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The contribution of selective spatial attention to sound detection and sound localization: Evidence from event-related potentials and lateralized alpha oscillations



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sound array.

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ARTICLE INFO	A B S T R A C T
Keywords: Selective attention Auditory search Alpha oscillations N2ac Sound localization Sound detection	Auditory selective attention can be directed toward spatial and non-spatial stimulus features. Here, we studied electrophysiological correlates of spatial attention under spatially-specific and purely feature-based demands. Using an auditory search paradigm, in which participants performed a target localization (left versus right) and a target detection task (present versus absent), we investigated whether attentional selection of a relevant sound from a two- or four-sound array necessarily involves the processing of spatial sound information. While the early N2 anterior contralateral component occurred irrespective of task, the subsequent lateralization of alpha power oscillations (8–12 Hz) over parieto-occipital scalp was modulated by the task-relevance of spatial information. Thus, the two correlates appear to reflect differential aspects of attentional orienting: We propose that the N2ac reflects an initial, modality-specific focusing of attention onto a lateralized target, while the subsequent alpha lateralization appears associated with the spatiotopic access to presumably supramodal representations of the

1. Introduction

In everyday hearing situations, we are often confronted with a sheer abundance of information. In order to detect, localize, and selectively focus on a particular stimulus of interest (e.g., a speaker's voice during a noisy poster session at a conference), we are required to segregate competing sound sources and inhibit irrelevant acoustic information. The behavioral implications and neural underpinnings of selective attention have been investigated in a vast amount of studies, including early work on the dichotic listening paradigm (Cherry & Taylor, 1954; Cherry, 1953; Moray, 1959; Wood & Cowan, 1995), and across different modalities (e.g., Eimer & Schröger, 1998; Hillyard, Hink, Schwent, & Picton, 1973; Lavie, 1995; Näätänen, Gaillard, & Mäntysalo, 1978; Posner, Cohen, & Rafal, 1982). For instance, numerous studies have shown that attention can be guided to a spatial position as well as to specific features or objects (Liu, Stevens, & Carrasco, 2007; Shomstein & Yantis, 2006; for reviews see Maunsell & Treue, 2006; Shinn-Cunningham, 2008). In the visual system, retinotopic maps in visual cortex allow for a precise coding of space and lead to faster spatial than non-spatial attention effects (Luck, 2005). In contrast, vibrations arriving at the cochlea are first decomposed in terms of their frequency. The resulting tonotopy is preserved in many subsequent processing steps along the auditory pathway, whereas representations of auditory space are based on more extensive computations using interaural time and level differences as well as monaural spectral cues (Blauert & Braasch, 2008). Thus, while attentional selection of a stimulus in visual space initially involves the processing of its spatial position, it remains unclear, whether or not selective auditory attention is as strictly related to the encoding of spatial sound information.

The goal of the present study was to clarify the contribution of spatial attention to target selection in a feature-based auditory search. In particular, we examined electrophysiological measures of attentional orienting during an auditory target detection and target localization task using a multi-source sound array. We simultaneously presented two or four animal vocalizations from different horizontal positions and asked listeners to either detect or localize a target sound within this lateralized sound array. The analysis focused on (a) event-related potentials (ERPs) and (b) lateralized EEG alpha band activity as correlates of spatially selective processing during the search for relevant auditory information. Regarding ERPs, we focused on the N2ac (i.e., the anterior contralateral N2 subcomponent; Gamble & Luck, 2011), that has been linked to the spatial aspects of the focusing of attention within an auditory scene (Lewald & Getzmann, 2015). Previous studies found that the N2ac can be elicited in both simple detection (Gamble & Luck,

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2011) and more complex localization (Lewald & Getzmann, 2015) or discrimination tasks (Gamble & Woldorff, 2015). Gamble and Woldorff (2015) proposed that the N2ac reflects the focusing of attention onto a lateralized target stimulus that occurs after the initial detection of the target sound by means of a rapid template matching mechanism. Yet, even when no further in-depth processing of the target or its location is required after the initial target detection, an N2ac component has been found (Gamble & Luck, 2011). The authors assumed that even though the location was not explicitly task-relevant, participants shifted their attention towards the location of the target sound. In the present study, the direct comparison of sound localization and sound detection in the same auditory search task allows for a systematic investigation of spatial and non-spatial aspects of attentional processing during featurebased auditory search. If sound detection does, similar to sound localization, result in the spatially specific allocation of attention, an N2ac should be present, even though the processing of the target location is not explicitly required. Additionally, we tested whether or not the N2ac varies with increased attentional demands by modulating the search set size (2 animal vocalizations vs. 4 animal vocalizations). Traditional interpretations regarding an analogous visual component - that is, the N2pc (N2 posterior contralateral; Eimer, 1996; Luck & Hillyard, 1994) suggest larger ERP amplitudes in more complex search conditions or with an increased number of distractors (Luck, Girelli, Mcdermott, & Ford, 1997). Thus, if the mechanisms of attentional selection are sensitive to attentional demands, larger N2ac amplitudes should occur in the more demanding high-load compared to low-load conditions.

As a second electrophysiological measure, we focused on oscillatory activity in the EEG. Similar to contralateral negativities in the ERP, lateralized alpha power (8-12 Hz) at parieto-occipital sites has been associated with the selective orienting of attention toward relevant information and the inhibition of irrelevant stimuli outside of the focus of attention (Kelly, Lalor, Reilly, & Foxe, 2006; Rihs, Michel, Thut, 2007; Worden, Foxe, Wang, & Simpson, 2000; for reviews on alpha oscillations as an inhibitory mechanisms see Foxe & Snyder, 2011; Jensen & Mazaheri, 2010; Strauss, Woestmann, & Obleser, 2014). Lateralization is typically reflected by decreases in alpha power in regions processing the attended stimulus - that is, contralateral to the attended location (Ikkai, Dandekar, & Curtis, 2016; Kelly, Gomez-Ramirez, & Foxe, 2009; Yamagishi, Goda, Callan, Anderson, & Kawato, 2005) - and increases in alpha power in regions processing irrelevant distractors that is, ipsilateral to the attended location (Kelly et al., 2006; Sauseng et al., 2005; Van Der Lubbe, Bundt, & Abrahamse, 2014; Worden et al., 2000). While the majority of studies still stems from the visual domain, the spatially-specific modulation of alpha power in sensory-specific cortex regions has by now been demonstrated across a wide range of modalities, including the anticipation of tactile events (van Ede, de Lange, Jensen, & Maris, 2011), nociceptive (Van der Lubbe, Blom, De Kleine, & Bohlmeijer, 2017), and auditory stimuli (Frey et al., 2014; Müller & Weisz, 2012; Wöstmann, Herrmann, Maess, & Obleser, 2016). Corroborating the functional significance of auditory alpha power, Wöstmann, Vosskuhl, Obleser, and Herrmann, (2018) showed that transcranial alternating current stimulation in the alpha frequency range over left auditory cortex regions impaired the attentional selection of speech contralateral to stimulation. Notably, some studies reporting sensory-specific alpha lateralization also found spatially-specific modulations of the alpha band over parietal and parieto-occipital electrodes sites (Van der Lubbe et al., 2017; Wöstmann et al., 2016). Consistently, a number of auditory spatial cueing studies that directed the participants' attention to one side of the upcoming auditory scene in anticipation of a target sound (Ahveninen, Huang, Belliveau, Chang, & Hämäläinen, 2013; Banerjee, Snyder, Molholm, & Foxe, 2011; Kerlin, Shahin, & Miller, 2010; Thorpe, D'Zmura, & Srinivasan, 2012) have reported alpha lateralization over posterior electrode sites that bear a striking resemblance to the topographies shown in visual attention studies. This overlap of alpha modulations over posterior areas across modalities has raised the notion of a central control system for the

deployment of attention in space regardless of modality (Farah, Wong, Monheit, & Morrow, 1989). Further evidence for such a higher-order attention system, that flexibly monitors and distributes attentional resources, can be derived from retroactive cueing studies demonstrating alpha lateralization to be related to shifting attention within visual working memory representations (Myers, Walther, Wallis, Stokes, & Nobre, 2015; Poch, Campo, & Barnes, 2014; Schneider, Mertes, & Wascher, 2016; Van Der Lubbe et al., 2014; Wilsch & Obleser, 2015). More specifically, it has been hypothesized that alpha lateralization reflects the spatiotopic access to previously encoded information held in working memory (Myers et al., 2015). In addition, only recently, (unlateralized) auditory alpha desynchronization has been shown to be associated with retroactive attention to auditory object representations (Alain et al., 2018; Backer, Binns, & Alain, 2015; Lim, Wöstmann, & Obleser, 2015; see Backer & Alain, 2014 or Wilsch & Obleser, 2015 for a review). Taken together, these findings highlight the functional relation of alpha power modulations to a higher-order, potentially supramodal control mechanism for orienting attention in both perceptual and mnemonic space.

However, it remains a matter of debate to what extent such a supramodal attentional mechanism observed in spatial cueing tasks is also involved in the (non-spatial) search for targets within an auditory scene. Only a hand full of visual attention studies has investigated, whether the same mechanisms of alpha lateralization apply to nonspatial, feature-based attentional orienting (de Lange, Rahnev, Donner, & Lau, 2013; Snyder & Foxe, 2010; van Diepen, Miller, Mazaheri, & Geng, 2016; Wildegger, van Ede, Woolrich, Gillebert, & Nobre, 2017), yielding inconsistent results. With respect to attentional orienting in auditory search, we propose that a lateralization of posterior alpha power should be limited to task conditions that require the access to spatial target representations in working memory for selecting the desired behavioral response (i.e., sound localization). In contrast, a task that only requires the extraction of non-spatial features from the search array should be independent of the access to spatial target representations. Thus, we expect a lateralization of posterior alpha power in the localization but not the detection task.

In summary, the present study aims at unraveling the neural underpinnings of attentional orienting in auditory scenes. The electrophysiological measures of interest allow for an investigation of potential supramodal attention effects and shed light on the role of spatial processing in selective auditory attention.

