifacts (critical time window 0.5–0.8 s relative to the cue/target onset), and contaminated epochs were excluded. Due to the break following each trial, participants were comfortably able to blink, leaving the period of interest mostly unaffected (maximum rejection of 10% of trials). To assure that our results are not confounded by any imbalance in trial numbers, within one

participant the amount of trials was equalized for all cue and target conditions.

Following preprocessing spectral estimation (Fourier transformation) was performed on Hanning tapered time windows from 0.5 to 1 s (in steps of 0.0021 s) relative to the stimulus onset (cue or target, respectively). The length of the time windows was frequency dependent (5 cycles of the respective frequency), and spectral power was calculated from 1 to 35 Hz in steps of 1 Hz. Cue related neuronal reactivity following cue and target presentation was then estimated by normalizing the time frequency maps using the average power in the 0.5 to 0.23 s time window prior to cue presentation (Pow_{base}), which was subtracted from the cue/target locked time frequency representation (Pow_{active}). Finally, this difference was then normalized by the respective baseline power estimation (i.e.: $(Pow_{active} - Pow_{base})/Pow_{base}$), thus yielding relative changes with a value of zero indicating no change with respect to baseline. An exploratory look at target locked time frequency maps for each condition separately suggested strong modulations in the alpha to beta bands at temporal sensors also already at pretarget intervals (see Fig. 2; note that also target locked activity was normalized using a pre cue period). Due to the main interest of this study in attentional alpha activity modulations as outlined in Introduction, the rest of the spectral analysis focused exclusively on this frequency band (here defined broadly as 5–15 Hz). To assess the attentional effect statistically, a contrast was devised which putatively controls for trivial physical differences between the left versus right stimulation condition and processes related to presenting the conditions as blocks (e.g. overall greater but ear unspecific attention to cues in the informative condition). This was achieved by subtracting within one side of stimulation each individual time frequency representations of uninformative from informative (i.e. informative [left cue/target] – uninformative [left cue/target] and informative [right cue/target] – uninformative [right cue/target]), leaving within each stimulation side the net effect of cue validity. Since this effect is hypothesized to be different depending on the cued ear, paired t tests were calculated between the right and left ear presentation (positive valued thus indicating stronger alpha when the cue/target was presented to the right ear). Note that nonspecific processes associated with presenting conditions in blocks would not show up in this interaction measure, since they can be assumed to be identical with regard to cued ear. To first secure the overall cueing effect and gaining an insight into its time course (tested between 0.4–0.7 s relative to cue onset and 0.3–0.8 relative to target onset), power was averaged over the aforementioned frequency range, and a nonparametric cluster based permutation test was performed (Maris and Oostenveld 2007). In brief, this test first calculates paired t tests for each time point, which are then thresholded at $P < 0.05$. The sum within each coherent spatiotemporal cluster (T_{sum}) is retained, and the procedure is repeated 1000 times on shuffled data in which the condition assignment within each individual swapped randomly. On each permutation, the maximum T_{sum} is retained yielding a distribution of 1000 T_{max} values. From this distribution, the cluster probability of each empirically observed T_{sum} can be derived. Clusters are labeled as significant with a P value of ≤ 0.05 . This cluster level analysis revealed a trend level effect in the pretarget as well as a significant effect in the posttarget period, which we then followed up by averaging over the aforementioned time period and by repeating the analysis without correction for multiple comparisons. The intention of this follow up analysis was to obtain a data driven indicator at which frequency the effects were most pronounced (11 Hz; data not shown), which was later used to guide source analysis. Furthermore, for a sensor at which the effect was most pronounced (MRT13), power values at 11 Hz were extracted for each individual and a 2×2 repeated measures analysis of variance (ANOVA) with factors side \times cue validity was performed for both time intervals and followed up by a planned contrast between informative and uninformative for each cue/target side. The purpose of this was to assess whether effects are driven by a synchronization within one condition, desynchronization in the other, or by both.

To estimate probable brain regions driving the observed differences, we utilized the well established frequency domain adaptive spatial technique of dynamical imaging of coherent sources (DICSs, Gross et al. 2001). For each participant, an anatomically realistic

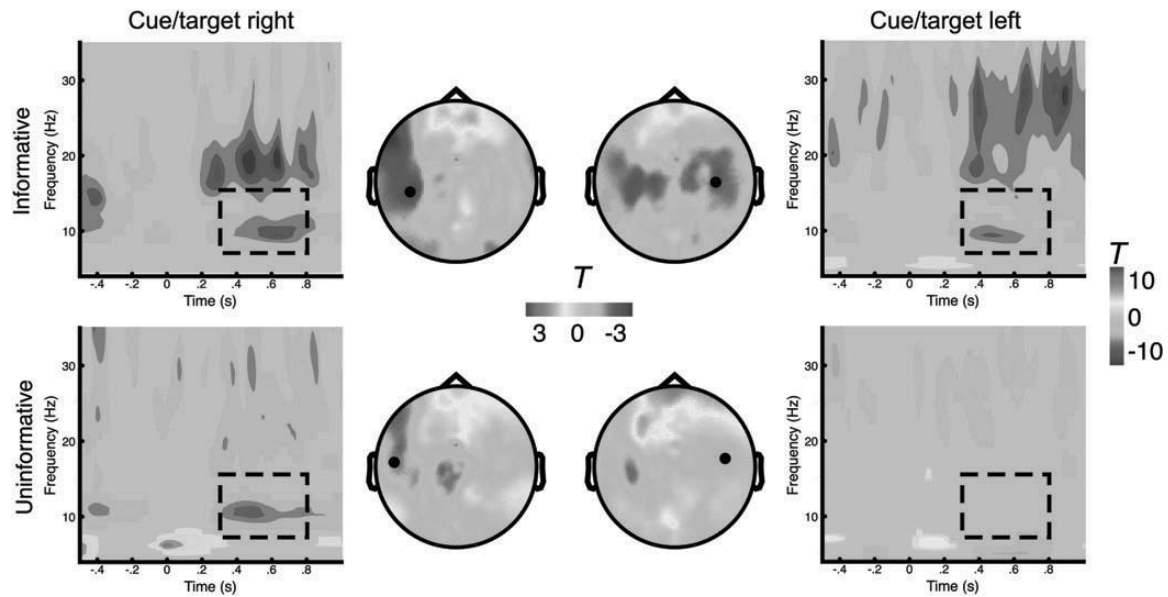


Figure 2. Sensor level desynchronization patterns in a period surrounding the target stimulus (target onset at 0 s). The upper panel summarizes sensor level oscillatory dynamics for the informative, the lower panel for the uninformative condition. The left part of the figure depicts these results for right ear stimulation, whereas the right panel shows the results for left ear stimulation. Sensor level topographies show statistical changes relative to the precue baseline for a 300–800 ms time and 6–15 Hz frequency window. Representative time–frequency plots are shown for representative sensors (starting from top panel left in a clockwise direction: M1T24, M1T42, M1T13, M1T22). All plots clearly evidence a target-related decrease of alpha-like activity over temporal sensors. Interestingly, but beyond the scope of the current study, a decrease in the beta band can also be observed.

