RESEARCH ARTICLE

Anticipatory alpha oscillation predicts attentional selection and hemodynamic response

Chenguang Zhao¹ | Jialiang Guo¹ | Dongwei Li¹ | Ye Tao¹ | Yulong Ding^{2,3} | Hanli Liu⁴ | Yan Song^{1,5}

¹State Key Laboratory of Cognitive Neuroscience and Learning and IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, China

²School of Psychology, South China Normal University, Guangzhou, China

³Brain and Cognition Laboratory, Department of Psychology, Sun Yat-Sen University, Guangdong, China

⁴Department of Bioengineering, The University of Texas at Arlington, Arlington, Texas

⁵Center for Collaboration and Innovation in Brain and Learning Sciences, Beijing Normal University, Beijing, China

Correspondence

Yan Song, State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, China.
Email: songyan@bnu.edu.cn

Funding information

National Natural Science Foundation of China, Grant/Award Numbers: 31871099, 61761166003, 81771479; National Defense Basic Scientific Research Program of China, Grant/Award Number: 2018110B011; Fundamental Research Funds for the Central Universities, Grant/Award Number: 2017XTCX04

Abstract

In covert visual attention, one fundamental question is how advance knowledge facilitates subsequent neural processing and behavioral performance. In this study, with a rapid event-related simultaneous electroencephalography (EEG) and functional near infrared spectroscopy recording in humans, we explored the potential contribution of anticipatory electrophysiological activation and hemodynamic activation by examining how anticipatory low-frequency oscillations and changes in oxygenated hemoglobin (HbO) concentration influence the subsequent event-related potential (ERP) marker of attentional selection. We found that expecting a target led to both a posterior lateralization of alpha-band (8–12 Hz) oscillation power and a lateralization of HbO response over the visual cortex. Importantly, the magnitude of cue-induced alpha lateralization was positively correlated with the nearby HbO lateralization in the visual cortex, and such a cue-induced alpha lateralization predicted the subsequent target-evoked N2pc amplitudes assumed to reflect attentional selection. Our results suggest that each individual's attentional selection biomarker as reflected by N2pc is predictable in advance via the anticipation-induced alpha lateralization, and such cue-induced alpha lateralization seems to play an important role in the functional coupling effects between the low-frequency EEG and the nearby hemodynamic activation.

KEYWORDS

alpha oscillation, covert visual attention, EEG, fNIRS, N2pc

1 | INTRODUCTION

Human beings are exposed to a large number of visual stimuli in daily life. We focus our attention on visual stimuli that are most relevant to our current goals, and ignore behaviorally irrelevant input. In laboratory studies, an experimental paradigm known as visual search has been used extensively to investigate the factors that govern this attentional selectivity. One fundamental question in visual search is how advance knowledge facilitates subsequent perceptual processing (Moran & Desimone, 1985; Posner, 1980). Numerous electroencephalography (EEG) studies have revealed that the modulation of posterior

alpha oscillations (8–12 Hz) following an attentional cue is one robust neural marker signifying selective sensory biasing by covert attention via top-down mechanisms (Kelly, Lalor, Reilly, & Foxe, 2006; Sauseng et al., 2005; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Worden, Foxe, Wang, & Simpson, 2000). When covert attention is directed to one side of the visual field, alpha oscillation is more strongly suppressed over the hemisphere contralateral to the attended hemifield (Rajagovindan & Ding, 2011; Sauseng et al., 2005; Thut et al., 2006; Worden et al., 2000). This lateralized reduction of alpha activity is thought to reflect an increase in cortical excitability in task-relevant sensory neurons to facilitate the processing of upcoming stimulus

inputs (Romei et al., 2008; Sauseng et al., 2005; Thut et al., 2006). One recent study showed that the magnitude of cue-induced alpha lateralization was positively correlated with BOLD in the dorsal anterior cingulate cortex and dorsolateral prefrontal cortex, implicating a role of executive control in attention (Liu, Bengson, Huang, Mangun, & Ding, 2016). The alpha modulation is likely, on the basis of these findings, to play an important role in attentional processes by gating streams of information through the brain (Buffalo, Fries, Landman, Buschman, & Desimone, 2011; Fries, Reynolds, Rorie, & Desimone, 2001; Goldman, Stern, Engel Jr., & Cohen, 2002; Haegens, Nacher, Luna, Romo, & Jensen, 2011; Romei et al., 2008; Spaak, Bonnefond, Maier, Leopold, & Jensen, 2012).

Besides the modulation of posterior alpha oscillations, evidence from neuroimaging studies have revealed that, anticipation for lateral targets involves the hemodynamic modulation of putative attentional control structures (e.g., in frontal-parietal circuits) and some spatiotopic modulations of the visual cortex. These typically take the form of increased hemodynamic activations in those parts of the visual cortex representing the hemifield or retinotopic location in which a visual target is anticipated (Chawla, Rees, & Friston, 1999; Hopfinger, Buonocore, & Mangun, 2000; Huang et al., 2015; Kastner & Ungerleider, 2000; Macaluso, Eimer, Frith, & Driver, 2003; Ress, Backus, & Heeger, 2000; Ruff & Driver, 2006). This lateralized increment of hemodynamic activations provides direct empirical support for the notion that visual selective attention operates in part by means of top-down signals that can modulate activity in the occipital cortex in a preparatory fashion.

Although the hemispheric lateralization of the alpha and hemodynamic activity during anticipation has been proven to be highly robust phenomena, it has not been clearly demonstrated whether they reflect some overlapping neural mechanisms and how they influence the subsequent attentional processing of targets (Eimer & Grubert, 2014; Huang et al., 2015). The simultaneous recording of EEG and fMRI (or functional near infrared spectroscopy, fNIRS) opens avenues to address the gap between hemodynamic activities at higher spatial resolution and EEG at a higher temporal resolution (Huang et al., 2015; Laufs et al., 2003; Moosmann et al., 2003; Scheeringa et al., 2011). Most importantly, the fNIRS signals and the EEG/ERP signals are not affected by each other. Therefore, concurrent fNIRS-EEG recording could potentially provide a detailed picture of the relationship between the cortical hemodynamics and the electrophysiological activity. On the other hand, there is an important issue in the concurrent fNIRS-EEG recording study: the ERP studies adopted rapid event-related design, while blocked experimental designs and protocols have been commonly utilized in most fNIRS studies to investigate cerebrovascular functions in response to different kinds of stimuli and conditions. Recently, with the use of the general linear model (GLM) for fNIRS data analysis, event-related designs have been incorporated in fNIRS studies (Ferrari & Quaresima, 2012; Plichta et al., 2006; Schaeffer et al., 2014). However, to our knowledge, none of the currently published studies have used the simultaneous recording of EEG and fNIRS based on the rapid event-related design.

In the present study, we recorded simultaneous fNIRS-EEG from human adults performing a cued visual-spatial attention task. By using rapid event-related design, we manipulated on a trial-by-trial basis advance information about the cued visual side in which a target would appear and examined two primary questions regarding the neural correlates of spatial attention. First, do the parieto-occipital hemodynamic lateralized activity and the cue-induced modulation of the lateralized alpha effect, to some extent, reflect some overlapping neural mechanisms of attentional control? If so, we should expect a significant correlation between the two measures. Second, how do parieto-occipital hemodynamic lateralized activity and anticipatory alpha oscillations influence the subsequent attentional processing of targets? Here, we focus on the N2-posterior-contralateral (N2pc) component, a robust biomarker of visual attentional selection. Interestingly, the N2pc was a lateralized component, which was isolated by subtracting the ipsilateral ERP waveform from the contralateral ERP waveform to the targets. The modulation of the N2pc by task set and anticipation has been interpreted as evidence for top-down attentional control (An et al., 2012; Gaspar, Rousselet, & Pernet, 2011; Kiss, Jolicoeur, Dell'acqua, & Eimer, 2008; Qu et al., 2014). In this case, we expect that there might be a significant correlation between anticipatory alpha lateralization/hemodynamic lateralization and subsequent target-elicited N2pc during visual search (Huang et al., 2015).