2. Materials and methods

2.1. Participants

16 healthy, right-handed participants ($M_{age} = 25.5$, age range = 21-30 years, 8 female) took part in the study. Prior to the experiment, standard pure tone audiometry (Oscilla USB 100, Inmedico, Lystrup, Denmark) was conducted for all participants, to ensure normal hearing thresholds. All participants reached non-clinical hearing levels below or equal to 25 dB for frequencies from 0.125 to 4 kHz. For frequencies above 4 kHz (i.e., 6 and 8 kHz), four participants showed marginally increased hearing levels of 30 dB (1 subject at 6 kHz, 1 subject at 8 kHz) and 35 dB (1 subject at 6 kHz, 1 subject at 8 kHz). These outliers were considered negligible; thus, participants were not excluded from analysis. In a screening questionnaire, all participants reported normal or corrected-to-normal vision and no history of neurological or psychiatric disorders. Before starting the experimental procedure, participants received written information about the study's purpose and procedure and gave their informed consent for participation. The study was approved by the Ethical Committee of the Leibniz Research Centre for Working Environment and Human Factors and conducted in accordance with the Declaration of Helsinki. Subjects received a payment of 10 euros per hour for participation.

2.2. Materials and stimuli

The experiment was conducted in a dimly lit, quiet room. Participants were comfortably seated in front of a computer monitor. All sound stimuli were presented via over-ear headphones (AKG K-271 Studio headphones). The sounds were eight animal vocalizations ('birds chirping', 'dog barking', 'frog croaking', 'sheep bleating', 'cat meowing', 'duck quacking', 'cow mooing', 'rooster crowing') chosen from an online sound archive (Marcell, Borella, Greene, Kerr, & Rogers, 2000) based on their familiarity and recognizability. Using the software Cool Edit 2000 (Syntrillium Software Corporation, Phoenix, AZ, USA), the animal sounds were cut to an equal duration of 600 ms (with a 10 ms on/off ramp) while keeping the spectro-temporal characteristics of the original sounds unaltered. The sounds were presented at a sampling rate of 48 kHz. The animal vocalizations were either presented as single sounds or as sound arrays of two (low-load) or four (high-load) simultaneous sounds. Each trial consisted of a sequence of a target sound and a sound array that was randomly chosen from a large pool of possible combinations. A total number of 56 different two-sound arrays (each array presented up to 4 times per condition) and 96 different four-sound arrays (each array presented up to 3 times per conditions) was presented in combination with one of the eight possible target sounds (all target sounds were presented equally often per condition). The selection of trial sequences was kept constant across all participants. The individual sounds were presented at an average sound level of 58.6 dB (A), resulting in a slightly higher overall level for sound arrays containing two (64.5 dB(A)) or four (67.5 dB(A)) sound stimuli. The stimuli in the sound arrays were lateralized at different azimuthal positions (\pm 60° and \pm 20° for the four-sound arrays and \pm 40° for the twosound arrays), while the single sounds were always presented at the central (0°) position. Virtual sound locations were generated via headrelated-transfer-function (HRTF) filter coefficients (Wenzel, Arruda, Kistler, & Wightman, 1993; Wightman & Kistler, 1989) recorded from a KEMAR (Knowles Electronic Mannequin for Acoustic Research) dummy head microphone (for a detailed description of the method, see Getzmann & Lewald, 2010). HRTFs simulate the filter properties of the head and external ears of the listener and allow for an externalized perception of the headphone signal, that is, the sounds appear to originate from the outside rather than the inside of the head (Hartmann & Wittenberg, 1996; Wightman & Kistler, 1989).

2.3. Procedure and task

Throughout the experiment, the participants were first presented a single sound from the center position (defining the target animal sound) followed by a sound array containing two or four simultaneously

(1) Auditory search, low load:



presented sounds (Fig. 1). In the detection task, participants indicated whether the target was present or not. In the localization task, they indicated whether the target was presented to the left or the right side of the sound array, or whether the target was not present in the sound array. These non-target trials in the localization task were necessary to prevent participants from selectively attending to only one ear in order to infer the target position in a given trial. Using this strategy, a participant selectively attending to the right ear, would be able to infer that the target was presented on the left side, simply because he or she did not detect the target on the right side. Adding target-absent trials inevitably led to unequal numbers of response alternatives across tasks (i.e., two vs. three response alternatives), potentially influencing performance. However, keeping the stimuli identical across tasks to avoid sensory confounds was given priority over enforcing an equal number of response alternatives when designing the experiment.

Taken together, the factors Task (localization, detection) and Load (two-sound array, four-sound array) were manipulated, resulting in a 2×2 factorial repeated-measures design. The number of trials belonging to each response category (i.e., yes or no for detection; left, right, or no for localization) was counterbalanced within each of the four conditions.

The conditions were presented block-wise; each block starting with an initial set of ten practice trials for the participants to become familiar with the task. Prior to each block, participants were informed about the number of stimuli in the sound array and the upcoming task. Accuracy and speed were equally emphasized. Each trial began with a 500-800 ms period of silence. Target sound and sound array were presented for a total duration of 600 ms each with a 1000 ms interstimulus interval (ISI). A new trial was automatically initiated by the participant's response, however, no later than 3000 ms after sound array offset. A black fixation cross (0.5° visual angle) was displayed in the center of the computer screen to minimize eye movements during the EEG recording. After the response, the fixation cross vanished for 200 ms and then reappeared to indicate the beginning of a new trial. The participants responded using their right middle finger, index finger, and thumb. The response pad consisted of three buttons arranged on a vertical line. The allocation of responses (yes vs. no; left vs. right vs. no) to response keys was counterbalanced across participants. This minimizes the possibility that potential compatibility effects introduced through the combination of response-key and response-finger influence the lateralized effects in the EEG. A total of 816 trials were presented. The low- and high-load localization conditions contained 144 and 288 trials, respectively. More specifically, the localization conditions contained 48 target-present trials for each target lateralization, resulting in 96 target-present trials in low-load conditions (i.e., 48 × target left, $48 \times$ target right) and 192 target-present trials in high-load conditions

Fig. 1. Experimental design. Participants were presented a single target sound (from a center position) followed by a sound array containing two (1) or four (2) simultaneous sounds. In two-sound arrays, the sounds were presented at $\pm 40^{\circ}$, whereas in four-sound arrays, the sounds were presented at $\pm 20^{\circ}$ and $\pm 60^{\circ}$, respectively. Participants were instructed to either indicate the position of the target sound (detection task) or the presence or absence of the target sound (detection task) via button press. Following the response, the fixation cross vanished for 200 ms and then reappeared to indicate the beginning of a new trial (not depicted). *ISI* = *inter-stimulus interval*.

(i.e., $48 \times target$ inner left, $48 \times target$ outer left, $48 \times target$ inner right, $48 \times$ target outer right). To ensure an equal number of response alternatives for each condition, low-load and high-load trials contained 48 and 96 target-absent trials, respectively. Both the high- and low-load detection conditions contained 192 trials. These were composed of 96 target-present trials and 96 target-absent trials, each. Note, however, that the low-load detection condition comprised 48 trials per target lateralization (i.e., $48 \times \text{target}$ left, $48 \times \text{target}$ right), whereas the high-load detection condition included 24 trials per target lateralization (i.e., $24 \times target$ inner left, $24 \times target$ outer left, $24 \times target$ inner right, $24 \times$ target outer right). The order of task blocks was counterbalanced across participants. In order to minimize fatigue, participants took short rest periods (2-5 min) in-between the separate task blocks. An additional break occurred in the middle of the high-load localization condition to compensate for its longer duration. Participants received no feedback regarding their performance at any time during the experiment.

2.4. Data analysis

Statistical analysis of behavioral data, as well as EEG data, was performed using R (R Core Team, 2016). As measures of effect size, partial eta squared (η_p^2 , Cohen, 1973) and Hedges' g_{av} (Lakens, 2013) are reported for all main effects and interactions in analyses of variance (ANOVA) and for subsequent post-hoc *t*-tests, respectively. *P* values were FDR-corrected for multiple comparisons when appropriate (Benjamini & Hochberg, 1995). Data were considered to meet the assumption of normality if both the Shapiro-Wilk test yielded insignificant results (p > .05) and if the respective skew and kurtosis values (divided by two times the standard error) fell below a threshold of one (Field, Miles, & Field, 2012). If these conditions were violated, nonparametric rank-based analyses (i.e., R package 'nparLD' by Noguchi, Gel, Brunner, & Konietschke, 2012) were applied.

2.4.1. Behavioral data

Error rates and reaction times were analyzed by conducting separate non-parametric rank-based analyses, approximating the distribution of the ANOVA-type statistics (Noguchi et al., 2012). The analyses included the within-subject factors Load and Task. Reported mean errors include missed responses (no response within the maximum response interval of 3000 ms following the sound array), since the majority of participants (10 out of 16) did not omit any responses. Overall, the average percentage of misses was extremely low ($0.12\% \pm 0.20$ standard deviation). The analysis of reaction times was limited to correct responses.

2.4.2. EEG recording and processing

The continuous EEG was recorded using 64 Ag/AgCl active electrodes (ActiCap; Brain Products, Gilching, Germany) with a sampling rate of 1000 Hz (BrainAmp DC-amplifier). Electrode positions were distributed across the scalp according to the extended 10/20 System. During recording, midline electrodes AFz and FCz served as ground and reference electrodes, respectively. Electrode impedance was kept below 10 k Ω .