headmodel was generated based on individual headshapes (Nolte 2003), and leadfields were calculated for grid points separated by 1 cm. Together, with the sensor level cross spectral density matrix, calculated using the multitaper method with a target frequency of $11 (\pm 3)$ Hz, this allowed the estimation of spatial filters that optimally passes information for each grid point while attenuating influences from other regions. Besides of the temporal window of the posttarget cluster level effect (0.2–0.655 s relative to target onset; matching 5 cycles of the frequency of interest), the analysis was also performed on a pretarget interval (0.245–0.7 s relative to cue onset), which was according to the nonparametric permutation test significant at trend level only (see Results for justification). Furthermore, a 455 ms period (0.655–0.2 s) prior to cue onset was chosen as baseline time window. It is important to emphasize that baseline and (pre- or post-) target-related activity were also concatenated in order to derive a common spatial filter. Source level data were baseline normalized analogously to the sensor level data and then interpolated onto “pseudo” individual magnetic resonance images (MRIs) that were created based on an affine transformation of the “headshape” of an MNI template and the individually gained headshape points. This transformation matrix was then applied to the template MRI. Source analysis results were normalized onto a common MNI template brain for later group statistics. The source level statistic consisted first in the calculation of the analogous sensor level contrast that putatively accounts for mere differences of physical stimulation between the left and right ear stimulation (see above). This contrast values for right versus left ear stimulation were then entered into a voxelwise t test, and results were subsequently visualized at an uncorrected $P < 0.05$. Furthermore for distinct regions of interest (ROIs) that drove the interaction effect (rSTG and rIPS; see Introduction), a time-resolved DICS was performed in order to obtain a clearer picture of the pre- and posttarget alpha dynamics at the source level. For this purpose, DICS was calculated from 0.65 to 0.9 s with regard to cue/target onset in steps of 0.05 s. Settings of the DICS were identical as described above. Data were normalized as described above using a 0.65 to 0.25 s precue period. Analogous to the sensor level statistics, a 2×2 repeated measures ANOVA with factors side \times cue validity was performed (at 500 ms postcue/target, i.e. an effective time window of ~ 0.272 to 0.723 s) and followed up by a planned contrast between informative and

uninformative for each cue/target side. Moreover, the purpose of this was to assess whether effects are driven by a synchronization within one condition, desynchronization in the other, or by both.

Apart of mere power effects, a further aim of the study was to scrutinize the network dynamics that may be involved in mediating the present auditory spatial attention effects in the cue–target (i.e. anticipation) period. Based on the DICS effects and the current literature on attentionally modulated alpha (Capotosto et al. 2009), we defined 2 ROIs: 1) The right STG (rSTG) and 2) right IPS. For this analysis, spatial filters were first created for these 2 regions on 5–15 Hz band-pass filtered pretarget data (including a 0.65 to 0.9 s period for the filter calculation) using the LCMV beamformer (van Veen et al. 1997). These spatial filters were subsequently multiplied with the sensor level time series in order to derive pretarget source waveforms for each of the ROIs. Finally, partial directed coherence (PDC; Baccalá and Sameshima 2001) was calculated between these ROIs, which was derived from multivariate autoregressive models fitted separately for each condition. To obtain a time-resolved measurement, PDC calculation was performed on blocks of 0.4 s, starting from 0.65 to 1 s in steps of 0.05 s. The model order was set to 15, conforming thus with the analysis approach by Supp et al. (2007). Normalization as described above was performed using a period of 0.65 to 0.25 s, thus making statements possible whether directional coupling increased or decreased following the cue in one of the conditions depending of the cued ear. In general terms, PDC is a computational implementation of Granger causality in the frequency domain, thus yielding a directional measure. To estimate task-related coupling changes (pre- and post-), target-related PDC was normalized by the respective (precue) baseline estimate in a manner analogous to the power effects. To assess the effect statistically, the interaction sensitive contrast (see above) was performed globally on 5–15 Hz, which implied 2 time periods with differential effects with regard to coupling direction. This descriptive analysis was followed up by identifying the spectrally resolved maximum t values for the early and late periods and repeated measures ANOVA as described above.

All offline treatment of MEG data was carried out using functions supplied by the fieldtrip toolbox (<http://fieldtrip.fcdonders.nl/>; Oostenveld et al. 2011) or in-house functions that build on top of this toolbox.

Results

In the current experiment, data from a cued auditory spatial attention task (Weisz, Hartmann, et al. 2011; Weisz, Lecaigard, et al. 2011) were reanalyzed with respect to oscillatory activity in the alpha band on both the sensor as well as source level. The main goal of the study was to investigate whether auditory alpha activity is modulated by the validity of a preceding acoustic cue. In a second step, we were interested to what extent effective connectivity is altered between relevant auditory and nonauditory nodes within the context of auditory spatial attention during the cue target period. Prior to the description of the effects, a brief summary of the behavioral data as well as general neuromagnetic emergence pattern will be given.

Behavioral Data

The behavioral data have already been described in detail in the previous companion paper (Weisz, Hartmann, et al. 2011; Weisz, Lecaigard, et al. 2011) on the auditory steady state response and will be only briefly summarized: Task performance was on average high (~80% accuracy), even though we observed a high interindividual variability (53–92% accuracy). Congruency between cue target was statistically significant ($F_{1,10} = 9.03$, $P = 0.01$) as well as the interaction between congruency and cue validity ($F_{1,10} = 5.01$, $P = 0.05$). Overall performance was better when cue and target were presented to the same ear as opposed to the case when they were presented to different ears (84% vs. 75%). However, this effect was largely reflected by the valid (i.e. informative) condition (87% vs. 69%; $t_{10} = 2.64$, $P = 0.02$), whereas in the invalid (i.e. uninformative) condition the congruency effect was absent (81% vs. 80%; $t_{10} = 1.79$, $P > 0.05$). Similar patterns could be observed for the reaction times (RTs) (congruency effect: $F_{1,10} = 6.36$, $P = 0.03$; congruency \times cue validity effect: $F_{1,10} = 6.93$, $P = 0.02$). Overall, RTs were faster when cue and target were congruent (836 vs. 914 ms), but again this effect was mainly restricted to the informative condition (821 vs. 979 ms; $t_{10} = -2.71$, $P = 0.02$), whereas the uninformative condition did not exhibit such a congruency effect (850 ms in both cases; $t_{10} = 0.02$, $P = 0.99$).