2 | MATERIALS AND METHODS

2.1 | Participants

Thirty healthy undergraduate and graduate students participated in our experiments twice in 2 days as paid volunteers. All the participants had normal or corrected-to-normal vision and were right-handed. They were new to psychophysical experiments and unaware of the purposes of the study. Four subjects were removed for too much ocular or myogenic artifacts by two-step procedure (Sawaki, Geng, & Luck, 2012, see details below). Data from the remaining 26 participants (8 males, age range = 19–29 years, mean age = 22.07 years) were used. The current research was approved by the Beijing Normal University Institutional Review Board, and informed consent was obtained from each participant.

2.2 | Behavioral procedure

An example of the stimuli and trial design are illustrated in Figure 1. The stimuli were presented on a 21-in. gamma linearized CRT monitor (1920 pixels $\times$ 1,080 pixels, 60 Hz frame rate) with a black background (0.5 cd/m^2) at a distance of 57 cm. At the beginning of each trial, a cue display appeared for 200 ms. Each cue display consisted of two colored arrows ($0.1^\circ \times 0.5^\circ$, centered 3.0° to the left and right of fixation): the yellow arrow ($25 \pm 0.1 \text{ cd/m}^2$, $x = 0.45$, $y = 0.48$; pointed to the left or right, randomized with equal probability) was fully predictive (with 100% validity) with respect to the side where the following yellow target circle would appear, while the opposite green arrow ($28 \pm 0.1 \text{ cd/m}^2$, $x = 0.297$, $y = 0.586$) had no predictive value.

FIGURE 1 Illustration of the sequence of events within a trial. The yellow arrow in the cue display was fully predictive (with 100% validity) with respect to the side where the following yellow target circle would appear, while the opposite green arrow had no predictive value. Participants were required to identify the orientation of the gray line (horizontal or vertical) inside the yellow target circle. In visual search array, the location of a red circle (distractor) was randomized to produce three display configurations: Midline distractor with lateral target (66%), lateral distractor with the same target side (17%), and lateral distractor with the opposite target side (17%) [Color figure can be viewed at wileyonlinelibrary.com]

Following a 1,200–1,600 ms interstimulus interval (ISI), a visual search array was presented for 200 ms. Each visual search array consisted of 10 unfilled circles ($1.7^\circ \times 1.7^\circ$, 0.3° thick outline, 13.5 cd/m^2 mean optical luminance) positioned along the circle at a distance of 9.2° visual angle from the central fixation cross. Among the circles, a lateral yellow circle (target) was simultaneously presented with a red circle (distractor), whose location was randomized and varied to produce three display configurations (Figure 1): midline distractor (66%), lateral distractor on the same target side (17%), and lateral distractor on the opposite target side (17%). A vertical or horizontal gray line (gray: $11.1 \pm 0.1 \text{ cd/m}^2$, $x = 0.312$, $y = 0.329$) was contained within each of the circles. Participants were instructed to maintain their gaze at fixation and deploy their attention to the cued side but to ignore other items including the distractor circle, and report the orientation of the gray line (vertical or horizontal) inside the target circle presented on the cued side. They were instructed to respond by pressing one of two buttons with their right hand as quickly and accurately as possible. The experiment contained 20 blocks for a total of 400 trials per participant (i.e., 20 trials per block per participant). Participants were encouraged to rest and to start the next block of trials when ready. The protocol lasted ~30 min.

2.3 | EEG recording and analysis

Participants' EEG and optical signals were recorded simultaneously while they were performing the task. The EEG data were acquired using a SynAmps EEG amplifier and Scan 4.5 package (NeuroScan, Inc.) from a EEG cap with 32 silver chloride electrodes mounted on an elastic cap (Wuhan Greentek Pty. Ltd.) according to the international 10–20 system (Figure 2a). To detect eye movements and blinks, the EOG was recorded from electrodes placed at the outer canthi of each

eye, and above and below the left eye. All electrodes, except those for monitoring eye movements, were physically referenced to the left mastoid and were then off-line re-referenced to the average of the left and right mastoids. Electrode impedance was kept below $5 \text{ k}\Omega$. The EEG was amplified with DC-200 Hz, digitized on-line at a sampling interval of 1 ms, and then off-line filtered with a digital band-pass of 0.1–40 Hz.

All EEG/ERP analyses were conducted using MATLAB and the related packages EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). Trials were automatically excluded if they contained an incorrect response, if the RT was shorter than 200 ms or longer than 800 ms, if the EEG exceeded $\pm 100 \mu\text{V}$ in any channel, if the vertical EOG exceeded $\pm 80 \mu\text{V}$, or if the horizontal EOG exceeded $\pm 50 \mu\text{V}$ during the cue or stimulus epochs. Data from two participants were discarded because of the high ratio of excluded trials (>40% of trials). To assess residual eye movements, we computed the averaged horizontal EOG waveforms for left- and right-target trials during the cue and stimulus epochs. Two participants with residual horizontal EOG activity $> 3.2 \mu\text{V}$ (corresponding to an ocular deviation of $\pm 0.1^\circ$) were excluded. Among the final set of participants, artifacts led to an average rejection rate of 17.5% of trials (range 2.48%–39.5%). There were ~120–195 EEG trials for each hemifield targets in the analysis.

A fast Fourier transform with Hanning window tapering (EEGLAB's default algorithm) and a padding ratio of four was used. Event-related spectral perturbation maps (ERSPs) were computed over a frequency range of 4–40 Hz. Differences in time–frequency power can reflect event-related differences in ongoing oscillatory power (i.e., “induced” activity). Alternatively, they could be explained by the ERP exhibiting strong power in (low-)frequency components (“evoked” activity; Yeung, Bogacz, Holroyd, Nieuwenhuis, & Cohen,

FIGURE 2 (a) Close-up view of the EEG cap with integrated NIRS fiber probes (Hitachi ETG-4000). EEG was recorded from 32 scalp positions (black) according to the international 10–20 system. fNIRS data were obtained using two sets of 3×5 optodes with seven detectors (blue) and eight sources (red), resulting in two 22 channels symmetrically fitted on each lateral side of the head. (b) Left view of the fNIRS optode configuration. All the fNIRS optodes and six EEG electrodes (P3/P4, P7/P8, Cz and Oz) are labeled with vitamin E capsules (bright spheres in the figure). (c) Cerebral projections of two 22 channels (blue) overlaid on the participants' scalp [Color figure can be viewed at wileyonlinelibrary.com]

2007). To evaluate this, we disentangled nonphase-locked from phase-locked power. We first subtracted the trial-average activity in the time domain (i.e., the ERP) from the raw EEG activity of every single trial and then recomputed the time–frequency power as described above. Because removing the ERP from the data effectively removes any phase-locked component, the resulting power is nonphase-locked. Phase-locked power is then simply the result of total power (acquired as described in the previous paragraph) minus nonphase-locked power. This method has been described in Cohen and Donner (2013).