Further pre-processing of the data was conducted using the opensource MATLAB * toolboxes EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). The raw data were filtered offline using a 0.5 Hz high-pass filter (6601point FIR filter; transition band width 0.5 Hz; cut-off frequency 0.25 Hz) and a 30 Hz low-pass filter (441-point FIR filter, transition band width 7.5 Hz, cut-off frequency 33.75 Hz), re-referenced to the average of 64 electrodes, and segmented into epochs from -1000 to 4600 ms relative to the onset of the target sound. A 600-ms interval preceding the first sound stimulus served as baseline. A semi-automatic artifact rejection procedure, based on independent component analysis (ICA), was applied. For faster analysis, ICA decomposition was derived from a subset of the original data, down-sampled to 200 Hz and containing only every second trial. After retrieving the 'original' dataset with 1000 Hz sampling rate, artifacted components reflecting eye blinks, eye movements, and generic discontinuities were rejected using the automatic algorithm ADJUST (Mognon, Jovicich, Bruzzone, & Buiatti, 2011). Additionally, independent components with a residual variance above 40% in the dipole solution were subtracted to eliminate additional artifacts. This was done because artifact independent component scalp maps do usually not resemble the projection of a single dipole (Onton & Makeig, 2006). A single-equivalent current dipole model for each of these scalp maps was computed by means of a spherical head model (Kavanagh, Darcey, Lehmann, & Fender, 1978), as implemented in the DIPFIT plug-in of the EEGLAB toolbox. By visual inspection, any remaining artifactual independent components were removed. On average, a total of 21.93 independent components were rejected from the data for each participant (range: 16-27). Finally, automatic artifact rejection implemented in EEGLAB (threshold limit: 1000 µV, probability threshold: 5 std. dev.) was performed. On average, 16.57% trials were excluded due to artifacts (range = 5.88%-27.82%). Further analyses of EEG data included only correct responses, excluding those that occurred earlier than 120 ms or later than 1500 ms post sound array (total of 108 trials, mean per subject = 6.75 trials, range = 0-36 trials). After preprocessing, the epochs were pruned to 4100 ms following the time-locking event, allowing for a 1000 ms interval following the longest possible response time. The latter was relevant for the response-locked analysis described in Section 2.4.4. Since we were interested in effects of spatial attentional deployment towards the auditory target, only target-present trials were included.

2.4.3. ERP data

Processes of selective spatial attention during auditory search were explored by analysis of lateralized ERPs, that is, the contralateral and ipsilateral portions of the ERP relative to the target position in the search array. In particular, a lateralized shift of attention within the auditory sound array was quantified by the negative area under the contralateral minus ipsilateral difference wave at an electrode cluster comprising electrodes FC3/4 and C3/4 in a 100-ms time window. The choice of electrodes is in accordance with previous studies of N2ac amplitudes (Gamble & Woldorff, 2015). The time windows for analyses were determined by means of the fractional area latency (FAL) measure (Kiesel, Miller, Jolicoeur, & Brisson, 2008; Luck & Hillyard, 1990): First, in correspondence with previously reported time windows for the N2ac (Gamble & Luck, 2011), the mean area under the difference curve was measured between 200 and 500 ms after sound array onset. Subsequently, the time point at which this area is divided in two equal halves, that is, the 50% FAL, was determined. This step yielded a FAL of 342 ms (in both localization conditions and the low-load detection condition) and 348 ms (in the high-load detection condition), relative to sound array onset. Finally, a 100-ms time window was set around this latency, resulting in time windows starting at 292 ms (for low- and high-load localization and low-load detection) and 298 ms (for high-load detection). Corresponding scalp topographies were based on the same time windows (cf., Fig. 3). To test for differences in the area under the curve between conditions, a two-way repeated-measures ANOVA with the factors Load and Task was conducted.

This technique of assessing the area under the difference curve as an estimate of ERP amplitude has been successfully applied in previous EEG studies (e.g., Sawaki, Geng, & Luck, 2012; Schneider et al., 2016), but necessarily results in non-zero values, thus producing a bias. In order to account for this bias when assessing the significance of the single ERP effects within the four conditions, we used a nonparametric permutation approach (Groppe, Urbach, & Kutas, 2011; Luck, 2014; Mertes, Wascher, & Schneider, 2016; Sawaki et al., 2012; Schneider et al., 2016). This approach estimates the distribution of area under the curve values that would be expected in case of a null effect. More specifically, trials were randomly labeled as left or right target trials. From the resulting waveforms, the negative area under the difference

wave was calculated (for the time windows stated above) and averaged across participants. This permutation procedure was iterated 1000 times to produce a random distribution of area values. If the area value obtained from the actual (non-permuted) data was greater than 95% of the values measured from the randomized waveforms, the effect was considered significant.

2.4.4. Time-frequency data

For the analysis of time-frequency data, as described below, the original data were down-sampled to 500 Hz. In order to obtain eventrelated spectral perturbations (ERSPs; cf., Delorme & Makeig, 2004) of the single-trial EEG data, we performed a convolution with three-cycle complex Morlet wavelets. The number of cycles in the wavelets used for higher frequencies expanded with a factor of 0.5 with respect to the expanding number of cycles used in the corresponding fast fourier transformation (FFT). Epochs consisted of 300 time points between -721 and 3819 ms relative to target sound onset. Computations were based on frequencies ranging from 6 to 30 Hz in 48 logarithmic steps. This resulted in 3-cycle wavelets at the lowest frequency (i.e., 6 Hz) and 7.5-cycle wavelets at the highest frequency (i.e., 30 Hz). In order to investigate lateralized effects in oscillatory power, the contralateral and ipsilateral portions of the alpha band (8-12 Hz) were measured from 458 to 656 ms relative to the onset of the sound array. Mean alpha power was measured at electrodes PO7 and PO8. While most studies on posterior alpha lateralization include a selection of several electrodes that varies from study to study, we find PO7/8 to be most frequently involved (e.g., Gould, Rushworth, & Nobre, 2011; Myers et al., 2015; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Van Der Lubbe et al., 2014; van Driel, Gunseli, Meeter, & Olivers, 2017; van Ede, Niklaus, & Nobre, 2017). To keep the family wise error rate as low as possible, we decided to limit the analysis to one pair of electrodes. Time windows were based on a 200-ms interval around the peak in alpha suppression following the sound array measured in the grand average ERSP (i.e., the average across contralateral and ipsilateral portions) across all conditions at electrodes PO7/PO8. Mean alpha power was submitted to a 2 (Load: two-sound array vs. four-sound array) \times 2 (Task: localization vs. detection) \times 2 (Asymmetry: contralateral vs. ipsilateral) repeatedmeasures ANOVA. Finally, post-hoc t-tests were performed to test for a significant decrease in alpha power contralateral (compared to ipsilateral) to the target sound. In addition, we calculated an alpha lateralization index that is frequently reported to capture the asymmetric modulation of alpha power in one measure (Haegens, Handel, & Jensen, 2011; Tune, Wöstmann, & Obleser, 2018; Wildegger et al., 2017):

(ipsilateral alpha power—contralateral alpha power) (ipsilateral alpha power + contralateral alpha power)

The index yields a positive value when alpha power is higher over the ipsilateral hemisphere relative to the target sound (and/or lower over the contralateral hemisphere). Accordingly, negative values indicate higher alpha power over the contralateral hemisphere relative to the target sound (and/or lower alpha power over the ipsilateral hemisphere). To properly calculate the lateralization index, the raw, nonbaseline-corrected power values were used. All other parameters (e.g., cycles, number of frequencies, electrodes, measurement window) were kept constant. Alpha lateralization indices were submitted to a 2 (Load) \times 2 (Task) repeated-measures ANOVA. To test if the mean lateralization indices differed significantly from zero, one sample *t*-tests were conducted.

To investigate a potential interaction between posterior alpha power asymmetries and the anterior N2ac, a multivariate ANOVA (MANOVA) including both N2ac area values and mean alpha power as dependent variables was performed. Note that, since the area measure used for the N2ac refers to the contralateral minus ipsilateral difference curves, the respective differences in alpha power were calculated for the combined analysis. Thus, the MANOVA did not include the factor Asymmetry. To convert the measurement values into a comparable unit of measurement, values were z-transformed.

Finally, to investigate the extent to which alpha lateralization reflects response-related processes, response-locked ERSPs were also analyzed. Thus, the same single-trial EEG data used for the stimuluslocked analysis were time-locked on the response, creating epochs ranging from -2760 pre-response to 1000 ms post-response. Computations were based on the same settings as described above for the stimulus-locked trials. The resulting response-locked epochs contained 300 time points ranging from 2481 before to 719 after the timelocking event. The contralateral and ipsilateral portions of the alpha band were measured at electrodes PO7 and PO8 in a 200 ms time window from 190 before to 12 ms after response onset. Analogous to the stimulus-locked analysis, the time window was set around the peak in alpha suppression preceding the response in the grand average ERSP. Mean alpha power was submitted to a 2 (Load: two-sound array vs. four-sound array) imes 2 (Task: localization vs. detection) imes 2 (Asymmetry: contralateral vs. ipsilateral) repeated-measures ANOVA.

3. Results

3.1. Behavioral performance

Fig. 2 illustrates the mean error rates (A) and mean reaction times (B) in each condition. Non-parametric rank-based methods were applied, using the 'nparLD' R package (Noguchi et al., 2012), due to non-normal distribution of the behavioral data in some conditions. Please note, that only the numerator degrees of freedom of the F distribution are reported, since the nparLD package sets the denominator degrees of freedom to infinity (fur further details, see Noguchi et al., 2012). Analysis of error rates showed a trend towards a main effects of Task, F(1) = 2.87, p = .089, and a significant effect of Load, F(1) = 14.95, p = .0001. These indicate better performance (i.e., fewer errors) for detection (M_{ER} = 5.84%, SE = 2.42) compared to localization (M_{ER} = 8.81, SE = 3.99) and in low-load (M_{ER} = 4.39%, SE = 1.82) compared to high-load trials (M_{ER}

Fig. 2. Mean proportion of errors (A) and reaction times (B) dependent on task and search set size. Error bars indicate the standard error of the mean. Please note that the tasks included different numbers of response alternatives (i.e., two versus three response choices in sound detection and sound localization, respectively), leading to different levels of chance for sound detection (i.e., 50%) compared to sound localization (i.e., 33.3%).