To summarize, the behavioral data indicate that our experimental manipulation was successful in inducing attentional modulations that depended on the information content (validity) of the cue. This was, in particular, pronounced as attentional costs (reduced accuracy and enhanced RTs) in case of incongruency only when the cue was informative.

Descriptive Alpha Desynchronization Pattern

Before describing the attentional effects in statistical terms below, this part will descriptively illustrate the sensor level oscillatory dynamics in a period preceding and following the target (Fig. 2). Overall, marked decreases (relative to precue baseline) of power are evident largely in the period following the actual target, even though power decreases are also evident at pre- as well as peristimulus intervals. The maximum decrease in the alpha range (displayed 6–15 Hz) can be observed over bilateral temporal sensors and appear to be descriptively larger in the informative (i.e. valid cue; upper panel) condition. It is noteworthy, however, that while the overall pattern between the 2 cueing conditions appears to be similar when auditory stimuli are presented to the right ear, pronounced differences in the sensor level patterns are seen

when the auditory stimuli are presented to the left, in which clear power decreases at bilateral sensors are seen when the cue was informative but less evident when it was uninformative. It should be also mentioned that the “alpha” desynchronization at right temporal sensors (see lower right in Fig. 2) appeared at a somewhat lower frequency (~6–8 Hz; still in the “tau” range as shown by Lehtelä et al. 1997). Furthermore, mentionable but beyond the scope of the present study are the strong beta band reductions that are consistently seen on the identical sensors as those of the alpha band decreases.

Even though the patterns described are suggestive of an attentional modulation in particular over right hemispheric regions, statistical assessment was performed on contrasts that reduced the influences of different ears of stimulation as well as preparation of motor responses. This will be treated in the subsequent section followed up by an analysis of the major effects on the level of generators.

Alpha Attention Effects: Sensor Level

To assess statistical effects of attentional modulations paired *t* tests were calculated between contrasts that effectively eliminated the influence of physically presenting the stimulus to the left or right ear (see Materials and Methods). Nonparametric statistical analysis revealed a cluster at trend level ($P = 0.07$) in the 8–14 Hz frequency range in the pretarget period, covering approximately a 500–700 ms postcue onset time window (see Fig. 3A,B, left panel). In the posttarget period, a significant cluster ($P = 0.03$) emerged, beginning approximately at 280 ms and extending throughout the entire target period even though the effect being most pronounced at ~400 ms posttarget onset. The topography in this frequency range for this effect was overall strongly lateralized to the right for both time periods and covered in particular temporal sensors in the pretarget period, whereas in the posttarget period a shift from temporal to central/parietal sensors can be observed. The spectral profile of the statistical values indicated the effect to be maximal at ~11 Hz in the pretarget period and ~12.5 Hz in the posttarget period (Fig. 3B). For both time ranges the effects are thus in the upper alpha frequency range and not directly overlapping with the “classical” tau rhythm (Lehtelä et al. 1997). It is worth noting that the effects reported at the pre- (including peritarget) interval are at trend level only. Due to the strong topographical overlap of the pretarget effect with the later cluster level effect (early parts of the posttarget effect) and the specific a priori hypothesis that auditory cortical alpha activity is already modulated by cue validity in the pretarget period (see Introduction), we decided to follow up the pretarget effect on a sensor as well as source level (see below).

For the relevant periods in the pre- and posttarget intervals (520–700 ms postcue and 270–490 ms relative to target onset), individual values for each condition were extracted at 11 or 12.5 Hz, respectively, at a representative right temporal sensor (MRT13) exhibiting a strong effect. Repeated measures ANOVAs confirmed the cue validity \times side interaction (pretarget: $F_{1,10} = 13$, $P = 0.004$; posttarget: $F_{1,10} = 22.95$, $P = 0.0007$) as implied by the previous contrast driven approach. Using planned contrast (paired *t* tests contrasting informative vs. uninformative within the left- or right-sided cue/target presentation), we were able to follow up which factors contributed mostly to this interaction pattern (Fig. 3C). In the pretarget interval (see Fig. 3C, left panel), the contrast for cue validity was