Then, the time interval was cue-locked from -500 ms to $1,000$ ms around cue onset, and the alpha modulation index (MI) from cue-locked data was used to investigate the cue-elicited modulation in the alpha band (8–12 Hz). The degree of lateralization for alpha band power was defined by using the formula (Vollebregt et al., 2015) as follows:

For left MI:

$$\text{Left modulation index (LMI)} = \frac{\left(\alpha_{\text{Left-cued trials}}^{\text{Left electrodes}} - \alpha_{\text{Left-cued trials}}^{\text{Right electrodes}} \right)}{\frac{1}{2} \left(\alpha_{\text{Left-cued trials}}^{\text{Left electrodes}} + \alpha_{\text{Left-cued trials}}^{\text{Right electrodes}} \right)}$$

For right MI:

$$\text{Right modulation index (RMI)} = \frac{\left(\alpha_{\text{Right-cued trials}}^{\text{Right electrodes}} - \alpha_{\text{Right-cued trials}}^{\text{Left electrodes}} \right)}{\frac{1}{2} \left(\alpha_{\text{Right-cued trials}}^{\text{Right electrodes}} + \alpha_{\text{Right-cued trials}}^{\text{Left electrodes}} \right)}$$

For combined MI:

$$\text{Combined MI} = \text{LMI} - \text{RMI}.$$

Epochs beginning 200 ms before and ending 400 ms after visual search display onset were chosen to obtain the averaged stimulus-

elicited ERP waveforms. The 200 ms prestimulus period served as the baseline. ERP difference waves were computed by subtracting the ERP waveforms measured from electrodes on the ipsilateral hemisphere to the target from symmetrical electrodes on the contralateral hemisphere. Note that the contralateral waveform for the target was the average of the left-hemisphere electrode when the target was in the right visual field and the right-hemisphere electrode when the target was in the left visual field. Similarly, the ipsilateral waveform for the target was the average of the left-hemisphere electrode when the target was in the left visual field and the right-hemisphere electrode when the target was in the right visual field. Because the overall optical luminance of the stimuli was bilateral, this subtraction eliminates most common ERP components, with N2pc remaining in the difference wave (Luck, Ford, Sarter, & Lustig, 2012). The N2pc label stems from the latency of the component, which is in the range of the visual N2, and its scalp topography, which is posterior and contralateral to an attended stimulus (Hickey, Di Lollo, & McDonald, 2009). We measured the N2pc at the P7/8 electrode sites, where they showed the largest amplitudes.

A cluster based permutation test was performed to identify time clusters for which the left MI differed significantly from the right MI (van Ede, de Lange, Jensen, & Maris, 2011). This test controls multiple comparisons by identifying significant clusters of time points rather than individual time points. The longest significant time cluster was used for further analyses. Similar analyses were conducted for ERP data.

2.4 | Optical signal recording and analysis

Participants' optical signals and EEG were recorded simultaneously while the participants were performing the task. fNIRS measurements

were conducted with a continuous wave system (ETG-4000, Hitachi Medical Co., Japan) using two different wavelengths (695 ± 20 and 830 ± 20 nm) with a sampling frequency of 10 Hz. Two probe sets of 3×5 optodes were used in this study with each probe set consisting of eight emitters and seven detectors, forming 22 measurement channels per set (and 44 channels in total). The emitters and detectors were positioned alternately in space with the two-piece flexible holders and with an emitter–detector distance of 30 mm. The two-piece flexible holders were then mounted on the same elastic cap with 32 silver chloride electrodes (Figure 2a), so they symmetrically covered the bilateral occipital, parietal and temporal cortices with the Oz electrode just at the middle between left CH1 and right CH1 (Figure 2b). For co-registration of fNIRS channels on the participants' cortical regions, all locations of fNIRS channels and six EEG electrodes (P3/4, P7/8, Cz, and Oz) were marked on one participant's scalp by attaching vitamin E capsules (visible in structural MR imaging) when this participant underwent a structural MRI scan. NIRS_SPM was used to project the measurement channels onto the cortical surface and to further determine the anatomical localization of each fNIRS measurement channel (Figure 2c). The structural MRI data were acquired using a SIE-MENS TRIO 3-Tesla scanner in the Imaging Center for Brain Research, Beijing Normal University. During MRI data acquisition, the participant was lying supine in the MRI scanner with his head attached with the vitamin E capsules that were accurately placed at the actual fNIRS optode locations. The T1-weighted structural image was acquired using magnetization-prepared rapid gradient echo sequence: 176 slices, TR = 2,600 ms, TE = 3.02 ms, FOV = 256×224 mm², voxel size = 1 mm $\times$ 1 mm $\times$ 1 mm, flip angle = 8°, and slice orientation = sagittal.

Optical data were subjected to an identical preprocessing procedure for each channel using HomER (Huppert, Diamond, Franceschini, & Boas, 2009), applying the modified Beer–Lambert law to convert relative changes in light intensities to changes of HbO and HbR (Cope et al., 1988). The filtered band-pass frequency was from 0.02 to 0.1 Hz to remove the high-frequency (>0.1 Hz) physiological noises, and low-frequency (<0.02 Hz) baseline drifts. In addition, for correction of movement artifacts, trials at the beginning and end of measurements were removed if their z-transformed HbO signals showed abrupt signal changes, resulting in HbO or HbR concentrations more than two standard deviations above or beneath the mean.

The preprocessed fNIRS time series were analyzed in an event-related way with a model-based approach applying the GLM; namely, hemodynamic response functions were convolved with the event sequence (Plichta et al., 2007; Plichta, Heinzel, Ehli, Pauli, & Fallgatter, 2007). Specifically, the preprocessed data were analyzed according to the two-stage ordinary least squares (OLSs) estimation methodology (Bullmore et al., 1996; Marchini & Smith, 2003). We used Gaussian hemodynamic response functions with a peak time of 6.5 s as predictors for the HbO and HbR time series. A delta function indicating the onset of cue display presentations was convolved with the predictors, and the first-stage OLS estimation was performed. Resulting residuals were inspected for model conformity. At the second stage, beta weights (β), which represent the amplitudes of the hemodynamic response, were re-estimated for each channel at the single subject level.

To perform an analysis on lateralization effect, similar to that conducted in ERP analysis, lateralization index (LI) of HbO responses was computed using the following formula. The LI was computed by combining two difference: for right-cued trials, subtract the β value of the right channel from the left channel; for left-cued trials, subtract the β value of the left channel from the right channel. Then these subtractions were subsequently averaged by dividing by two:

Lateralization index (LI)

$$= \frac{\left(\beta_{\text{Left channel}}^{\text{Right channel}} - \beta_{\text{Left channel}}^{\text{Left channel}} \right) + \left(\beta_{\text{Right channel}}^{\text{Left channel}} - \beta_{\text{Right channel}}^{\text{Right channel}} \right)}{2}$$

Finally, the *t*-map was generated in EasyTopo toolbox (Tian & Liu, 2014).

3 | RESULTS

3.1 | Behavioral performance

The behavioral results indicated that participants were able to discriminate the target rapidly and accurately. The mean RT for targets was 692 ± 90 ms, and the mean target discrimination accuracy was $97.14\% \pm 2.21\%$.

3.2 | EEG results

3.2.1 | Alpha-band power is lateralized by cue

First, to study hemispheric modulation of EEG oscillations following the cue initiated allocation of attention, we contrasted the alpha-band power for left versus right cues for each hemisphere separately and in combination. The time-course of alpha band power for left-cued trials minus right-cued trials, normalized by their mean and averaged over left and right (Figure 3a) occipital and parietal electrodes demonstrated a clear modulation induced by cue array. Then, topographically, the difference in the degree of alpha suppression between two hemispheres gave rise to the hemispheric lateralization pattern seen in Figure 3b, in which alpha power from the attend-right condition was subtracted from the attend-left condition. Note that the significant target lateralized effect was found in the parieto-occipital cortical areas (P3/4, P7/8, O1/2) from topographic maps of combined MI (400–800 ms, Figure 3b). This lateralization pattern in posterior alpha matches findings reported in prior studies of visual spatial attention (e.g., Thut et al., 2006; Vollebregt et al., 2015; Worden et al., 2000).