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Fig. 3. N2ac component for the four experimental conditions at electrodes FC3/4 and C3/4, averaged together to form an electrode cluster. Waveforms depict the contralateral (black lines) and ipsilateral (blue lines) portions of the anterior ERP relative to the position of the target sound. Areas shaded in grey mark the time windows used for analyses. The corresponding topographies are based on a contralateral-minus-ipsilateral difference waveform; consequentially, voltage maps are zero at the midline. Because the subtraction was mirrored across both hemispheres, the topographies are symmetrical (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

= 10.27%, SE = 4.03). The interaction of Task and Load did not reach significance, F(1) = 0.98, p = .323 Regarding reaction times, the analysis revealed a significant main effect of Task, indicating faster responses in detection (M_{RT} = 755.40 ms, SE = 92.97) compared to localization trials (M_{RT} = 858.09 ms, SE = 96.78), F(1) = 7.73, p = .005. A significant main effect of Load demonstrated that participants responded faster in low-load (M_{RT} = 744.42 ms, SE = 92.01) compared to high-load trials (M_{RT} = 856.74 ms, SE = 96.18), F(1) = 16.10, p = .00006. No significant interaction of Load and Task was found, F(1) = 0.47, p = .49.

3.2. Electrophysiological results

3.2.1. ERP analyses

Fig. 3 shows the grand average ERPs obtained at a fronto-central electrode cluster (FC3/4, C3/4) contralateral and ipsilateral to the target sound, separately for all four search conditions. Analysis of the negative area under the difference curve following the sound array (see 2.4.3 for exact time windows) revealed a significant main effect of Load, F(1,15) = 5.93, p = .03, $\eta_p^2 = 0.28$, reflecting smaller N2ac amplitudes in high-load conditions (mean area under the curve, low-load: 0.06 μ V*s versus high-load: 0.04 μ V*s). There was neither a significant modulation of the N2ac by Task, F(1,15) = 0.71, p = .41, $\eta_p^2 = 0.05$, nor a significant interaction of Load and Task, F(1,15) = 0.74, p = .40, $\eta_p^2 = 0.05$. The subsequent permutation tests confirmed the significance of an N2ac component in all conditions; although in the high-load detection condition, the area under the curve (0.039) only scarcely exceeded the critical cut off (0.038) that marks 95% of the values measured from the randomized waveforms (cf., Fig. 4 for results of the permutation analyses).

Corresponding scalp topographies were based on the contralateral minus ipsilateral difference waveforms (cf., Fig. 3) and are thus zero at the midline. Overall, the obtained scalp distribution of the N2ac strongly resembles topographical maps from previous studies (Gamble & Luck, 2011; Lewald & Getzmann, 2015).

3.2.2. Time- frequency analyses

3.2.2.1. Stimulus-locked ERSPs. The contralateral and ipsilateral portions of alpha power, time-locked to the onset of the target sound, are illustrated in Fig. 5. Data were collapsed across load within each task condition for illustrative purposes, since there was no significant main effect of Load, F(1,15) = 0.02, p = .89, $\eta_p^2 < 0.01$. The ANOVA revealed a significant main effect of Asymmetry, indicating, in general,

a stronger decrease in contralateral (M = -1.63 dB, SE = 0.38) compared to ipsilateral alpha power (M = -1.11 dB, SE = 0.38), F (1,15) = 17.44, p = .001, $\eta_p^2 = 0.33$. More important, there was a significant interaction of Asymmetry and Task, arising from a clear-cut difference in asymmetry between tasks, F(1,15) = 7.34, p = .02, $\eta_p^2 =$ 0.33: As illustrated by the topographical maps and line plots (cf., Fig. 5), there is a pronounced lateralization of alpha power in localization trials, while it is only faintly visible in detection trials. Post-hoc comparisons of ipsilateral and contralateral alpha power confirm a significant asymmetry for localization trials, t(15) =-3.94, p = .002, $g_{av} = 0.48$, while it does not reach statistical significance for detection trials, t(15) = -1.25, p = .23, $g_{av} = 0.10$. The analysis of the alpha lateralization index confirms this pattern of results: The respective ANOVA revealed a significant main effect of Task, F(1,15) = 13.19, p = .002, $\eta_p^2 = 0.47$, while neither the main effect of Load, F(1,15) = 0.02, p = .88, $\eta_p^2 = 0.001$, nor the interaction of Load and Task reached significance, F(1,15) = 0.20, p = .66, $\eta_p^2 =$ 0.013. Post-hoc one sample t-tests, contrasting the mean alpha lateralization index against zero, indicated a significant lateralization of alpha power for sound localization (M = 0.008, SE = 0.002), t (15) = 3.84, p = .003, g_{av} = 0.96, while it failed to reach significance for sound detection (M = 0.0006, SE = 0.001), t(15) = 0.50, p = .63, $g_{av} = 0.12.$

To test if the anterior N2ac component and the posterior alpha power modulations reflect distinct attentional processes, we performed a MANOVA including both measures as dependent variables. Accordingly, we were particularly interested in potential interactions between Measure (N2ac vs. Alpha power) and the factors Load and Task. A significant interaction of Task and Measure, F(1,15) = 6.28, p = .02, $\eta_p^2 = 0.30$, corroborates the notion that the lateralization reflected in the N2ac component occurs irrespective of task, t(15) = 0.84, p = .41, whereas alpha lateralization occurred in localization trials but not in detection trials, t(15) = -2.71, p = .03. In addition, the analysis revealed a significant interaction of Load and Measure, F(1,15) = 5.01, p = .04, $\eta_p^2 = 0.25$, that indicates a greater N2ac in low-load compared to high-load trials, t(15) = 2.43, p = .056, whereas the alpha asymmetry was not affected by Load, t(15) = -0.92, p = .37. No other interaction effects reached significance (all p values > .32).

3.2.2.2. Response-locked ERSPs. The observation that the lateralization of alpha power occurred relatively close to the average response time arose the question to what extent it reflected response-related



Fig. 4. Results of the non-parametric permutation test for the N2ac components. Blue bars illustrate the random distribution of area values obtained from 1000 permutations, in which right and left target labels were randomly assigned to the trials. The frequency of measured values is denoted on the y-axis and the respective area values are denoted on the x-axis. The red lines indicate the grand average value obtained from the actual, non-permuted data. The yellow area represents the top 5% of the random distribution. The N2ac effect is considered significant if the actual area value falls within the top 5% of the random distribution, that is, if the red lines fall within the yellow area. Please note that the signed negative area under the curve was measured; however, since mathematically, area values are restricted to non-negative numbers, depicted values are positive (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

processes. Thus, we also analyzed the ERSP data in a response-locked fashion. Fig. 6 illustrates the response-locked portions of contralateral and ipsilateral alpha power. Again, data were collapsed across load conditions for better clarity of the graph since there was no significant effect of Load, F(1,15) = 0.79, p = .39, $\eta_p^2 = 0.05$. The analysis revealed a significant effect of asymmetry that is consistent with the greater decrease in contralateral (M = -1.47 dB, SE = 0.29) compared to ipsilateral alpha power (M = -1.10 dB, SE = 0.30), F (1,15) = 20.84, p < .001, $\eta_p^2 = 0.58$. Analogous to the results of the stimulus-locked analysis, the asymmetry appeared more pronounced in localization trials compared to detection trials (cf., Fig. 6). A trend towards an interaction of Task and Asymmetry supported this observation, F(1,15) = 3.87, p = .07, $\eta_p^2 = 0.21$. Post-hoc

comparisons of contralateral and ipsilateral alpha power revealed a significant asymmetry for both sound localization, t(15) = -3.68, p = .004, $g_{av} = 0.38$, and sound detection trials, t(15) = -2.78, p = .01, $g_{av} = 0.17$.

4. Discussion

Previous work on visual attention has provided conclusive evidence that spatial location is a firmly embedded feature in one's representation of non-spatial information (Foster, Bsales, Jaffe, & Awh, 2017; Johnston & Pashler, 1990; Tsal & Lavie, 1993). While this prioritization of spatial information is relatively undisputed in the visual domain, it remains unresolved whether spatial information is as tightly bound to

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Fig. 5. Posterior asymmetries (PO7/8) of alpha power (8–12 Hz). Line plots illustrate the contralateral and ipsilateral portions of alpha power for both task conditions. Since, there was no significant effect of load, plots were averaged across the two load conditions. The topographies are based on the left-minus-right target difference (a and c) and the contralateral minus ipsilateral difference (b and d), respectively. Because the contralateral minus ipsilateral subtraction was mirrored across both hemispheres, topographies b and d are symmetrical. (e and f) Grand average time-frequency plots of contralateral minus ipsilateral power at electrodes PO7/PO8 for both task conditions. Please note that some studies report similar lateralized effects in adjacent frequency bands (e.g. posterior theta power [4–7 Hz; Harris, Dux, Jones, & Mattingley, 2017; Thorpe et al., 2012; Van Der Lubbe et al., 2014] or beta power over motor cortex [15–30 Hz; Mok, Myers, Wallis, & Nobre, 2016; Thorpe et al., 2012]. However, an inspection of those frequency bands in the present data revealed no considerable effects.

non-spatial features in audition. In the present study, the contribution of spatial sound information to attentional orienting was investigated using an auditory search task, in which participants were instructed to report either the presence or absence of a target sound (sound detection) or its horizontal location (sound localization) within a sound array containing either two or four simultaneously presented animal vocalizations.