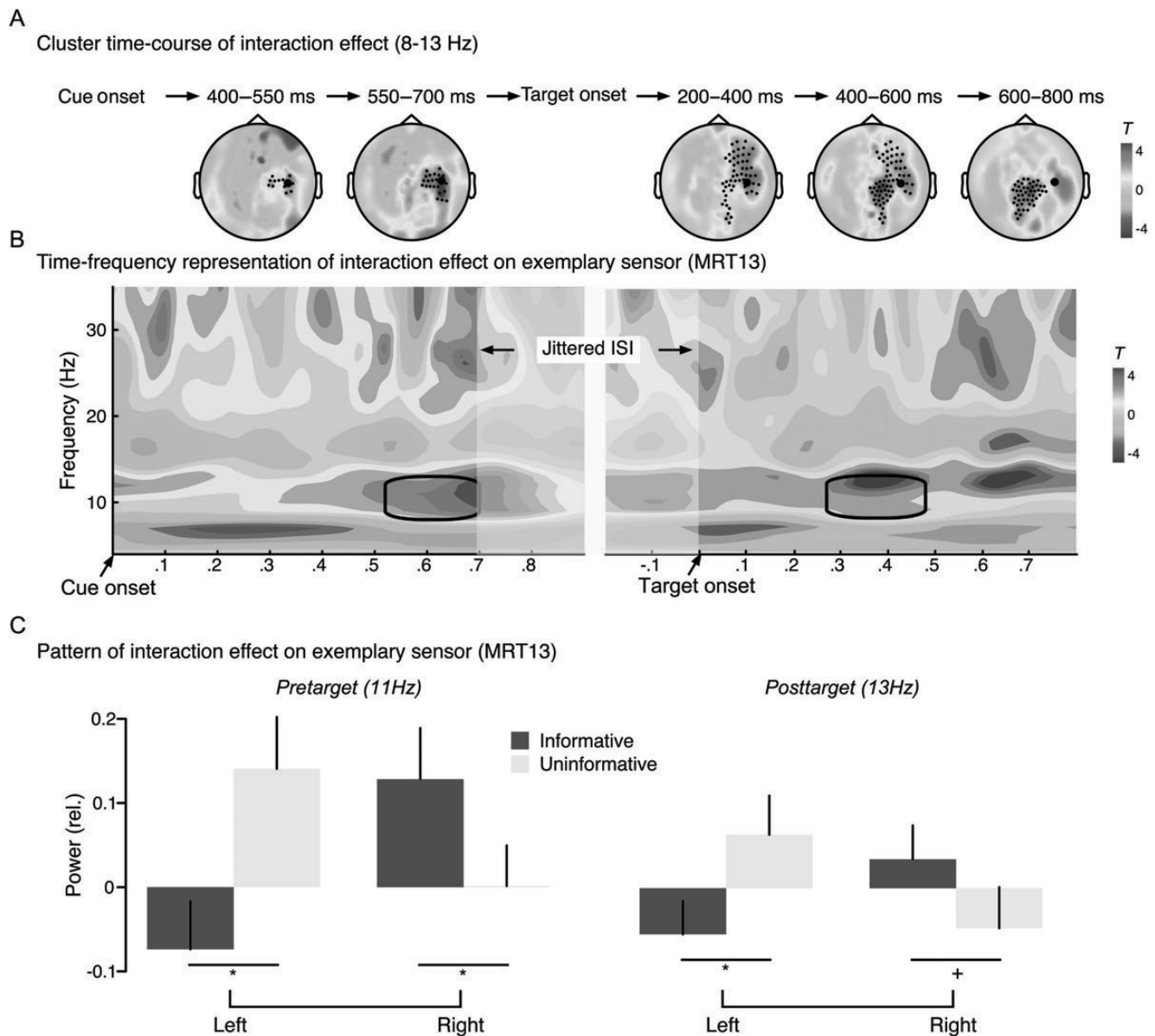


Figure 3. Sensor level patterns of attentional modulations of alpha activity, calculated via contrasting informative – uninformative for left versus right ear stimulation. The applied contrast excluded mere physical differences of stimulation side could (see Materials and Methods), thus revealing cue side \times validity effects. (A) For a frequency band (8–13 Hz) centered around alpha activity, effects could be observed mainly at right temporal sensors in the pretarget period, extending to frontal and particularly parietal sensors at later intervals. (B) Time frequency representation of statistical effect for a representative sensor from the sensor cluster (MRT13) indicates that the alpha effect commences \sim 400 ms postcue onset and reaches its maximum at \sim 700 ms, that is, the shortest possible cue–target latency. The effect is interrupted around sound onset, thus reflecting the impact of the evoked response on the overall alpha pattern (see in particular right panel). Also note that while, in the pretarget period, the maximum effect is \sim 11 Hz, it is slightly higher in the posttarget interval (13 Hz). (C) Separate planned contrasts indicate that, at the pretarget interval, the effect is mainly driven by alpha increase when the preceding cue is informative and presented to the right ear and the reversed pattern when an informative cue is presented to the left ear (left panel). In the posttarget period, a similar pattern could be observed, however, to an overall weaker extent, for example, only reaching the trend level for right ear stimulation (*: $P \leq 0.05$; +: $P \leq 0.1$).

significant for both cued ears; however, in a reversed sense: that is, whereas alpha activity was relatively “decreased” following an informative cue presented to the left ear ($t_{10} = -2.78$, $P = 0.02$), an increase was observed for informative cues presented to the right ear ($t_{10} = 2.25$, $P = 0.05$). This pattern was very similar in the posttarget interval even though less pronounced (see Fig. 3C, right panel; note, however, that MRT13 may not be an optimal choice due to the greater spatial dynamics in the posttarget period): that is, following a target presented to the left ear, a relative decrease was present when the preceding cue was informative ($t_{10} = -2.64$, $P = 0.02$)

and on a trend level vice versa for the right ear ($t_{10} = 2.11$, $P = 0.06$). To summarize, cue validity impacted alpha activity in a differential manner at right temporal sensors, while left temporal sensors did not exhibit a significant modulation. Most remarkably, a relative alpha increase could be observed at these sensors when acoustic stimulation was ipsilateral and the preceding cue was informative when compared with the uninformative case and vice versa for the case when acoustic stimulation was on the contralateral (i.e. left) ear. The next part will attempt to identify the main generators responsible for these sensor level effects.

Alpha Attention Effects: Source Level

To derive probable generators contributing to the sensor level effect, we employed a frequency domain beamformer (see Materials and Methods) and performed the analogous contrast as described for the sensor data in the previous section. The analysis was applied to the pre (0.245–0.7 s postcue onset) and posttarget (0.2–0.655 s posttarget onset) period separately. Common to both periods was a strong lateralization of alpha (8–14 Hz; centered around maximum sensor level effect) effects to the right hemisphere, as could be expected from the sensor level data. However, as also suggested by the sensor level data, the dominant focus of the effect appears to change from pre to posttarget period (Fig. 4): while in the pretarget period the strongest effect was observable at rSTG (Brodmann area [BA] 21/22; see Fig. 4, upper panel left), the effect was most pronounced at the right inferior parietal lobe (rIPL; BA 40; see Fig. 4, upper panel right) in the posttarget period. Note that besides of these 2 regions, other right lateralized areas also exhibited an interaction effect (as implied by our contrast) in particular in the posttarget period, for example, inferior temporal gyrus, inferior frontal gyrus, middle frontal gyrus, anterior cingulate, and lingual gyrus. However, for the sake of a parsimonious description, subsequent post hoc analysis as well as connectivity analysis (see below) will focus on rSTG and rIPL (latter region in the vicinity of parietal effects described by Capotosto et al. 2009) as 2 ROIs.

For both ROIs, a time resolved DICS was computed (baseline normalized with a precue period; see Materials and Methods) in order to capture the temporal dynamics of the effect at these sources. For the rSTG in the pretarget period, a clear desynchronization of alpha power \sim 300 to 600 ms postcue onset can be observed when a preceding informative cue was presented to the right left ear when compared with the analogous cue presented in an uninformative context (see Fig. 4; middle left panel). The pattern was reversed in case the cue was presented to the right ear, that is, alpha power was relatively increased in rSTG when the preceding cue was informative. An interaction plot at 500 ms postcue onset (i.e. effectively integrating a time period between 0.272 and 0.727 s) is displayed as inset (cue validity \times side: $F_{1,10} = 8.98$, $P = 0.01$): This post hoc analysis indicates that the pretarget effect is driven in particular by a relative increase of alpha power in rSTG when the preceding cue was presented to the right ear and informative when compared with the same cue in an uninformative context (informative vs. uninformative: $t_{10} = 2.55$, $P = 0.02$). An analogous contrast for left ear stimulation yielded a trend level effect in the opposite direction (informative vs. uninformative: $t_{10} = -1.96$, $P = 0.07$). With regard to the pretarget period, as expected from the other analysis no interaction effect was observed for the rIPL (see Fig. 4; bottom left panel). However, at the same time period for which we report the interaction for rSTG, a main effect for cue can be found for rIPL ($F_{1,10} = 4.82$, $P = 0.05$): This effect is driven by the fact that alpha power was overall relatively reduced at rIPL when the preceding cue was informative, thereby likely reflecting laterality (cue side) unspecific attentional effects introduced by blocking of conditions.