3.2.2 | ERPs are lateralized by the subsequent target selection

Figure 3c shows the ERP waveforms in response to the subsequent visual search arrays from electrodes over the visual cortex contralateral and ipsilateral to the target (P7 and P8). Following the presentation of search array, the N2pc component was present as a negative deflection in the ERP waveform at contralateral relative to ipsilateral

FIGURE 3 Results of parieto-occipital alpha oscillation during the cue period. (a) Time-course of the combined MI (left electrode MI minus right electrode MI) average over all subjects across three pairs of electrodes (P3/4, P7/8, O1/2) in the 8–12 Hz alpha band. The gray line shows the time window in which the MI in the left and right electrodes differed significantly between 400 and 800 ms ($p < .050$). (b) Scalp topographies of MI. Topographic representation of the combined MI (400–800 ms) over all subjects in the alpha band. The alpha power that was clearly lateralized with respect to the spatial cue only during the cue period appears restricted to the posterior electrodes (P3/4, P7/8, and O1/2). The black dotted box represents the coverage of fNIRS measurement channels per set. (c) Grand averaged ERPs at contralateral and ipsilateral electrode sites relative to the target (averaged over P7 and P8). (d) Topographic maps of N2pc (220–320 ms) [Color figure can be viewed at wileyonlinelibrary.com]

scalp sites, beginning at ~200 ms poststimulus, thus suggesting the existence of target lateralized effect in brain activity. This can also be observed in the contralateral-minus-ipsilateral difference waves shown in Figure 3c. The topographic map of the N2pc component is plotted in Figure 3d. The scalp distribution is qualitatively similar to those observed in prior N2pc studies (Hickey et al., 2009; Luck & Hillyard, 1994a, 1994b; Sawaki et al., 2012). To assess the statistical significance of this target lateralized effect, we measured the mean ERP voltage from 220 ms to 320 ms relative to the mean voltage during the 200 ms prestimulus baseline period. All measurements were taken from original ERP waveforms. Paired t -tests revealed that the target contralateral N2 was significantly more negative relative to ipsilateral N2 at P7/P8 ($t_{[25]} = -6.48, p < .001$).

3.2.3 | Correlation between cue-induced alpha lateralization and subsequent biomarker of attentional selection

We used the time–frequency correlation to investigate the relationship between the cue-induced alpha lateralization and subsequent

biomarker of attentional selection (N2pc). First, we calculated the combined MI by subtracting the left and right hemisphere MIs to obtain time–frequency modulation representation (Figure 4a). Statistical analyses in the all band (4–40 Hz) and the time (–200–800 ms) that showed the most pronounced task-related spectrogram (see black outlines in Figure 4a) was defined (paired t -test, $p < .050$, FDR corrected for a prior defined frequency range 4–40 Hz across the entire time period), which demonstrated a clear modulation effect mainly constrained to this time–frequency ROI. Combined MI values within parieto-occipital electrodes (P3/4, P7/8, O1/2) were extracted at a time range of –200–800 ms with 60 ms time windows at 5 ms intervals in 200 steps for each subject. A correlation coefficient between anticipatory combined MI values and subsequent target-evoked N2pc component at each frequency and at each time interval was determined. All of these pixels constituted the time–frequency correlation map related to target-evoked N2pc component. Then, sustained correlations (highlighted by black outlines in Figure 4b; $p < .050$, FDR corrected) were found within the frequency range of 8–12 Hz from 400 ms to 600 ms, which suggested that a strong relationship between alpha-band activity and N2pc amplitudes was

FIGURE 4 Relationship between anticipatory alpha signals and the subsequent target-elicited N2pc amplitudes within and between participants. (a) Time–frequency map of the MI (normalized modulation in power for left MI minus right MI) shows a significant difference between left and right electrodes. The areas highlighted by black outlines in the time–frequency map show the correlation statistical analysis at the significance level ($p < .050$) that was used to assess cue-related effects on the grand-average time–frequency representations and to define the electrodes in the parieto-occipital area (P7/8, P3/4, O1/2). (b) Time–frequency correlation map shows the significant correlation between combined alpha MI (expressed as MI%) and the subsequent target-elicited N2pc amplitudes. (c) Anticipatory alpha oscillation lateralization (expressed as the combined MI that was averaged over the time–frequency windows highlighted by black outlines in the time–frequency correlation map) during the cue period as a function of the subsequent N2pc amplitudes during visual search between participants. (d) For each individual, the trials were divided in high and low alpha lateralization and subsequently averaged. The bar graphs illustrated the normalized N2pc from high and low alpha lateralization pools, which confirmed that trials dominated by higher anticipatory alpha lateralization were characterized by larger target-elicited N2pc amplitude for each individual ($p < .050$) [Color figure can be viewed at wileyonlinelibrary.com]

evident within several intervals. Therefore, we simply averaged the alpha-band energy within 400–600 ms. The significantly positive correlation between target-evoked N2pc amplitudes and combined alpha MI averaged within 400–600 ms is shown in Figure 4c ($r = .536$, $p < .004$). To eliminate effect of alpha lateralization during prestimulus baseline, we re-analyzed the N2pc by baseline correction without alpha band power. The results suggested that the N2pc effect was not affected by the $-200-0$ ms period of prestimulus alpha activity (See Figure S1 for descriptions of detailed analysis and statistical results).

To further confirm the close relationship between the alpha oscillation and the subsequent N2pc, for each participant, the EEG data were split in two pools of high and low alpha lateralization. Then, we constructed separate ERP waveforms for each pool. The N2 lateralization was calculated for each pool and normalized to the individual mean value for each subject. We found that trials dominated by stronger alpha hemispheric lateralization during the cue period had larger target-elicited N2pc amplitudes in the following visual search

(Figure 4d; $t_{(25)} = -2.08$, $p < .050$). That is, the degree of alpha lateralization was predictive of the following target-elicited N2pc amplitudes across trials. Therefore, there was a close relationship between cue-induced alpha lateralization and subsequent biomarker of attentional selection in between and within subjects.

3.3 | fNIRS results

3.3.1 | HbO signals are lateralized during the cued covert spatial task

We quantified lateralized modulation of HbO by quantifying the lateralization index of HbO signal for each pair of symmetrical channels. One sample t -test showed a significant lateralized effect in the parieto-occipital cortex (Figure 5a). A significant HbO lateralized effect was found in two channels near the region between P3/4 and P7/8 (CH10: $t_{(25)} = 4.642$, $p < .010$; CH14: $t_{(25)} = 2.310$, $p < .030$; uncorrected). These results demonstrate a strong lateralization in hemodynamic activity during this cue covert spatial task. This

FIGURE 5 (a) The lateralization index map of HbO signals (left; middle) and a 3D rendered t-map (right) to display brain regions where the HbO changes are significantly lateralized from the baseline induced by the cued visual spatial task (CH10: $t = 4.642$, $p < .010$; CH14: $t = 2.310$, $p < .050$; uncorrected). (b) Correlation map (left; middle) showing the region (CH14) where there was a significant correlation between the lateralized HbO signals and the combined MI of alpha activity ($p < .050$ uncorrected). Scatter plot (right) depicting the close relationship between the lateralized HbO signals and the lateralized alpha power between subjects. (c) Correlation map (left) showing the region (CH14 and CH10) where there were significant correlations between lateralized HbO signals and the subsequent N2pc amplitudes ($p < .050$ uncorrected). Scatter plot (right) depicting the close relationship between the HbO lateralization index from V4 cortex (CH 10) and the subsequent N2pc amplitude ($r = .390$, $p < .040$) [Color figure can be viewed at wileyonlinelibrary.com]

lateralization pattern in HbO signals matches one previous concurrent fNIRS-EEG study with a block design (Huang et al., 2015).

3.3.2 | HbO-EEG/ERP coupling

We investigated whether HbO lateralization was correlated with individual differences in alpha oscillation lateralization (P3/4, P7/8, O1/2). Significant channels of correlation between lateralized alpha power and lateralization index of HbO signal were used to create functional ROIs.

The significant coupling effect was only found in the CH14 channel ($r = .440$, $p < .020$). As illustrated in Figure 5b, greater lateralization of HbO signal was closely and positively correlated with larger combined alpha MI across all participants (the mean values averaged over 400–600 ms), which suggested that the more lateralized the posterior alpha was, the more lateralized the posterior HbO signals in the visual cortex were. Then, we tested whether the HbO lateralization was correlated with individual differences in ERP attentional selection biomarker (N2pc). A significant correlation effect was found in CH10 and CH14. As

illustrated in Figure 5c, greater anticipatory lateralized HbO signals (LI of HbO signal) were closely and positively correlated with larger N2pc amplitude (P7/P8 electrodes; $r = .390$, $p < .040$). Note that the locations with significant correlations (CH10 or CH14) were similar to the regions where there was significant HbO lateralization (Figure 5a) over the parieto-occipital cortical areas. As mentioned in Section 2, by using structural MR imaging, we used NIRS_SPM to project the measurement channels onto the cortical surface and to further determine the anatomical localization of each fNIRS measurement channel. The results showed that the anatomical localization of CH10 and CH14 was in the region of V4.