Here we present evidence that the involvement of spatially-specific attentional mechanisms in feature-based auditory search largely depends on whether we look at early, modality-specific attentional orienting (indicated by the N2 anterior contralateral component, i.e., N2ac) or at rather late, potentially supramodal, attentional modulations (indicated by alpha lateralization). More specifically, we found that the modality-specific N2ac component, indicating an initial shift of auditory spatial attention towards the relevant target sound, occurred regardless of whether spatial information was relevant for the task (i.e., sound localization) or not (i.e., sound detection). The N2ac was followed by a lateralization of alpha power over parieto-occipital electrodes suggesting the access to supramodal spatial representations of the sound array. To elaborate to what extent the observed alpha lateralization reflects a response-related process, we compared stimulusand response-locked ERSPs. Both analyses yielded a highly similar pattern of results, revealing a considerably stronger alpha lateralization when participants were required to localize the relevant target sound compared to when indicating its presence or absence. Sound detection

elicited only a faint asymmetry that did not reach significance in the stimulus-locked analysis. Following a short discussion of the behavioral results, we will integrate the electrophysiological findings with respect to recent attention literature and discuss the relative contribution of both measures to spatially-specific processing during auditory search.

On the behavioral level, the task and load manipulation produced intuitive results. First, analyses revealed a significant effect of task for both error rates and reaction times. That is, participants responded faster and made fewer errors in the sound detection task compared to the localization task. Given that in auditory processing, sound localization requires additional computational effort (Blauert & Braasch, 2008), this finding is not surprising. Consistently, ERP studies have identified different stages of feature conjunction with early, parallel single-feature processing followed by conjunction-specific activations (Woods, Alho, & Algazi, 1991; Woods, Alho, & Algazi, 1994). However, it should be noted that the sound detection task included only two response alternatives (i.e., yes or no), while in the localization task, participants chose from three response alternatives (i.e., left, right, or target absent). This additional target absent response was included to control for strategy (cf., Section 2.3). Consequentially, both the additional computational effort for sound localization and the greater number of response alternatives could contribute to the worse performance in the localization compared to the detection task. In addition to this task effect, significantly longer reaction times and more errors were found for high-load compared to low-load conditions. This could be due



Fig. 6. Results of the response-locked time-frequency analysis. Line plots illustrate the contralateral and ipsilateral portion of alpha power (8–12 Hz) at electrodes PO7/PO8 for both task conditions. Plots were averaged across load conditions for illustrative purposes. The scalp topographies are based on the left-minus-right target difference (a and c) and the contralateral minus ipsilateral difference (b and d), respectively. (e and f) Grand average time-frequency plots of contralateral minus ipsilateral power at electrodes PO7/PO8 for both task conditions.

to the increased number of stimuli as well as to a greater effect of masking in the high-load condition. Increased masking was introduced by the increased number of stimuli in high-load trials that led to different angles of separation between the sound sources (i.e., 40° of separation in high-load trials compared to 80° of separation between neighboring sounds in low-load trials). Thus, the load manipulation in the present study inevitably entailed a manipulation of task difficulty.

On the electrophysiological level, the observation of an N2ac component in both the localization (Lewald & Getzmann, 2015) and the detection task (Gamble & Luck, 2011) is consistent with previous results. Analogously, the N2 posterior contralateral component (i.e., N2pc), the visual counterpart of the N2ac, has been found in both visual localization and detection paradigms (Schneider & Wascher, 2013). Hence, in line with findings from visual search, initial target detection in auditory search may begin with an analysis of task-relevant nonspatial features, allowing for the deployment of spatial attention towards the relevant location, that in turn allows for the in-depth processing of the target (Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004). As already pointed out by Gamble and Luck (2011) in their original N2ac paper, though it seems plausible that the N2ac directly reflects the focusing of attention onto a lateralized target, it might as well just be a "downstream consequence of shifting attention and identifying a target" (p. 12). It is important to note that we cannot directly distinguish between these two possibilities.

The present study was the first to systematically investigate modulations of N2ac amplitude by search set size under different task

demands. Our analysis revealed no significant modulation of the N2ac component by task. Yet, we observed a reduction of N2ac amplitudes in high-load conditions. This suggests that the strength of the N2ac depends to some degree on the spatial resolution of the auditory scene in which attention is deployed. Hence, when azimuthal positions within the two-sound arrays ($\pm 40^{\circ}$) were spatially easy to distinguish (i.e., high spatial resolution), there was strong evidence of an N2ac component. In the four-sound array, however, perceptual load increased (for a review on effects of auditory perceptual load, see Murphy, Spence, & Dalton, 2017), resulting in lower spatial resolution. Consequentially, spatial specificity of attentional selection may be less pronounced, as reflected by diminished N2ac amplitudes for high-load conditions. Although this contradicts traditional interpretations of the visual N2pc (Luck et al., 1997), more recent studies reported comparable results, showing the N2pc component to be attenuated when shifting attention within a working memory representation of four compared to two objects (Dell'Acqua, Sessa, Toffanin, Luria, & Jolicoeur, 2010). The authors similarly argue that the diminished ERP amplitude may be due to less efficient encoding of the search array in the high-load condition. The significant effects of load on reaction times and error rates corroborate this interpretation. Alternatively, the increased masking effects in high-load trials could have reduced the spatial specificity of attentional selection in the four-sound array.

Similar to lateralized ERPs, modulations of oscillatory alpha power have been found to be involved in the spatially-specific deployment of attention and the inhibition of unattended, irrelevant stimuli (Jensen & Mazaheri, 2010; Sauseng et al., 2005). The observed alpha lateralization in localization trials in the present study is in line with earlier findings from visual (Kelly et al., 2006; Sauseng et al., 2005; Worden et al., 2000) and auditory spatial cueing tasks (Ahveninen et al., 2013; Kerlin et al., 2010; Thorpe et al., 2012) as well as studies on the deployment of visual attention to working memory representations (Myers et al., 2015; Poch et al., 2014; Schneider et al., 2016; Van Der Lubbe et al., 2014; Wilsch & Obleser, 2015). Critically, in contrast to the majority of those previous studies, we did not directly manipulate spatial attention by presenting a spatial cue that directs the participants' attention to a certain location within the stimulus array. Instead, the initial search for the target sound in all of the conditions was feature-based; that is, participants had to skim through the whole stimulus array in order to detect and attend to the relevant target sound. So far, reports of alpha lateralization in such search conditions, that is, after the presentation of a stimulus array (rather than after a spatial cue) remain seldom, but can be found in a few visual attention studies (Bachman et al., 2018; van Diepen et al., 2016). Those findings suggest that alpha lateralization analogously tracks the locus of spatial attention in the absence of a spatial cue. Regarding the present results, we propose that posterior lateralized alpha power in sound localization reflects the access to spatial representations of the previously encoded sound array that may provide a template to initiate a spatially-specific response. In fact, a closer look at the time frequency plot (cf., Fig. 5e) reveals that the observed asymmetry seems to emerge right before the average response time. The corresponding response-locked portions of the alpha-band in sound localization support this line of argumentation: the lateralization of alpha power was still reliably evident in the response-locked data. If the observed alpha lateralization was exclusively related to stimulus-processing, the lateralization should be absent in the response-locked data; that is, since the stimulus-related portion of the asymmetry would vary in latency relative to the response, it would blur in the response-locked average.

To what extent is such a spatially-specific attentional mechanism also involved in the feature-based selection of sounds when the spatial position of the target remains irrelevant? By modulating the task-demands while keeping the actual search paradigm constant across conditions, the present study design allowed us to explicitly distinguish spatial and non-spatial aspects of attentional orienting in an auditory scene. If alpha lateralization operates analogously in feature-based attention, reflecting the enhanced processing of the target (Sauseng et al., 2005) or a suppression of irrelevant distractors (Jensen & Mazaheri, 2010; Klimesch, 2012; Strauss et al., 2014), it seems appealing to believe, at first, that it concurs with common ERP measures of selective spatial attention, such as the auditory N2ac (Gamble & Luck, 2011) (or the visual N2pc; Eimer, 1996; Luck & Hillyard, 1994). Our results, however, support a functional distinction between both measures: First of all, the different foci of the corresponding scalp topographies (i.e., an anterior vs. posterior pattern for N2ac and alpha lateralization, respectively) are indicative of distinct neural generators and suggest that the underlying processes are distinguishable in a functional nature. The significant interactions of Task and Measure as well as Load and Measure from the multivariate analysis of results further support the notion that they operate differently depending on task demands and perceptual load. Moreover, the observed N2ac effect occurs substantially earlier than the alpha power lateralization (cf., lower bound of analysis time windows for the N2ac [292-298 ms] and alpha power [458 ms]; note, however, that the time resolution of oscillatory activity is limited and the time windows can only present an approximation of the actual onset of the effect).

So far, studies investigating alpha lateralization with respect to feature-based attention remain scarce and are limited to the visual domain (Snyder & Foxe, 2010; van Diepen et al., 2016; Wildegger et al., 2017). Those studies that do exist, have almost exclusively focused on anticipatory modulations of alpha power in the cue-stimulus interval. Additionally, the operationalization of feature-based attention varies

substantially across studies, so that comparisons to our study are limited. Van Diepen et al. (2016) used a design most similar to ours, asking participants to search for a pre-defined target feature in a subset of uncued trials in a visual search paradigm. Subsequently, participants had to report the identity of a letter presented in the target stimulus, that is, perform a non-spatial discriminative response. The authors reported a significant lateralization of alpha power in trials that contained low-similarity distractors (compared to high-similarity distractors), that occurred considerably later than the frequently observed N2pc, commonly associated with attentional selection (Eimer, 1996). Hence, they concluded that alpha lateralization reflected the continued attentional processing rather than the initial attentional selection of the target. In the present study, the stimulus-locked analysis revealed no significant modulation of alpha power during sound detection. Though the faint effect still reached significance in the response-locked ERSP, the modulation was clearly less pronounced in sound detection trials than in sound localization trials. This suits the fact that no spatial information is needed to solve the sound detection task. Thus, the access to a spatially specific template of the previously encoded sound array appears to be only reliably present in sound localization trials, while being at most 'optional' in non-spatial sound detection. Critically, the absence of an alpha lateralization in the present sound detection task does not necessarily imply that participants did not deploy spatial attention towards the target sound. Instead, the occurrence of an N2ac suggests that participants initially focus their attention on the target even though the spatial location was irrelevant to the task, while the lack of an alpha lateralization may reflect the absence of attention towards a spatially-specific format of the target sound representation. Alternatively, one could also argue that the absence of alpha lateralization in the detection task could be due to the fact that it was easier than the localization task (as indicated by the behavioral results). Though, if task difficulty played a major role, we would analogously expect the alpha lateralization to be modulated by load, since low-load conditions were easier than high-load conditions (cf., main effect of load on reaction times and error rates). Yet, this was not the case. Hence, our results more likely point towards modality-specific differences in the relevance of spatial information in feature-based attention: The current auditory paradigm revealed that the initial attentional selection of the target sound based on the relevant target-features was followed by a shift in spatial attention (i.e., N2ac), even when the spatial position was irrelevant (i.e., sound detection condition). However, there was no pronounced sustained spatially-specific attentional processing in terms of a lateralization of posterior alpha power in the current sound detection task. In contrast, in the visual domain, spatial attention appears to be involved throughout the initial attentional selection and the continued attentional processing of the target under both spatially-specific and purely feature-based task demands (van Diepen et al., 2016). The contradiction to van Diepen and colleagues' (2016) findings may also arise from the differences between tasks: As pointed out by the authors, the visual search task required a further processing of the target after feature-based selection in order to perform the required discrimination task. Yet, no such in-depth processing of target-features was required after the target had been identified in the present auditory detection task. It remains to be shown whether or not an analogous, non-spatial auditory discrimination task would similarly induce lateralized alpha power.