In the posttarget period, for the rSTG (see Fig. 4; middle right panel), the time resolved DICS suggests a relatively reduced alpha power when a preceding informative cue was

presented to the left ear, starting already at target onset and extending to \sim 600 ms posttarget onset. However, this effect was not sufficiently strong to drive a clear interaction effect, and also a post hoc analysis (see inset figure) at 500 ms posttarget onset does not indicate the presence of strong effects at rSTG in the posttarget period. This was different for the rIPL for which a similar despite less pronounced mirror image pattern could be found as for the rSTG in the pretarget period (see Fig. 4; bottom right panel; $F_{1,10} = 8.60$, $P = 0.02$). A post hoc analysis (see inset figure) at 500 ms posttarget indicates that this effect is largely driven by left cue presentation with relatively decreased alpha power when the preceding cue was informative (informative vs. uninformative: $t_{10} = -1.88$, $P = 0.08$).

To summarize this part, several cortical areas turned out to be sensitive in the alpha band for the cue validity manipulation depending on the laterality of the acoustic presentation. These regions included among others mainly right auditory and parietal areas. Furthermore, the analysis revealed a different timing of effects in these 2 regions: Whereas modulation of alpha power by spatial attention appeared to be more pronounced in auditory cortex in the pretarget period, the same was true for rIPL in the posttarget period. However, a global difference in alpha power was also found for rIPL in the pretarget period, suggesting an overall greater engagement of this region in case of an informative cue. The subsequent section will address the issue of whether and how activity in rSTG could be top down modulated by rIPL.

Attention Induced Connectivity Changes

Due to the distributed nature of the alpha power effects, as well as previous literature, suggesting for example, the right IPS to play an important role in spatial processing in the visual as well as in the auditory modality (Bremmer et al. 2001; Carrasco et al. 2004; Capotosto et al. 2009), we analyzed time resolved connectivity between ROIs using PDC in the pretarget, that is, preparatory period (see Materials and Methods). Coordinates of seeds were determined in a data driven manner from the source power effects described above (i.e. rSTG and rIPL; see Fig. 5). Figure 5A shows the contrast of the cue validity effect (informative vs. uninformative) between right and left ear presentation, with negative values indicating relatively enhanced PDC for left informative cues and/or relatively reduced PDC for right informative cues. As can be seen from the global PDC modulations in the 5–15 Hz range (upper panel), 2 periods can be distinguished in which the dominant directionality of information flow appears to reverse: Whereas the contrast appears relatively more negative (see above) for rIPL \rightarrow rSTG at an earlier interval of the pretarget period (\sim 0–400 ms), this appears to be the case for rSTG \rightarrow rIPL in an interval ultimately preceding the target (\sim 500–750 ms). To obtain a clearer picture whether these effects are driven spectrally by a global modulation or whether specific frequencies are involved, we investigated the spectral profiles of the contrast at an early (300 ms) and late (650 ms) time points (see Fig. 5A, lower panel). Interestingly, while the early (rIPL \rightarrow rSTG) PDC effect appears to be most pronounced at 14 Hz, the later (rSTG \rightarrow rIPL) PDC effect was strongest at 11 Hz.

Analogous to the previously described power effects, this cue side \times validity interaction sensitive contrast does not clarify by which processes the effect is driven. For this purpose, post hoc tests were performed at the aforementioned time and