We also correlated each hemisphere alpha MI indices with the similar contrast in the hemodynamic fNIRS response. The results showed that the alpha MI of each hemisphere was negatively correlated with the similar HbO contrast in some occipital and temporal cortex (see Figure S2 for results).

3.3.3 | Unique contribution of alpha oscillations to individual differences in N2pc

We found that there was a significant correlation between the parieto-occipital hemodynamic activity lateralization and anticipatory

parieto-occipital alpha lateralization (Figure 5b), and both of them could predict the ERP marker of attentional selection (Figures 4c and 5c). These findings indicate that these two kinds of signals, to some extent, reflect some overlapping neural modulation mechanisms of attentional control. Then, we established a regression model to investigate which signal can explain more variance in the individual differences in N2pc amplitude. When adding the lateralized HbO signals as the primary predictor and adding the alpha MI as the secondary predictor, the amount of explained variance in individual differences in N2pc was significantly increased (F -change $[1,23] = 10.150$, $p < .050$). However, this increment effect disappeared when adding the alpha MI as the primary predictor and adding the lateralized HbO signals as the secondary predictor (F -change $[1,23] = 0.266$, $p = .658$). This result indicated that it is anticipatory alpha oscillation, not parieto-occipital hemodynamic HbO activity, mainly predicts subsequent attentional selection biomarker.

The above indication was proved by further partial correlation analysis. We used HbO lateralization and anticipatory alpha oscillation lateralization as control variates to explain variance in the subsequent N2pc amplitude, respectively. When HbO lateralization was controlled, alpha oscillation lateralization still showed a significant correlation with subsequent N2pc

FIGURE 6 Relationship between anticipatory alpha signals and the subsequent target-elicited N2pc amplitudes within and between participants in the control experiment. (a) Illustration of the sequence of stimuli in the control experiments. (b) Correlation statistical analysis at the significance level ($p < .050$, FDR corrected) that was used to assess cue-related effects on the grand-average time–frequency representations and define the electrodes in the parieto-occipital area (P7/8, P3/4, and O1/2). The time–frequency pixels display the significant correlation between combined MI (expressed as MI%) and subsequent N2pc amplitudes. (c) Anticipatory alpha oscillation lateralization (reflected as the combined MI) during the cue period as a function of the subsequent N2pc amplitudes during the visual search between participants. (d) For each individual, the trials were divided in high and low alpha lateralization and subsequently averaged. The bar graphs illustrated the normalized N2pc from high and low alpha lateralization pools, which confirmed that trials dominated by higher anticipatory alpha lateralization were characterized by larger target-elicited N2pc amplitude for individuals ($p < .050$) [Color figure can be viewed at wileyonlinelibrary.com]

amplitude (CH10: $r = .635$, $p < .001$; CH14: $r = .553$, $p < .004$). However, when alpha oscillation lateralization was controlled, HbO lateralization did not show a close relationship to the N2pc amplitude (CH10: $r = .268$, $p = .195$; CH14: $r = .107$, $p = .611$), further suggesting that the variance in the individual differences in N2pc amplitude is mainly explained by anticipatory alpha oscillation lateralization.

3.4 | Further analysis

We further investigated whether the alpha lateralization, the HbO lateralization and the subsequent N2pc could predict the behavioral performance by using the same methods mentioned in the above statistical analysis. (See Figure S3 for descriptions of detailed analysis and statistical results). The results suggested that both anticipatory alpha power and HbO signal might be the primary determinants of reaction times.

We also analyzed the β weights of HbR concentration by using the same methods as those applied to the HbO data. Neither a lateralized effect nor a reliable correlation between the HbR and combined MI were found to be significant. We further investigated the relationship between the HbR lateralization and the target-evoked N2pc. No significant correlation effect was found. These results support that HbO was the more sensitive indicator of changes in the regional cerebral blood flow in the fNIRS measurements (Cui, Bray, Bryant, Glover, & Reiss, 2011).

3.5 | Control experiment

In the above experiment, the yellow arrow was fully predictive (with 100% validity) with respect to the side where the following yellow target circle would subsequently appear, while the green arrow has no predictive value to the following yellow target circle and red distractor circle (see Figure 6a). Our findings may have resulted from the asymmetry sensory input (the physical differences between the yellow arrow and the green arrow) or some specific effects for the yellow color. To strictly exclude any possible confounding factors related to our results, a control experiment was performed, which was identical to the above experiment except that the colors of target and distractor were interchanged. That is, in the control experiment, the red arrow was fully predictive (with 100% validity) with respect to the side where the following red target circle would subsequently appear, while the green arrow still had no predictive value to the following red target circle and yellow distractor circle. Eight subjects who had participated in the original experiment, were invited to return to our laboratory for competition of the control experiment 2 months later. The results confirmed our reported findings shown in Figure 6. The magnitude of cue-induced alpha lateralization was marginally correlated with the HbO lateralization in V4 cortex (CH14, Spearman: $r = .640$, $p < .080$), and such a cue-induced alpha lateralization predicted the subsequent target-evoked ERP N2pc amplitudes in between subjects ($r = .740$, $p < .030$) and within subjects (Figures 6b, d), and this effect still existed after controlling HbO lateralization ($r = .670$, $p < .090$).

4 | DISCUSSION

In this study, by using a rapid event-related protocol, we investigated how neuronal oscillations detected by EEG in visual areas and adjacent hemodynamic activities recorded by simultaneous fNIRS influenced the attentional selection reflected by target-elicited ERPs in a cued visual-spatial attention task. We observed that expecting a target led to a larger decrease of posterior alpha-band (8–12 Hz) oscillations contralateral to the upcoming target. The degree of cue-induced alpha lateralization was positively correlated with the nearby HbO lateralization in the visual cortex, and such cue-induced alpha lateralization significantly predicted the subsequent target-evoked N2pc amplitudes. Our results indicate that there is a close relationship between the cortical hemodynamic and the EEG/ERP activity during a cued visuospatial task. Each individual's attentional selection bio-marker (N2pc) can be predicted in advance via the anticipation-induced alpha lateralization, and such cue-induced alpha lateralization seems to play an important role in the functional coupling effects between the low-frequency EEG and the nearby hemodynamic activation in the visual cortex. Here, all the results were not related to the inherent sensory features of the cues because they still existed when the cue color was changed in the control experiment.

4.1 | Alpha oscillatory activity predicts the subsequent target-elicited N2pc amplitude

Our present results were consistent with numerous studies by demonstrating that when covert attention is directed to one side of the visual field during the cue period, alpha oscillation power was significantly modulated with a stronger decrease in the hemisphere contralateral to the cued visual field (Kelly et al., 2006; Sauseng et al., 2005; Thut et al., 2006; Worden et al., 2000). Although previous studies have showed that anticipatory alpha lateralization has effects on behavioral performance, including perceptual detectability (Ergenoglu et al., 2004; Hanslmayr et al., 2007; Romei, Gross, & Thut, 2010), discriminability (van Dijk, Schoffelen, Oostenveld, & Jensen, 2008), and speed of visual and motor processing (Pogossyan, Gaynor, Eusebio, & Brown, 2009; Thut et al., 2006; Zhang, Wang, Bressler, Chen, & Ding, 2008), how and when this anticipatory alpha modulation influences subsequent attentional selection remain unknown. The novel and most critical point from our study is that there is a robust correlation between the modulation of anticipatory alpha-band oscillations and the subsequent N2pc amplitudes in between and within participants. The N2pc is a well-characterized index of this selective process of visual attention (Luck & Hillyard, 1994a, 1994b; Luck et al., 2012).