Given that alpha lateralization has been found across a variety of modalities, the present study adds to a growing body of evidence suggesting similar mechanisms of spatial attention in the auditory and visual domain. Such a supramodal control system for the deployment of attention in space (Farah et al., 1989) has received extensive support from parietal lobe lesion and neglect studies (Brozzoli, Demattè, Pavani, Frassinetti, & Farnè, 2006; Farah et al., 1989; Heilman & Van Den Abell, 1980; Posner, Walker, Friedrich, & Rafal, 1984; Vallar & Perani, 1987), EEG investigations (Eimer & Schröger, 1998; Kerlin et al., 2010; Thorpe et al., 2012) as well as functional magnetic resonance imaging (fMRI) studies (Macaluso, Eimer, Frith, & Driver, 2003; Smith et al., 2010). However, a recent comparison of oscillatory alpha-band mechanisms in a visual and auditory spatial cueing paradigm has questioned this notion (Banerjee et al., 2011). The authors provide evidence in favor of the so-called interactivity thesis, assuming an interaction of a supramodal control system with modality-specific systems. In particular, they found both common and distinct foci in the posterior scalp distribution of alpha power during the anticipatory deployment of spatial attention to auditory and visual target locations. While the observed posterior topographies are in line with scalp distributions reported in several auditory spatial cueing studies (Kerlin et al., 2010; Thorpe et al., 2012; Wöstmann et al., 2016), other have reported sensory-specific alpha power lateralization in auditory cortex regions (Müller & Weisz, 2012; Wöstmann et al., 2016), arguing in favor of a distinct auditory cortical alpha generator. Regarding the interpretation of the present results, several caveats should be pointed out: First, it remains possible that in addition to a parieto-occipital alpha mechanism, sensory-specific alpha modulations are involved as well, contributing to an auditory attention network comprising both sensory-specific and supramodal cortex regions. Second, when drawing conclusions with respect to the "supramodality" of alpha oscillations in the present study, we need to keep in mind that we neither directly compared auditory and visual search in the present study, nor did we localize the effect in non-sensory, supramodal brain regions. However, although we cannot rule out that alpha power modulations actually operate in a modality-specific manner, the current findings emphasize a crucial overlap between oscillatory alpha power as a mechanism of both visual and auditory spatial attention.

A final critical note concerns the distinction between spatial attention and task relevance in the present study. It is to be emphasized that we did not explicitly manipulate spatial attention in terms of instructing participants to attend to a particular ear or to direct their attention to either side of the sound array (e.g., by presenting a spatial cue). The critical manipulation of the present study concerns the task relevance of spatial information (sound localization vs. sound detection). Importantly, this manipulation of task does not imply that we created a spatial attention versus a non-spatial attention condition. Rather, we studied to what extent spatial attention (as indicated by the N2ac and posterior alpha lateralization) is involved in (a) purely feature-based auditory search (sound detection) as opposed to (b) a feature-based search that requires a spatially-specific response (sound localization).

Taken together, the present approach allowed us to show that the early N2ac component and the subsequent alpha lateralization seem to reflect differential aspects of attentional processing: Irrespective of the task-relevance of spatial information, the N2ac component indicated the initial attentional focusing onto the lateralized target sound. Subsequently, a rather decisional process, associated with the spatiotopic access to presumably supramodal representations of the previously encoded sound array, was reflected by a posterior lateralization of alpha power. Critically, the latter was modulated by the relevance of spatial information in the current task.

Declarations of interest

None.

References

- Ahveninen, J., Huang, S., Belliveau, J. W., Chang, W.-T., & Hämäläinen, M. (2013). Dynamic oscillatory processes governing cued orienting and allocation of auditory attention. *Journal of Cognitive Neuroscience*, 25, 1926–1943. https://doi.org/10.1162/ jocn_a_00452.
- Alain, C., Cusimano, M., Garami, L., Backer, K. C., Habelt, B., Chan, V., et al. (2018). Agerelated differences in orienting attention to sound object representations. *Neurobiology of Aging*, 66, 1–11. https://doi.org/10.1016/j.neurobiolaging.2018.01. 026.
- Bachman, M. D., Van Den Berg, B., Wang, L., Gamble, M. L., Clark, K., & Woldorff, M. G. (2018). Visual search alpha: A novel window into lateralized visual attention

processes. 25th Annual Meetinghttps://doi.org/10.13140/RG.2.2.22690.53441 p. 47.
Backer, K. C., & Alain, C. (2014). Attention to memory: Orienting attention to sound object representations. Psychological Research, 78, 439–452. https://doi.org/10.

Backer, K. C., Binns, M. A., & Alain, C. (2015). Neural dynamics underlying attentional orienting to auditory representations in short-term memory. *The Journal of Neuroscience*, 35, 1307–1318. https://doi.org/10.1523/JNEUROSCI.1487-14.2015.

1007/s00426-013-0531-7

- Banerjee, S., Snyder, A. C., Molholm, S., & Foxe, J. J. (2011). Oscillatory alpha-band mechanisms and the deployment of spatial attention to anticipated auditory and visual target locations: Supramodal or sensory-specific control mechanisms? *The Journal of Neuroscience*, 31, 9923–9932. https://doi.org/10.1523/JNEUROSCI.4660-10.2011.
- Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society*, 57, 289–300. https://doi.org/10.2307/2346101.
- Blauert, J., & Braasch, J. (2008). Räumliches Hören. In S. Weinzierl (Ed.). Handbuch Der Audiotechnik (pp. 87–121). Berlin: Springer-Verlag. https://doi.org/10.1007/978-3-540-34301-1.
- Brozzoli, C., Demattè, M. L., Pavani, F., Frassinetti, F., & Farnè, A. (2006). Neglect and extinction: Within and between sensory modalities. *Restorative Neurology and Neuroscience*, 24, 217–232.
- Cherry, C. E. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America*, 25, 975–979. https://doi. org/10.1121/1.1907229.
- Cherry, E. C., & Taylor, W. K. (1954). Some further experiments upon the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America*, 26, 554–559. https://doi.org/10.1121/1.1907373.
- Cohen, J. (1973). Eta-squared and partial eta-squared in fixed factor anova designs. Educational and Psychological Measurement, 33, 107–112. https://doi.org/10.1177/ 001316447303300111.
- de Lange, F. P., Rahnev, D. A., Donner, T. H., & Lau, H. (2013). Prestimulus oscillatory activity over motor cortex reflects perceptual expectations. *The Journal of Neuroscience*, 33, 1400–1410. https://doi.org/10.1523/JNEUROSCI.1094-12.2013.
- Dell'Acqua, R., Sessa, P., Toffanin, P., Luria, R., & Jolicoeur, P. (2010). Orienting attention to objects in visual short-term memory. *Neuropsychologia*, 48, 419–428. https:// doi.org/10.1016/j.neuropsychologia.2009.09.033.
- Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of singletrial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, 134, 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.
- Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity.
- Electroencephalography and Clinical Neurophysiology, 99, 225–234. https://doi.org/10. 1016/S0921-884X(96)95711-2.
- Eimer, M., & Schröger, E. (1998). ERP effects of intermodal attention and cross-modal links in spatial attention. *Psychophysiology*, 35, 313–327. https://doi.org/10.1017/ S004857729897086X.
- Farah, M. I., Wong, A. B., Monheit, M. A., & Morrow, L. A. (1989). Parietal lobe mechanisms of spatial attention: Modality specific or supramodal? *Neuropsychologia*, 27, 461–470. https://doi.org/10.1111/j.1741-5446.1994.00001.x.

Field, A., Miles, J., & Field, Z. (2012). Discovering statistics using R. London: Sage.