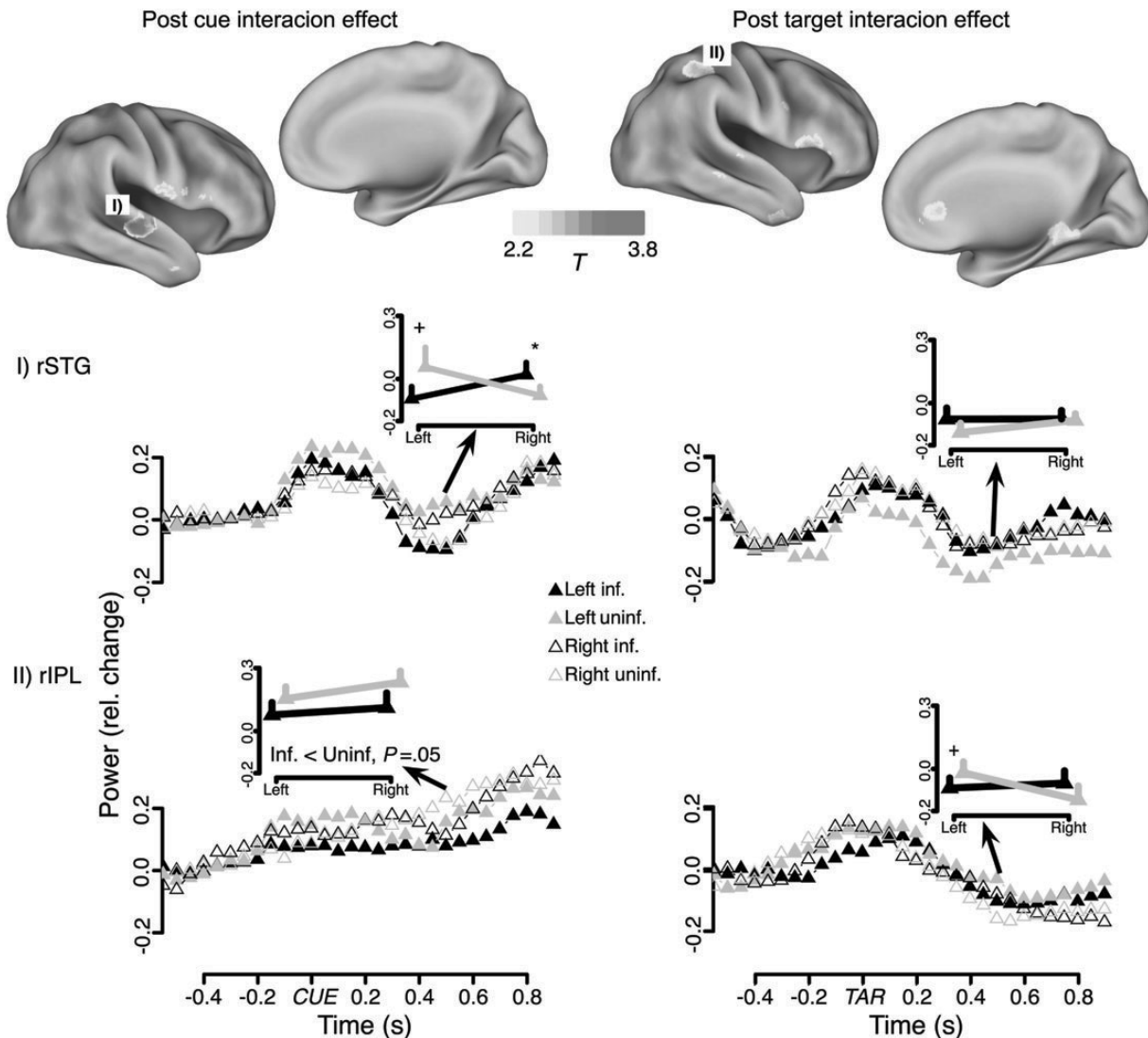


Figure 4. Source level patterns of attentional modulations of alpha activity, calculated via identical contrast as on sensor level (Fig. 3). Effects were to a great extent lateralized to the right hemisphere no matter whether for the pre- or posttarget period (upper panel). In particular, in the pretarget period, the effect was mainly confined to rSTG while becoming more distributed in the posttarget period. Time resolved DICS was performed for 2 ROIs (rSTG: middle panel; rIPL: lower panel) in order to visualize the temporal alpha band dynamics at these locations. Interaction plots are plotted for 500 ms postsound onset (cue or target, respectively). Importantly, this analysis shows in the pretarget period that the effect at rSTG (middle left panel) is driven by a relative increase of alpha power following a right informative cue and (at trend level) the reversed pattern when an informative cue was presented to the left ear (*: $P \leq 0.05$; +: $P \leq 0.1$).

frequency points (Fig. 5B). This analysis confirms for the early time window the presence of an cue validity \times side interaction for the rIPL \rightarrow rSTG PDC ($F_{1,10} = 18.83$, $P = 0.001$). The effect was caused in particular by a strongly increased rIPL \rightarrow rSTG coupling when an informative cue was presented to the left ear (informative vs. uninformative: $t_{10} = 3.03$, $P = 0.01$; see Fig. 5B, upper panel). Interestingly, a trend level effect was seen for right ear presentation, with a relatively decreased rIPL \rightarrow rSTG coupling when the cue was informative (informative vs. uninformative: $t_{10} = -1.78$, $P = 0.10$). For rSTG \rightarrow rIPL PDC, a trend level effect was present at the early interval for left cue presentation with relatively increased coupling when the cue was informative; however, the overall cue validity \times side interaction was not significant ($F_{1,10} = 1.54$, $P = 0.24$). Regarding the later time interval close to the actual target onset, the overall cue validity \times side interaction was weaker than for the early time interval and more pronounced for rSTG \rightarrow rIPL ($F_{1,10} = 3.06$, $P = 0.11$) than for rIPL \rightarrow rSTG ($F_{1,10} = 0.06$, $P = 0.82$). For the

rSTG \rightarrow rIPL PDC (Fig. 5B, lower panel), coupling was in particular increased when an informative cue was presented to the left ear (informative vs. uninformative: $t_{10} = 2.38$, $P = 0.03$).

Discussion

In the present study, we investigated alpha band dynamics within and beyond auditory cortical regions within an auditory spatial attention task. Attention was manipulated via validity of an acoustic cue, which was either informative or uninformative about the probable ear of target presentation. In a previous paper (Weisz, Hartmann, et al. 2011; Weisz, Lecaigard, et al. 2011) on the same dataset, we were able to demonstrate successfully the attentional modulation on a behavioral level as well as for the aSSR. Interestingly, the effect for this target related evoked response strongly indicated that the main effect of cue validity was a “downregulation of excitability” in the right auditory cortex, when the preceding cue was

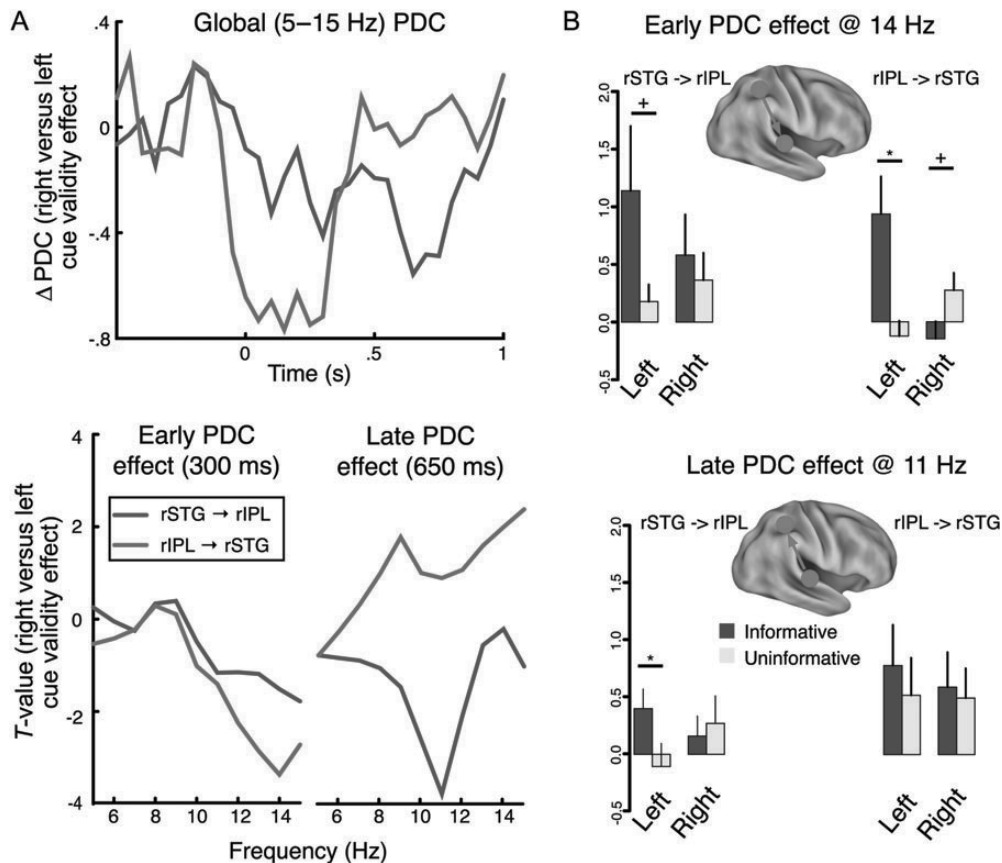


Figure 5. Source level PDC effects in the pretarget period between rSTG and rIPL. (A) Display of time resolved broadband (5–15 Hz; upper panel) contrast for right versus left ear cue validity (i.e. informative vs. uninformative) effect. Negative values indicate relatively stronger PDC for informative left cues, relatively reduced PDC for informative right cues or both (vice versa for positive values). Effects are color coded differentially for coupling directionality (blue: rSTG → rIPL; green: rIPL → rSTG). The figure indicates that while early latency effects are dominant for the “top down” (rIPL → rSTG) connection, later effects are dominant for the “bottom up” connection (rSTG → rIPL). Spectra of *T* values for both time windows (bottom panel) indicate that while the early “top down” effect is largest at 14 Hz, the late “bottom up” effect is most pronounced at 11 Hz. (B) Post hoc analysis (*: $P \leq 0.05$; +: $P \leq 0.1$) to elucidate which factors mainly drive the interaction effect, showing in particular for the early “top down” effect (upper panel) that an informative left cue leads to a relatively increased and informative right cues to a relatively decreased rIPL → rSTG coupling. Importantly, these coupling effects appear to precede local synchronization effects at rSTG. The later “bottom up” effect is mainly driven by an enhanced rIPL → rSTG coupling following left informative cues.