In the present study, our finding of a significant correlation between anticipatory alpha lateralization and N2pc amplitudes indicates that the N2pc may not only be indicative of stimulus-driven bottom-up attentional selection, but also at least to some degree, be related to the selective attention mechanism of anticipatory alpha modulation. On the one hand, the cue was fully predictive (with 100% validity) with respect to the visual field where the following target

circle would appear. Note that, the subjects only knew the visual field (left visual field or right visual field) of coming target, but not knew the specific location where the targets would appear. As showed in Figure S4, the target might be presented at any one of four locations (randomized with equal 25% probability) after the cue. On the other hand, active suppression to distractor was not a strong requirement in our task as the distractor appeared in a randomized manner. This design would encourage participants to shift most spatial attentional resources to the cued visual field (as reflected by the robust lateralization of anticipatory alpha-band oscillations) to complete the search for the coming target. Therefore, when the subjects deployed more attentional resources to the cued visual field in advance (as reflected by the higher alpha MI), the following target would attract more attentional resources (as reflected by the larger N2pc). So, it is not surprise that the higher alpha MI people and trials showed a larger N2pc here. This result further indicated that the N2pc is indeed a neural correlate of attentional capture by the relevant target.

Several previous studies suggested that alpha oscillations during prestimulus baseline can also influence subsequent attentional selection (Hanslmayr et al., 2007; Feller, Klimesch, Gruber, Freunberger, & Doppelmayr, 2011; van Dijk et al., 2008). Here, we found that N2pc effect was not affected by the $-200-0$ ms period of prestimulus alpha activity (see Figure S1). We suggested that this result might be related to the experimental paradigm. In the present study, there is a random 1,200–1,600 ms ISI between cue displays and visual search arrays, which might reduce the impact of the $-200-0$ ms period of prestimulus alpha activity. A recent study demonstrated that the parieto-occipital asymmetric alpha modulation could last for as long as 2,200 ms during the retention interval in a visual working memory task (Fukuda, Mance, & Vogel, 2015). We found only the 400–600 ms after the cue onset was the time window where alpha activity could predict the subsequent target-evoked N2pc amplitudes, suggesting that this time window might be the most critical cue period that would affect the following attentional selection of targets, which was consistent with numerous studies have indicated that sustained, attention-related asymmetric alpha modulation begins $\sim 400-600$ ms after cue onset (Rihs, Michel, & Thut, 2007; Thut et al., 2006; Worden et al., 2000). Further studies are needed to investigate time-varying functional role of alpha band power and how does these affect the target evoked N2pc, including the cue-induced alpha lateralization and prestimulus alpha lateralization.

4.2 | Relationship between fNIRS and EEG/ERP signals

Our present fNIRS results suggest that change of HbO in visual cortex is strongly lateralized in the cued visual-spatial attention task (Figure 5a), which was consistent with numerous single-unit and fMRI studies by demonstrating that neuronal activity and hemodynamic signals in the visual cortex showed some spatiotopic modulation responses when covert attention is directed to one side of the visual field (Chelazzi, Miller, Duncan, & Desimone, 1993; Hopfinger et al., 2000; Macaluso et al., 2003; Ruff & Driver, 2006; Tassinari, Aglioti, Chelazzi, Peru, &

Berlucchi, 1994). The lateralization of HbO signal was closely and positively correlated with modulation of posterior alpha power. More importantly, we found that both anticipatory alpha lateralization and the lateralized HbO signals can explain the variance of the variance of the subsequent N2pc amplitudes and the behavioral reaction times. This result was consistent with one previous concurrent fNIRS-EEG study with a block design, which also found that the N2pc amplitude can be predicted in advance through anticipatory HbO activity in the visual cortex (Huang et al., 2015). This result was also consistent with many previous studies, which showed anticipatory alpha activity could predict the behavioral performance (Bengson, Mangun, & Mazaheri, 2012; Mazaheri, Nieuwenhuis, van Dijk, & Jensen, 2009). Our present study extends previous evidence by demonstrating that the change of HbO in V4 was modestly predictive for N2pc, which is in line with source estimation procedures of EEG/MEG and fMRI experiments studies suggesting that the N2pc is generated in the human homologs of macaque area V4 (Hopfinger & West, 2006; Luck & Hillyard, 1994a, 1994b; Luck & Vogel, 1997). We also found that alpha-HbO coupling was an inverse neurovascular correlation which matches BOLD-alpha coupling reported in prior studies of simultaneous EEG-fMRI (e.g., Thut et al., 2006; Worden et al., 2000; Zumer, Scheeringa, Schoffelen, Norris, & Jensen, 2014).

On the other hand, we further found that anticipatory alpha oscillations, not parieto-occipital hemodynamic HbO activity, mainly influenced subsequent attentional selection. Anticipatory lateralized alpha power seems to play an important role in functional coupling between the HbO lateralization and the following target-evoked N2pc. It is known that hemodynamic response to a brief stimulus usually takes 5–6 s to reach its peak, so HbO signals taken by fNIRS would result from an integrated effect over the preparatory (i.e., cue) and subsequent target searching tasks/stimulations. In other words, lateralization index of HbO, to some extent, reflects shifts of whole spatial attention not only driven by preparatory period but also subsequent visual search. Higher order regions (top-down) and local recurrent activity (bottom-up) contribute as well. Accordingly, it is possible to speculate that occipital alpha activity, under top-down control, first serves to gate sensory information in early visual regions and then has effects on the nearby hemodynamic activation and the subsequent electrophysiological activity in late visual regions (V4), whereas target-evoked N2pc can reflect this top-down control on the attentional processing of targets.

4.3 | Concurrent fNIRS-EEG based on a fast event-related protocol

Compared with the millisecond range of signals in EEG/ERP, fNIRS deals with hemodynamic signals that are inherently slow. The hemodynamic response evoked by a brief stimulus returns to baseline after 10–12 s or more (Boynton, Engel, Glover, & Heeger, 1996; Buckner et al., 1996). Because of these slow signals, stimuli that are separated by less than one hemodynamic response cycle result in a temporal overlap of the recorded hemodynamic response. Therefore, using sufficiently long ISIs is one solution to prevent overlapping hemodynamic responses (Cui et al., 2011) in fNIRS studies. Most published articles employed blocked designs, with trials longer than 3–4 s and intertrial-

intervals (ITIs) of at least 4–7 s (Buss, Fox, Boas, & Spencer, 2014; Schneider et al., 2014) and even longer than 10 s. Recently, with the use of GLM for fNIRS data analysis, event-related designs have been incorporated in fNIRS studies (Ferrari & Quaresima, 2012). Plichta et al. (2006) utilized the event-related design with a trial period of 1.2 s but with a long ITI of 13.8 s to study processing of visual stimuli. More recently, Heilbronner and Munte (2013) employed a rapid stimulus onset asynchrony (SOA) of approximately 1.4 s, jittered between 1 and 2.5 s, to investigate age-related changes of neural activity with the classic Go/No-Go task. The latter study adopted a flexible post hoc response sorting due to the event-related design, without full temporal recovery of the hemodynamic signal. Another study also utilized a rapid event-related design with ~4 s SOA to compare fNIRS findings with fMRI findings in complex item–item associative recognition (Schaeffer et al., 2014). In the current study, we have a more complex (covert spatial attention shift and the following target selection) fast event-related protocol with SOA of ~1.4–1.8 s. In that aspect, this study may be marked as the first concurrent fNIRS–EEG study that used a fast event-related protocol (with short SOA and ITI) to extract hemodynamic changes from fNIRS measurements in response to high-level cognitive functions and ERP components. Further studies are needed to investigate the relationship between anticipatory fNIRS/alpha signals and another ERP component called the distractor positivity (P_D), which appears to reflect distractor suppression (Gaspar & McDonald, 2014; Hickey et al., 2009; Jannati, Gaspar, & McDonald, 2013; Sawaki et al., 2012).