- Foster, J. J., Bsales, E. M., Jaffe, R. J., & Awh, E. (2017). Alpha-band activity reveals spontaneous representations of spatial position in visual working memory. *Current Biology*, 27, 3216–3223. https://doi.org/10.1016/j.cub.2017.09.031.
- Foxe, J. J., & Snyder, A. C. (2011). The role of alpha-band brain oscillations as a sensory suppression mechanism during selective attention. *Frontiers in Psychology*, 2, 1–13. https://doi.org/10.3389/fpsyg.2011.00154.
- Frey, J. N., Mainy, N., Lachaux, J.-P., Müller, N., Bertrand, O., & Weisz, N. (2014). Selective modulation of auditory cortical alpha activity in an audiovisual spatial attention task. *The Journal of Neuroscience*, 34, 6634–6639. https://doi.org/10.1523/ JNEUROSCI.4813-13.2014.
- Gamble, M. L., & Luck, S. J. (2011). N2ac: An ERP component associated with the focusing of attention within an auditory scene. *Psychophysiology*, 48, 1057–1068. https://doi.org/10.1111/j.1469-8986.2010.01172.x.
- Gamble, M. L., & Woldorff, M. G. (2015). The temporal cascade of neural processes underlying target detection and attentional processing during auditory search. *Cerebral Cortex*, 25, 2456–2465. https://doi.org/10.1093/cercor/bhu047.
- Getzmann, S., & Lewald, J. (2010). Effects of natural versus artificial spatial cues on electrophysiological correlates of auditory motion. *Hearing Research*, 259, 44–54. https://doi.org/10.1016/j.heares.2009.09.021.
- Gould, I. C., Rushworth, M. F., & Nobre, A. C. (2011). Indexing the graded allocation of visuospatial attention using anticipatory alpha oscillations. *Journal of Neurophysiology*, 105, 1318–1326. https://doi.org/10.1152/jn.00653.2010.
- Groppe, D. M., Urbach, T. P., & Kutas, M. (2011). Mass univariate analysis of eventrelated brain potentials/fields I: A critical tutorial review. *Psychophysiology*, 48, 1711–1725. https://doi.org/10.1111/j.1469-8986.2011.01273.x.
- Haegens, S., Handel, B. F., & Jensen, O. (2011). Top-down controlled alpha band activity in somatosensory areas determines behavioral performance in a discrimination task. *The Journal of Neuroscience*, 31, 5197–5204. https://doi.org/10.1523/JNEUROSCI. 5199-10.2011.
- Harris, A. M., Dux, P. E., Jones, C. N., & Mattingley, J. B. (2017). Distinct roles of theta and alpha oscillations in the involuntary capture of goal-directed attention. *Neuroimage*, 152, 171–183. https://doi.org/10.1016/j.neuroimage.2017.03.008.
- Hartmann, W. M., & Wittenberg, A. (1996). On the externalization of sound images. The Journal of the Acoustical Society of America, 99, 3678–3688. https://doi.org/10.1121/ 1.414965.
- Heilman, K. M., & Van Den Abell, T. (1980). Right hemisphere dominance for attention: The mechanism underlying hemispheric asymmetries of inattention (neglect).

L.-I. Klatt et al.

Neurology, 30, 327-330. https://doi.org/10.1212/WNL.30.3.327.

- Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. *Science*, 182, 177–180. https://doi.org/10. 1126/science.182.4108.177.
- Hopf, J.-M., Boelmans, K., Schoenfeld, M. A., Luck, S. J., & Heinze, H.-J. (2004). Attention to features precedes attention to locations in visual search: Evidence from electromagnetic brain responses in humans. *The Journal of Neuroscience*, 24, 1822–1832. https://doi.org/10.1523/JNEUROSCI.3564-03.2004.
- Ikkai, A., Dandekar, S., & Curtis, C. E. (2016). Lateralization in alpha-band oscillations predicts the locus and spatial distribution of attention. *PLoS One*, 11, e0154796. https://doi.org/10.1371/journal.pone.0154796.
- Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: Gating by inhibition. Frontiers in Human Neuroscience, 4, 186. https://doi. org/10.3389/fnhum.2010.00186.
- Johnston, J. C., & Pashler, H. (1990). Close binding of identity and location in visual feature perception. Journal of Experimental Psychology Human Perception and Performance, 16, 843–856. https://doi.org/10.1037/0096-1523.16.4.843.
- Kavanagh, R. N., Darcey, T. M., Lehman, D., & Fender, D. H. (1978). Evaluation of methods for three-dimensional localization of electrical sources in the human brain. *IEEE Transactions on Biomedical Engeneering*, 25, 421–429. https://doi.org/10.1109/ TBME.1978.326339.
- Kelly, S. P., Gomez-Ramirez, M., & Foxe, J. J. (2009). The strength of anticipatory spatial biasing predicts target discrimination at attended locations: A high-density EEG study. *The European Journal of Neuroscience*, 30, 2224–2234. https://doi.org/10. 1111/j.1460-9568.2009.06980.x.
- Kelly, S. P., Lalor, E. C., Reilly, R. B., & Foxe, J. J. (2006). Increases in alpha oscillatory power reflect an active retinotopic mechanism for distracter suppression during sustained visuospatial attention. *Journal of Neurophysiology*, 95, 3844–3851. https:// doi.org/10.1152/jn.01234.2005.
- Kerlin, J. R., Shahin, A. J., & Miller, L. M. (2010). Attention gain control of ongoing cortical speech representations in a "cocktail party.". *The Journal of Neuroscience*, 30, 620–628. https://doi.org/10.1523/JNEUROSCI.3631-09.2010.
- Kiesel, A., Miller, J., Jolicoeur, P., & Brisson, B. (2008). Measurement of ERP latency differences: A comparison of single-participant and jackknife-based scoring methods. *Psychophysiology*, 45, 250–274. https://doi.org/10.1111/j.1469-8986.2007.00618.x.
- Psychophysiology, 45, 250–274. https://doi.org/10.1111/j.1469-8986.2007.00618.x. Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. Trends in Cognitive Sciences, 16, 606–617. https://doi.org/10.1016/j.tics. 2012.10.007.
- Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*, 1–12. https:// doi.org/10.3389/fpsyg.2013.00863.
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. Journal of Experimental Psychology Human Perception and Performance, 21, 451–468. https:// doi.org/10.1037/0096-1523.21.3.451.
- Lewald, J., & Getzmann, S. (2015). Electrophysiological correlates of cocktail-party listening. *Behavioural Brain Research*, 292, 157–166. https://doi.org/10.1016/j.bbr. 2015.06.025.
- Lim, S.-J., Wöstmann, M., & Obleser, J. (2015). Selective attention to auditory memory neurally enhances perceptual precision. *The Journal of Neuroscience*, 35, 16094–16104. https://doi.org/10.1523/JNEUROSCI.2674-15.2015.
- Liu, T., Stevens, S. T., & Carrasco, M. (2007). Comparing the time course and efficacy of spatial and feature-based attention. *Vision Research*, 47, 108–113. https://doi.org/10. 1016/j.visres.2006.09.017.
- Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: An open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, 8, 213. https://doi.org/ 10.3389/fnhum.2014.00213.
- Luck, S. (2014). Online chapter 13: A mass univariate approach and permutation statistics. An introduction to the event-related potential technique1689–1699. https://doi.org/10. 1017/CB09781107415324.004.
- Luck, S. J. (2005). The operation of attention Millisecond by millisecond Over the first half second. In H. Ogmen, & B. G. Breitmeyer (Eds.). The first half second: The microgenesis and temporal dynamics of unconscious and conscious visual processes (pp. 187– 206). Cambridge, MA: MIT Press.
- Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. Journal of Experimental Psychology Human Perception and Performance, 20, 1000–1014.
- Luck, S. J., & Hillyard, S. A. (1990). Electrophysiological evidence for parallel and serial processing during visual search. *Perception & Psychophysics*, 48, 603–617. https://doi. org/10.3758/BF03211606.
- Luck, S. J., Girelli, M., Mcdermott, M. T., & Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. *Cognitive Psychology*, 33, 64–87. https://doi.org/10.1006/ cogp.1997.0660.
- Macaluso, E., Eimer, M., Frith, C. D., & Driver, J. (2003). Preparatory states in crossmodal spatial attention: Spatial specificity and possible control mechanisms. *Experimental Brain Research*, 149, 62–74. https://doi.org/10.1007/s00221-002-1335-y.
- Marcell, M. M., Borella, D., Greene, M., Kerr, E., & Rogers, S. (2000). Confrontation naming of environmental sounds. *Journal of Clinical and Experimental Neuropsychology*, 22, 830–864. https://doi.org/10.1076/jcen.22.6.830.949.
- Maunsell, J. H. R., & Treue, S. (2006). Feature-based attention in visual cortex. Trends in Neurosciences, 29, 317–322. https://doi.org/10.1016/j.tins.2006.04.001.
- Mertes, C., Wascher, E., & Schneider, D. (2016). From capture to inhibition: How does irrelevant information influence visual search? Evidence from a spatial cuing paradigm. Frontiers in Human Neuroscience, 10. https://doi.org/10.3389/fnhum.2016. 00232 Article 232.
- Mognon, A., Jovicich, J., Bruzzone, L., & Buiatti, M. (2011). ADJUST: An automatic EEG

artifact detector based on the joint use of spatial and temporal features. *Psychphysiology*, 48, 229–240. https://doi.org/10.1111/j.1469-8986.2010.01061.x.

- Mok, R. M., Myers, N. E., Wallis, G., & Nobre, A. C. (2016). Behavioral and neural markers of flexible attention over working memory in aging. *Cerebral Cortex*, 26, 1831–1842. https://doi.org/10.1093/cercor/bhw011.
- Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *The Quarterly Journal of Experimental Psychology*, 11, 56–60. https://doi. org/10.1080/17470215908416289.
- Müller, N., & Weisz, N. (2012). Lateralized auditory cortical alpha band activity and interregional connectivity pattern reflect anticipation of target sounds. *Cerebral Cortex*, 22, 1604–1613. https://doi.org/10.1093/cercor/bhr232.
- Murphy, S., Spence, C., & Dalton, P. (2017). Auditory perceptual load: A review. Hearing Research, 352, 40–48. https://doi.org/10.1016/j.heares.2017.02.005.
- Myers, N. E., Walther, L., Wallis, G., Stokes, M. G., & Nobre, A. C. (2015). Temporal dynamics of attention during encoding vs. maintenance of working memory: Complementary views from event-related potentials and alpha-band oscillations. *Journal of Cognitive Neuroscience*, 27, 492–508. https://doi.org/10.1162/jocn_a_ 00727.
- Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective-attention effect on evoked potential reinterpreted. Acta Psychologica, 42, 313–329. https://doi.org/ 10.1016/0001-6918(78)90006-9.
- Noguchi, K., Gel, Y. R., Brunner, E., & Konietschke, F. (2012). nparLD: An R software package for the nonparametric analysis of longitudinal data in factorial experiments. *Journal of Statistical Software*, 50. https://doi.org/10.18637/jss.v050.i12.
- Onton, J., & Makeig, S. (2006). Information-based modeling of event-related brain dynamics. In C. Neuper, & W. Klimesch (Eds.). Progress in Brain Research (pp. 99–120). Elsevier B.V.. https://doi.org/10.1016/S0079-6123(06)59007-7.
- Poch, C., Campo, P., & Barnes, G. R. (2014). Modulation of alpha and gamma oscillations related to retrospectively orienting attention within working memory. *European Journal of Neuroscience*, 40, 2399–2405. https://doi.org/10.1111/ejn.12589.
- Posner, M. I., Cohen, Y., & Rafal, R. D. (1982). Neural systems control of spatial orienting. *Philosophical Transactions of the Royal Society B, 298*, 187–198. https://doi.org/10. 1098/rstb.1982.0081.
- Posner, M. I., Walker, J. A., Friedrich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orieting of attention. *The Journal of Neuroscience*, 4, 1863–1874. https:// doi.org/10.1523/JNEUROSCI.04-07-01863.1984.