informative and presented to the ipsilateral ear. An increasing amount of studies (for review see Jensen and Mazaheri 2010) indicate attentionally mediated regulation of cortical excitability in sensory regions to be reflected in alpha power. This view has been mainly built on findings in the visual domain, whereas the auditory modality has been far less studied (see below for the relationship of present findings to previous studies) and the presence of a “cognitive” auditory alpha rhythm has even been controversial (Niedermeyer 1999) or doubts have been raised about the feasibility to study it noninvasively (Gomez Ramirez et al. 2011). Our present study contributes among other things 2 important findings to this ongoing discussion: (1) In the pretarget period, informative cues lead to a differential modulation of right auditory cortical alpha power composed of (a) a relative reduction in power when the upcoming target is expected on the (contralateral) left ear and (b) a relative “enhancement” when the cue indicated an upcoming target on the ipsilateral ear. The latter finding nicely supports conclusions gained from our previous aSSR study (Weisz, Hartmann, et al. 2011; Weisz, Lecaigard, et al. 2011) that expecting a right sided target may lead to an anticipatory downregulation of excitability in the ipsilateral auditory cortex. Note that while cue validity related effects were also seen in right nonauditory regions, the auditory

cortex effect is clearly separable in terms of space but importantly also in time, with nonauditory alpha effects occurring mainly posttarget onset (see also below). (2) Despite alpha power effects occurring later in rIPS than in rSTG, effective connectivity analysis in the pretarget time window shows that modulation of information flow from rIPS to rSTG at 14 Hz is affected prior to the auditory cortical alpha effects. This early connectivity effect (~first 300 ms following cue onset) is to some extent a mirror image of the upcoming auditory cortical alpha power effect, that is, with a relative upregulation of rIPL → rSTG connectivity following an informative left cue and a relative (trend level) downregulation of connectivity following an informative right cue. In a later time period (~400 ms to target onset), the experimental manipulation mainly affects rSTG → rIPL connectivity, with the effect being mainly driven by a relative upregulation of connection strength following an informative left cue. This finding corroborates recent ideas that local synchronizations in the alpha band may reflect changes in the level to which affected regions are integrated into a wider spread network (Jensen and Mazaheri 2010), but also extends these ideas by showing that attentionally mediated alpha power modulations are “preceded” by altered information flow from rIPL to rSTG. While (relative) increases of alpha in auditory cortex have been shown in a working memory task (van

Dijk et al. 2010) and also in auditory/intersensory attention tasks using valid cues (Gomez Ramirez et al. 2011; Müller and Weisz 2011), this is the first study to show the influence of cue validity on auditory cortical alpha activity. In the following some of the reported effects will be scrutinized in more detail.

As stated in Introduction, the finding of alpha modulations in the context of spatial attention task is not new and has been shown numerous times in particular in the visual domain (e.g. Worden et al. 2000; Thut et al. 2006). Furthermore, a recent study using brief trains of TMS to entrain brain rhythms in the visual cortex showed reduced visual target detection in the visual field contralateral to the stimulated site and facilitative effects in the ipsilateral hemifield selectively at alpha frequencies (Romei et al. 2010; see, however, Weisz et al. forthcoming for a mixed finding in the auditory modality). This lends a causal support for the idea that alpha rhythms functionally reflect inhibited states. Overall, attentionally mediated alpha power modulations are far less well established in the auditory domain, to date (for a study on auditory working memory, see van Dijk et al. 2010). Some EEG studies have employed auditory stimuli in intersensory attention tasks in which attention was cued either to the visual or auditory modality without any spatial component to the task (e.g. Foxe et al. 1998; Fu et al. 2001), with the main effect on a surface level being posterior alpha increases when attention was cued to the auditory modality. A convincing argument that these effects are indeed top down driven is the fact that the pattern of results is independent of the sensory modality in which the cue is presented. The common interpretation of this effect has been a top down mediated downregulation of excitability (disengagement) in task irrelevant visual brain regions. Similar posterior alpha increases have been also observed in other EEG studies when auditory targets were used in isolation, that is, without accompanying visual distracters, and attention was cued to a distinct ear, for example, Kerlin et al. (2010) using monaurally and binaurally presented speech stimuli or Banjerie et al. (2011) focusing on a cue target period in a more classical Posner style task. Especially, the latter study appears interesting within the present context, due to the overall similarity to the present study, despite using valid cues only. In the same experiment, Banjerie et al. also recorded data using visual targets and were able to show similar parietal effects across sensory modalities, yet with slightly differing foci. Based on these findings, the authors speculate about a supramodal role of parietal regions in regulating spatial attention. This general idea finds support in the present study in which alpha power and especially connectivity effects (see also below) could be identified involving right IPS. The overall failure of noninvasive EEG studies analyzed on a surface level to produce strong evidence for “auditory” alpha modulations that have recently lead to the doubts whether they can be investigated noninvasively (Gomez Ramirez et al. 2011; see Hartmann et al. 2012 for an EEG study). Using MEG, Müller and Weisz (2011) could show attentional modulations of alpha activity in auditory cortex in a paradigm similar to an EEG study by Fu et al. (2001), that is, using a visual cue prior to presentation of the auditory target (in the case of Fu et al.: an auditory cue and a visual target). Alpha increases in the cue target period were observed in particular when the preceding cue instructed the participant to monitor the right ipsilateral ear. Using ECoG, the existence of attentionally induced alpha enhancements in the right auditory cortex have been recently confirmed by Gomez Ramirez et al.

(2011; note, however, that the electrode grid was placed over the right hemisphere in both investigated patients, excluding comments about other regions or strong inferences about lateralization effects). Our data support the Müller and Weisz (2011) study that directed attention can lead to relative alpha enhancements in auditory cortex and at least in the context of spatial attention these effects are strongly lateralized to the right auditory cortex.