5 | CONCLUSION

Our concurrent fNIRS–EEG study is the first to provide strong and converging evidence that each individual's attentional selection biomarker (N2pc) can be predicted in advance through the anticipation-induced alpha lateralization, and such cue-induced alpha lateralization seems to play an important role in the functional coupling effects between the low-frequency EEG and the nearby hemodynamic activation. Our findings shed new light on a more comprehensive understanding of the neurovascular coupling between oxygenated hemoglobin and EEG/ERP activity during attention processes.

ACKNOWLEDGMENTS

The present research was supported by the National Natural Science Foundation of China (No. 31871099, No. 61761166003, and No. 81771479), the National Defense Basic Scientific Research Program of China (2018110B011), and the Fundamental Research Funds for the Central Universities (No. 2017XTCX04).

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Yan Song <https://orcid.org/0000-0002-5923-7673>

REFERENCES

- An, A., Sun, M., Wang, Y., Wang, F., Ding, Y., & Song, Y. (2012). The N2pc is increased by perceptual learning but is unnecessary for the transfer of learning. *PLoS One*, 7(4), e34826.
- Bengson, J. J., Mangun, G. R., & Mazaheri, A. (2012). The neural markers of an imminent failure of response inhibition. *NeuroImage*, 59(2), 1534–1539.
- Boynton, G. M., Engel, S. A., Glover, G. H., & Heeger, D. J. (1996). Linear systems analysis of functional magnetic resonance imaging in human V1. *The Journal of Neuroscience*, 16(13), 4207–4221.
- Buckner, R. L., Bandettini, P. A., O'Craven, K. M., Savoy, R. L., Petersen, S. E., Raichle, M. E., & Rosen, B. R. (1996). Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic resonance imaging. *Proceedings of the National Academy of Sciences of the United States of America*, 93(25), 14878–14883.
- Buffalo, E. A., Fries, P., Landman, R., Buschman, T. J., & Desimone, R. (2011). Laminar differences in gamma and alpha coherence in the ventral stream. *Proceedings of the National Academy of Sciences of the United States of America*, 108(27), 11262–11267.
- Bullmore, E., Brammer, M., Williams, S. C., Rabe-Hesketh, S., Janot, N., David, A., ... Sham, P. (1996). Statistical methods of estimation and inference for functional MR image analysis. *Magnetic Resonance in Medicine*, 35(2), 261–277.
- Buss, A. T., Fox, N., Boas, D. A., & Spencer, J. P. (2014). Probing the early development of visual working memory capacity with functional near-infrared spectroscopy. *NeuroImage*, 85 Pt, 1, 314–325.
- Chawla, D., Rees, G., & Friston, K. J. (1999). The physiological basis of attentional modulation in extrastriate visual areas. *Nature Neuroscience*, 2(7), 671–676.
- Chelazzi, L., Miller, E. K., Duncan, J., & Desimone, R. (1993). A neural basis for visual search in inferior temporal cortex. *Nature*, 363(6427), 345–347.
- Cohen, M. X., & Donner, T. H. (2013). Midfrontal conflict-related theta-band power reflects neural oscillations that predict behavior. *Journal of Neurophysiology*, 110(12), 2752–2763.
- Cope, M., Delpy, D. T., Reynolds, E. O., Wray, S., Wyatt, J., & van der Zee, P. (1988). Methods of quantitating cerebral near infrared spectroscopy data. *Advances in Experimental Medicine and Biology*, 222, 183–189.
- Cui, X., Bray, S., Bryant, D. M., Glover, G. H., & Reiss, A. L. (2011). A quantitative comparison of NIRS and fMRI across multiple cognitive tasks. *NeuroImage*, 54(4), 2808–2821.
- Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, 134(1), 9–21.
- Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, 24(2), 193–198.
- Ergenoglu, T., Demiralp, T., Bayraktaroglu, Z., Ergen, M., Beydagi, H., & Uresin, Y. (2004). Alpha rhythm of the EEG modulates visual detection performance in humans. *Brain Research. Cognitive Brain Research*, 20(3), 376–383.
- Fellinger, R., Klimesch, W., Gruber, W., Freunberger, R., & Doppelmayr, M. (2011). Pre-stimulus alpha phase-alignment predicts P1-amplitude. *Brain Research Bulletin*, 85(6), 417–423.
- Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *NeuroImage*, 63(2), 921–935.