R Core Team (2016). R: A language and environment for statistical computing.

- Rihs, T. A., Michel, C. M., & Thut, G. (2007). Mechanisms of selective inhibition in visual spatial attention are indexed by α-band EEG synchronization. *European Journal of Neuroscience*, 25, 603–610. https://doi.org/10.1111/j.1460-9568.2007.05278.x.
- Sauseng, P., Klimesch, W., Stadler, W., Schabus, M., Doppelmayr, M., Hanslmayr, S., et al. (2005). A shift of visual spatial attention is selectively associated with human EEG alpha activity. *The European Journal of Neuroscience*, 22, 2917–2926. https://doi.org/ 10.1111/j.1460-9568.2005.04482.x.
- Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A common neural mechanism for preventin and terminating the allocation of attention. *The Journal of Neuroscience*, 32, 10725–10736. https://doi.org/10.1523/JNEUROSCI.1864-12.2012.
- Schneider, D., & Wascher, E. (2013). Mechanisms of target localization in visual change detection: An interplay of gating and filtering. *Behavioural Brain Research*, 256, 311–319. https://doi.org/10.1016/j.bbr.2013.08.046.
- Schneider, D., Mertes, C., & Wascher, E. (2016). The time course of visuo-spatial working memory updating revealed by a retro-cuing paradigm. *Scientific Reports*, 6, 1–12. https://doi.org/10.1038/srep21442.

Shinn-Cunningham, B. G. (2008). Object-based auditory and visual attention. Trends in Cognitive Sciences, 12, 182–186. https://doi.org/10.1016/j.tics.2008.02.003.

- Shomstein, S., & Yantis, S. (2006). Parietal cortex mediates voluntary control of spatial and nonspatial auditory attention. *The Journal of Neuroscience*, 26, 435–439. https:// doi.org/10.1523/JNEUROSCI.4408-05.2006.
- Smith, D. V., Davis, B., Niu, K., Healy, E. W., Bonilha, L., Fridriksson, J., et al. (2010). Spatial attention evokes similar activation patterns for visual and auditory stimuli. *Journal of Cognitive Neuroscience*, 22, 347–361. https://doi.org/10.1162/jocn.2009. 21241.
- Snyder, A. C., & Foxe, J. J. (2010). Anticipatory attentional suppression of visual features indexed by oscillatory alpha-band power increases: A high-density electrical mapping study. *The Journal of Neuroscience*, 30, 4024–4032. https://doi.org/10.1523/ JNEUROSCI.5684-09.2010.
- Strauss, A., Woestmann, M., & Obleser, J. (2014). Cortical alpha oscillations as a tool for auditory selective inhibition. *Frontiers in Human Neuroscience*, 8, 350. https://doi.org/ 10.3389/fnhum.2014.00350.
- Thorpe, S., D'Zmura, M., & Srinivasan, R. (2012). Lateralization of frequency-specific networks for covert spatial attention to auditory stimuli. *Brain Topography*, 25, 39–54. https://doi.org/10.1007/s10548-011-0186-x.
- Thut, G., Nietzel, A., Brandt, S. A., & Pascual-Leone, A. (2006). α-band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *The Journal of Neuroscience*, 26, 9494–9502. https://doi.org/10.1523/JNEUROSCI.0875-06.2006.
- Tsal, Y., & Lavie, N. (1993). Location dominance in attending to color and shape. Journal of Experimental Psychology Human Perception and Performance, 19, 131–139. https:// doi.org/10.1037/0096-1523.19.1.131.
- Tune, S., Wöstmann, M., & Obleser, J. (2018). Probing the limits of alpha power lateralization as a neural marker of selective attention in middle-aged and older listeners. *The European Journal of Neuroscience*. https://doi.org/10.1101/267989.
 Vallar, G., & Perani, D. (1987). The anatomy of spatial neglect in humans.
- Neurophysiological and Neuropsychological Aspects of Spatial Neglect, 45, 235–258. https://doi.org/10.1016/S0166-4115(08)61716-1.
- Van der Lubbe, R. H. J., Blom, J. H. G., De Kleine, E., & Bohlmeijer, E. T. (2017).

L.-I. Klatt et al.

Comparing the effects of sustained and transient spatial attention on the orienting towards and the processing of electrical nociceptive stimuli. *International Journal of Psychophysiology*, 112, 9–21. https://doi.org/10.1016/j.ijpsycho.2016.11.015.

- Van Der Lubbe, R. H. J., Bundt, C., & Abrahamse, E. L. (2014). Internal and external spatial attention examined with lateralized EEG power spectra. *Brain Research*, 1583, 179–192. https://doi.org/10.1016/j.brainres.2014.08.007.
- van Driel, J., Gunseli, E., Meeter, M., & Olivers, C. N. L. (2017). Local and interregional alpha EEG dynamics dissociate between memory for search and memory for recognition. *NeuroImage*, 149, 114–128. https://doi.org/10.1016/j.neuroimage.2017. 01.031.
- van Diepen, R. M., Miller, L. M., Mazaheri, A., & Geng, J. J. (2016). The role of alpha activity in spatial and feature-based attention. *eNeuro*, 3, e0204–16.2016. https:// doi.org/10.1523/ENEURO.0204-16.2016.
- van Ede, F., de Lange, F., Jensen, O., & Maris, E. (2011). Orienting attention to an upcoming tactile event involves a spatially and temporally specific modulation of sensorimotor alpha- and beta-band oscillations. *The Journal of Neuroscience*, 31, 2016–2024. https://doi.org/10.1523/JNEUROSCI.5630-10.2011.
- van Ede, F., Niklaus, M., & Nobre, A. C. (2017). Temporal expectations guide dynamic prioritization in visual working memory through attenuated α oscillations. *The Journal of Neuroscience*, 37, 437–445. https://doi.org/10.1523/JNEUROSCI.2272-16. 2016.
- Wenzel, E. M., Arruda, M., Kistler, D. J., & Wightman, F. L. (1993). Localization using nonindividualized head-related transfer functions. *Journal of the Acoustical Society of America*, 94, 111–123.
- Wightman, F. L., & Kistler, D. J. (1989). Headphone simulation of free-field listening. I: Stimulus synthesis. *The Journal of the Acoustical Society of America*, 85, 858–867. https://doi.org/10.1121/1.397557.
- Wildegger, T., van Ede, F., Woolrich, M., Gillebert, C. R., & Nobre, A. C. (2017). Preparatory α-band oscillations reflect spatial gating independently of predictions regarding target identity. *Journal of Neurophysiology*, 117, 1385–1394. https://doi.

org/10.1152/jn.00856.2016.

- Wilsch, A., & Obleser, J. (2015). What works in auditory working memory? A neural oscillations perspective. *Brain Research*, 1640, 193–207. https://doi.org/10.1016/j. brainres.2015.10.054.
- Wood, N. L., & Cowan, N. (1995). The cocktail party phenomenon revisited: Attention and memory in the classic selective listening procedure of Cherry (1953). *Journal of Experimental Psychology General*, 124, 243–262. https://doi.org/10.1037/0096-3445. 124.3.243.
- Woods, D. L., Alho, K., & Algazi, A. (1994). Stages of auditory feature conjunction: An event-related brain potential study. *Journal of Experimental Psychology Human Perception and Performance*, 20, 81–94. https://doi.org/10.1037/0096-1523.20.1.81.
- Woods, D. L., Alho, K., & Algazi, A. (1991). Brain potential signs of feature processing during auditory selective attention. *NeuroRep*, 2, 189–192. https://doi.org/10.1097/ 00001756-199104000-00007.
- Worden, M. S., Foxe, J. J., Wang, N., & Simpson, G. V. (2000). Anticipatory biasing of visuospatial attention indexed by retinotopically specific α-band electroencephalography increases over occipital cortex. *The Journal of Neuroscience*, 20, RC63. https://doi.org/10.1523/JNEUROSCI.20-06-j0002.2000.
- Wöstmann, M., Herrmann, B., Maess, B., & Obleser, J. (2016). Spatiotemporal dynamics of auditory attention synchronize with speech. *Proceedings of the National Academy of Sciences of the United States of America*, 113. https://doi.org/10.1073/pnas. 1523357113.
- Wöstmann, M. W., Vosskuhl, J., Obleser, J., & Herrmann, C. S. (2018). Opposite effects of lateralised transcranial alpha versus gamma stimulation on auditory spatial attention. *Brain Stimulation*, 11, 752–758. https://doi.org/10.1016/j.brs.2018.04.006.
- Yamagishi, N., Goda, N., Callan, D. E., Anderson, S. J., & Kawato, M. (2005). Attentional shifts towards an expected visual target alter the level of alpha-band oscillatory activity in the human calcarine cortex. *Cognitive Brain Research*, 25, 799–809. https:// doi.org/10.1016/j.cogbrainres.2005.09.006.