Motivated by the framework of Jensen and Mazaheri (2010), which states that local modulations of alpha power gate the information flow in functional brain networks, we also performed an effective connectivity analysis using PDC. In particular, an alpha increase would route information flow by transiently decoupling the putatively task irrelevant region expressing pronounced alpha activity (a prediction not directly tested in this study, likely requiring the application of graph theoretical measures). However, the framework remains to some extent unspecific with regard to the issue how these relevant alpha modulations are implemented in a top down manner. Even though our noninvasive results cannot offer a mechanistic explanation, they strongly point to a crucial role of the right IPS thus corroborating a recent rTMS study by Capotosto et al. (2009). In a visuospatial attention task, these authors were able to show that applying bursts of rTMS to diverse regions of the dorsal frontoparietal attention network (Corbetta and Shulman 2002) prior to cue onset disrupted alpha desynchronization in contralateral occipital regions. In the context of the present study, the interesting finding was that, when rTMS was applied to the right IPS, the posterior alpha effect was in fact composed of 2 parts that become pronounced in a contrast: (1) The normal anticipatory desynchronization pattern after sham stimulation and (2) a weak increase (synchronization) of alpha activity following real rTMS. Similarly, our present data also suggest a temporal sequence in the sense that firstly connectivity from parietal to auditory regions is modulated, with subsequent effects on auditory cortical alpha power: that is, increased rIPL → rSTG connectivity (following left informative cues) was followed by relative alpha decreases in rSTG and vice versa for decreased rIPL → rSTG connectivity. It is not entirely clear to what extent the effects in Capotosto et al. (2009) in the visual modality, and our findings are mediated by common connectivity principles, but it is tempting speculate based on the current data that one general mechanism contributing to attentionally mediated local alpha increases and decreases in putatively task relevant and irrelevant regions may be a preceding modulation input from the right parietal cortex to these respective brain regions, with decouplings leading to alpha increases. It is interesting to note that this top down connectivity effect in our study was mainly pronounced in the lower beta range, which supports recent notions claiming a central role of beta oscillations in mediating top down effects (e.g. Buschman and Miller 2007; for review see Siegel et al. 2012). Apart from the alpha power effect described above, this connectivity finding provides strong support for the idea that the right IPS may be a crucial supramodal region in allocating spatial attention. Unlike Capotosto et al., but also Müller and Weisz (2011), we did not find effects involving the FEFs. It has to be emphasized, however, that in the latter study the approach of investigating connectivity differed to some extent: Whereas in Müller and Weisz (2011), we used the right auditory cortex as seed region and testing functional connectivity via phase synchrony (Lachaux

et al. 2000) to all other voxels, in the present study, we applied PDC to a subset of ROIs that exhibited spatial attentional alpha power effects. Since the FEF was not identified in the first step, it was not included in the subsequent analysis. It is thus possible that slight differences in design and analysis of spatial attention experiments may emphasize different portions of the frontoparietal attention network with the local synchronization effects in sensory brain regions being, however, a fairly robust finding. More studies will be needed in future, that link alpha power effects to changes in connectivity patterns in order to shed more light on this issue and to perhaps disentangle the respective roles of the right IPS and FEF.

A notable result and conforming to our previous study (Müller and Weisz 2011) is the striking right hemispheric dominance of effects in the alpha band in the context of audiospatial attention. This dominance pattern was apparent not only for auditory regions, but also for higher level areas such as the IPS and the ACC. In the light of previous works, however, in the visual domain, this right hemispheric dominance pattern is not a surprising result. Previous works, for example by Corbetta and Shulman (2002) and Nobre et al. (1997), have shown left hemispheric involvement in attending the right hemifield, whereas the right hemisphere was involved in attending both hemifields. For sound localization, similar patterns have been reported for the auditory cortex (Zatorre and Penhune 2001; Spierer et al. 2009). Within the context of this spatial attention study, one could thus assume a default stronger attention toward left ear input, since information from this ear is processed by both auditory cortices (the attentional bias may be dependent on the attended feature; see e.g. the so called right ear advantage for verbal input; Kimura 1967). This assumption is conceptually close to the pseudoneglect phenomenon in the visual domain (Bowers and Heilman 1980; Orr and Nicholls 2005), even though we are not aware of comparable studies in the auditory modality. We hypothesize that if a relevant target is anticipated to arrive at the right ear, then this putative left ear advantage can be overwritten in a top down manner by inhibiting the right auditory cortex, reflected by increased oscillatory activity in the alpha band. As described above, this increase in alpha activity appears to follow reduced top down communication from right IPS to right auditory cortex. Disregarding the exact functional interpretation, our study confirms a special role of the right hemisphere including the right auditory cortex in attending acoustic space.

Of course, the current study includes some limitations: One concern could, for example, be the use of auditory cues, which were used because we were initially mainly interested in the aSSR (Weisz, Hartmann, et al. 2011; Weisz, Lecaigard, et al. 2011). Indeed, auditory cues of course influence the pretarget alpha dynamics within the same modality. While being a valid argument (e.g. alpha increases following cue presentation may be obscured by an overall decrease), in our previous study (Müller and Weisz 2011), we could identify similar patterns in auditory cortical regions following the presentation of a visual cue. Furthermore, the right hemispheric power modulations were clearly modulated by cue validity (i.e. informative vs. uninformative). Since apart from the context, these conditions were identical in terms of physical characteristics, this precludes an explanation that the observed effects were only determined by the acoustic cue. Another issue could be that the observed effects are solely driven by posterior

alpha modulations, as seen in previous EEG experiments which failed to identify attentional modulations of auditory cortical alpha activity. While our sensor results can be indeed considered as ambiguous, it is obvious that posterior and auditory cortical effects are clearly separable in terms of spatial location, but also in terms of temporal dynamics: Sensor as well as source level results imply a greater alpha modulation in rSTG in the pretarget period, whereas in the posttarget period rIPL seems more modulated. The connectivity effects also imply a clear temporal sequence of dominant coupling directions, supporting the notion that auditory and parietal processes are separate processes that interact depending on the attentional context.

In conclusion, our data supports the notion that spatial attention modulates alpha activity in relevant sensory brain regions beyond the visual modality. While previous successful studies, showing attentional modulations of auditory cortical alpha employed fully valid cues guiding attention either to the relevant ear (Müller and Weisz 2011) or modality (Gomez Ramirez et al. 2011), our study is the first to actually demonstrate that cue validity itself (i.e. whether it is informative or not concerning laterality of the upcoming target) influences auditory cortical alpha activity already prior to target presentation. The effect was most pronounced in the right auditory cortex when a valid cue guided attention to the contralateral ear lead to relative alpha increases and vice versa when attention was cued to the ipsilateral ear. Our findings support the notion of Jensen and Mazaheri (2010) that an important aspect of selective attention is to block information processing in task irrelevant brain regions, which is putatively mediated via increases of alpha activity in the respective regions. Going beyond the previous EEG/MEG literature and in line with previous rTMS (Capotosto et al. 2009) and fMRI experiments (Corbetta and Shulman 2002), we could demonstrate that the alpha increase in the right auditory cortex is accompanied by a distributed and strongly right lateralized network of cortical regions. Our study underscores, in particular, the outstanding role of the right IPS in also mediating auditory spatial attention.

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