- Fries, P., Reynolds, J. H., Rorie, A. E., & Desimone, R. (2001). Modulation of oscillatory neuronal synchronization by selective visual attention. *Science*, 291(5508), 1560–1563.
- Fukuda, K., Mance, I., & Vogel, E. K. (2015). Alpha power modulation and event-related slow wave provide dissociable correlates of visual working memory. *The Journal of Neuroscience*, 35(41), 14009–14016.
- Gaspar, C. M., Rousselet, G. A., & Pernet, C. R. (2011). Reliability of ERP and single-trial analyses. *NeuroImage*, 58(2), 620–629.
- Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. *The Journal of Neuroscience*, 34(16), 5658–5666.
- Goldman, R. I., Stern, J. M., Engel, J., Jr., & Cohen, M. S. (2002). Simultaneous EEG and fMRI of the alpha rhythm. *Neuroreport*, 13(18), 2487–2492.
- Haegens, S., Nacher, V., Luna, R., Romo, R., & Jensen, O. (2011). Alpha-oscillations in the monkey sensorimotor network influence discrimination performance by rhythmical inhibition of neuronal spiking. *Proceedings of the National Academy of Sciences of the United States of America*, 108(48), 19377–19382.
- Hanslmayr, S., Aslan, A., Staudigl, T., Klimesch, W., Herrmann, C. S., & Bauml, K. H. (2007). Prestimulus oscillations predict visual perception performance between and within subjects. *NeuroImage*, 37(4), 1465–1473.
- Heilbronner, U., & Munte, T. F. (2013). Rapid event-related near-infrared spectroscopy detects age-related qualitative changes in the neural correlates of response inhibition. *NeuroImage*, 65, 408–415.
- Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience*, 21(4), 760–775.
- Hopfinger, J. B., Buonocore, M. H., & Mangun, G. R. (2000). The neural mechanisms of top-down attentional control. *Nature Neuroscience*, 3(3), 284–291.
- Hopfinger, J. B., & West, V. M. (2006). Interactions between endogenous and exogenous attention on cortical visual processing. *NeuroImage*, 31(2), 774–789.
- Huang, J., Wang, F., Ding, Y., Niu, H., Tian, F., Liu, H., & Song, Y. (2015). Predicting N2pc from anticipatory HbO activity during sustained visuospatial attention: A concurrent fNIRS-ERP study. *NeuroImage*, 113, 225–234.
- Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). HomER: A review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics*, 48(10), D280–D298.
- Jannati, A., Gaspar, J. M., & McDonald, J. J. (2013). Tracking target and distractor processing in fixed-feature visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology. Human Perception and Performance*, 39(6), 1713–1730.
- Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience*, 23, 315–341.
- 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(6), 3844–3851.
- Kiss, M., Jolicoeur, P., Dell'acqua, R., & Eimer, M. (2008). Attentional capture by visual singletons is mediated by top-down task set: New evidence from the N2pc component. *Psychophysiology*, 45(6), 1013–1024.
- Laufs, H., Kleinschmidt, A., Beyerle, A., Eger, E., Salek-Haddadi, A., Preibisch, C., & Krakow, K. (2003). EEG-correlated fMRI of human alpha activity. *NeuroImage*, 19(4), 1463–1476.
- Liu, Y., Bengson, J., Huang, H., Mangun, G. R., & Ding, M. (2016). Top-down modulation of neural activity in anticipatory visual attention: Control mechanisms revealed by simultaneous EEG-fMRI. *Cerebral Cortex*, 26(2), 517–529.
- 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.
- Luck, S. J., Ford, J. M., Sarter, M., & Lustig, C. (2012). CNTRICS final bio-marker selection: Control of attention. *Schizophrenia Bulletin*, 38(1), 53–61.
- Luck, S. J., & Hillyard, S. A. (1994a). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, 31(3), 291–308.
- Luck, S. J., & Hillyard, S. A. (1994b). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology. Human Perception and Performance*, 20(5), 1000–1014.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, 390(6657), 279–281.
- 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(1), 62–74.
- Marchini, J. L., & Smith, S. M. (2003). On bias in the estimation of autocorrelations for fMRI voxel time-series analysis. *NeuroImage*, 18(1), 83–90.
- Mazaheri, A., Nieuwenhuis, I. L., van Dijk, H., & Jensen, O. (2009). Pre-stimulus alpha and mu activity predicts failure to inhibit motor responses. *Human Brain Mapping*, 30(6), 1791–1800.
- Moosmann, M., Ritter, P., Krastel, I., Brink, A., Thees, S., Blankenburg, F., ... Villringer, A. (2003). Correlates of alpha rhythm in functional magnetic resonance imaging and near infrared spectroscopy. *NeuroImage*, 20(1), 145–158.
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, 229(4715), 782–784.
- Plichta, M. M., Heinzel, S., Ehlis, A. C., Pauli, P., & Fallgatter, A. J. (2007). Model-based analysis of rapid event-related functional near-infrared spectroscopy (fNIRS) data: A parametric validation study. *NeuroImage*, 35(2), 625–634.
- Plichta, M. M., Herrmann, M. J., Baehne, C. G., Ehlis, A. C., Richter, M. M., Pauli, P., & Fallgatter, A. J. (2006). Event-related functional near-infrared spectroscopy (fNIRS): Are the measurements reliable? *NeuroImage*, 31(1), 116–124.
- Plichta, M. M., Herrmann, M. J., Baehne, C. G., Ehlis, A. C., Richter, M. M., Pauli, P., & Fallgatter, A. J. (2007). Event-related functional near-infrared spectroscopy (fNIRS) based on craniocerebral correlations: Reproducibility of activation? *Human Brain Mapping*, 28(8), 733–741.
- Pogosyan, A., Gaynor, L. D., Eusebio, A., & Brown, P. (2009). Boosting cortical activity at Beta-band frequencies slows movement in humans. *Current Biology*, 19(19), 1637–1641.
- Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, 32(1), 3–25.
- Qu, Z., Wang, Y., Zhen, Y., Hu, L., Song, Y., & Ding, Y. (2014). Brain mechanisms underlying behavioral specificity and generalization of short-term texture discrimination learning. *Vision Research*, 105, 166–176.
- Rajagovindan, R., & Ding, M. (2011). From prestimulus alpha oscillation to visual-evoked response: An inverted-U function and its attentional modulation. *Journal of Cognitive Neuroscience*, 23(6), 1379–1394.
- Ress, D., Backus, B. T., & Heeger, D. J. (2000). Activity in primary visual cortex predicts performance in a visual detection task. *Nature Neuroscience*, 3(9), 940–945.
- Rihs, T. A., Michel, C. M., & Thut, G. (2007). Mechanisms of selective inhibition in visual spatial attention are indexed by alpha-band EEG synchronization. *The European Journal of Neuroscience*, 25(2), 603–610.
- Romei, V., Brodbeck, V., Michel, C., Amedi, A., Pascual-Leone, A., & Thut, G. (2008). Spontaneous fluctuations in posterior alpha-band EEG activity reflect variability in excitability of human visual areas. *Cerebral Cortex*, 18(9), 2010–2018.
- Romei, V., Gross, J., & Thut, G. (2010). On the role of prestimulus alpha rhythms over occipito-parietal areas in visual input regulation: Correlation or causation? *The Journal of Neuroscience*, 30(25), 8692–8697.
- Ruff, C. C., & Driver, J. (2006). Attentional preparation for a lateralized visual distractor: Behavioral and fMRI evidence. *Journal of Cognitive Neuroscience*, 18(4), 522–538.
- Sauseng, P., Klimesch, W., Stadler, W., Schabus, M., Doppelmayr, M., Hanslmayr, S., ... Birbaumer, N. (2005). A shift of visual spatial

- attention is selectively associated with human EEG alpha activity. *The European Journal of Neuroscience*, 22(11), 2917–2926.
- Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A common neural mechanism for preventing and terminating the allocation of attention. *The Journal of Neuroscience*, 32(31), 10725–10736.
- Schaeffer, J. D., Yennu, A. S., Gandy, K. C., Tian, F., Liu, H., & Park, H. (2014). An fNIRS investigation of associative recognition in the pre-frontal cortex with a rapid event-related design. *Journal of Neuroscience Methods*, 235, 308–315.
- Scheeringa, R., Fries, P., Petersson, K. M., Oostenveld, R., Grothe, I., Norris, D. G., ... Bastiaansen, M. C. (2011). Neuronal dynamics underlying high- and low-frequency EEG oscillations contribute independently to the human BOLD signal. *Neuron*, 69(3), 572–583.
- Schneider, S., Christensen, A., Haussinger, F. B., Fallgatter, A. J., Giese, M. A., & Ehlis, A. C. (2014). Show me how you walk and I tell you how you feel - a functional near-infrared spectroscopy study on emotion perception based on human gait. *NeuroImage*, 85(Pt 1), 380–390.
- Spaak, E., Bonnefond, M., Maier, A., Leopold, D. A., & Jensen, O. (2012). Layer-specific entrainment of gamma-band neural activity by the alpha rhythm in monkey visual cortex. *Current Biology*, 22(24), 2313–2318.
- Tassinari, G., Aglioti, S., Chelazzi, L., Peru, A., & Berlucchi, G. (1994). Do peripheral non-informative cues induce early facilitation of target detection? *Vision Research*, 34(2), 179–189.
- Thut, G., Nietzel, A., Brandt, S. A., & Pascual-Leone, A. (2006). Alpha-band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *The Journal of Neuroscience*, 26(37), 9494–9502.
- Tian, F., & Liu, H. (2014). Depth-compensated diffuse optical tomography enhanced by general linear model analysis and an anatomical atlas of human head. *Neuroimage*, 85(Pt 1), 166–180.
- van Dijk, H., Schoffelen, J. M., Oostenveld, R., & Jensen, O. (2008). Pre-stimulus oscillatory activity in the alpha band predicts visual discrimination ability. *The Journal of Neuroscience*, 28(8), 1816–1823.
- 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(6), 2016–2024.
- Vollebregt, M. A., Zumer, J. M., Ter Huurne, N., Castricum, J., Buitelaar, J. K., & Jensen, O. (2015). Lateralized modulation of posterior alpha oscillations in children. *NeuroImage*, 123, 245–252.
- Worden, M. S., Foxe, J. J., Wang, N., & Simpson, G. V. (2000). Anticipatory biasing of visuospatial attention indexed by retinotopically specific alpha-band electroencephalography increases over occipital cortex. *The Journal of Neuroscience*, 20(6), RC63.
- Yeung, N., Bogacz, R., Holroyd, C. B., Nieuwenhuis, S., & Cohen, J. D. (2007). Theta phase resetting and the error-related negativity. *Psychophysiology*, 44(1), 39–49.
- Zhang, Y., Wang, X., Bressler, S. L., Chen, Y. H., & Ding, M. Z. (2008). Pre-stimulus cortical activity is correlated with speed of visuomotor processing. *Journal of Cognitive Neuroscience*, 20(10), 1915–1925.
- Zumer, J. M., Scheeringa, R., Schoffelen, J. M., Norris, D. G., & Jensen, O. (2014). Occipital alpha activity during stimulus processing gates the information flow to object-selective cortex. *PLoS Biology*, 12(10), e1001965.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Zhao C, Guo J, Li D, et al. Anticipatory alpha oscillation predicts attentional selection and hemodynamic response. *Hum Brain Mapp*. 2019;40: 3606–3619. <https://doi.org/10.1002/hbm.24619>