Attention and Temporal Expectations Modulate Power, Not Phase, of Ongoing Alpha Oscillations

Rosanne M. van Diepen[1], Michael X Cohen[2], Damiaan Denys[1,3], and Ali Mazaheri[4]

Abstract

■ The perception of near-threshold visual stimuli has been shown to depend in part on the phase (i.e., time in the cycle) of ongoing alpha (8–13 Hz) oscillations in the visual cortex relative to the onset of that stimulus. However, it is currently unknown whether the phase of the ongoing alpha activity can be manipulated by top–down factors such as attention or expectancy. Using three variants of a cross-modal attention paradigm with constant predictable stimulus onsets, we examined if cues signaling to attend to either the visual or the auditory domain influenced the phase of alpha oscillations in the associated sensory cortices. Importantly, intermixed in all three experiments, we included trials without a target to estimate the phase at target presentation without contamination from the early evoked responses. For these blank trials, at the time of expected target and distractor onset, we examined (1) the degree of the uniformity in phase angles across trials, (2) differences in phase angle uniformity compared with a pretarget baseline, and (3) phase angle differences between visual and auditory target conditions. Across all three experiments, we found that, although the cues induced a modulation in alpha power in occipital electrodes, neither the visual condition nor the auditory cue condition induced any significant phase-locking across trials during expected target or distractor presentation. These results suggest that, although alpha power can be modulated by top–down factors such as attention and expectation, the phase of the ongoing alpha oscillation is not under such control. ■

INTRODUCTION

The modulation of the power of oscillatory activity in the alpha range (8–13 Hz) has been proposed to play a pivotal mechanistic role in attention by gating information flow to relevant sensory regions through the inhibition of irrelevant regions (Jensen & Mazaheri, 2010; Klimesch, Sauseng, & Hanslmayr, 2007; Fu et al., 2001). Supporting this hypothesis are a number of studies reporting that the power of alpha activity is suppressed in task-relevant regions but increased in regions processing unattended information (Mazaheri, van Schouwenburg, et al., 2014; Bauer, Kennett, & Driver, 2012; Bauer, Kluge, et al., 2012; Haegens, Luther, & Jensen, 2012; Haegens, Handel, & Jensen, 2011; Kerlin, Shahin, & Miller, 2011; Hanslmayr et al., 2007; Jokisch & Jensen, 2007; Medendorp et al., 2007; Rihs, Michel, & Thut, 2007; Sauseng et al., 2005; Thut et al., 2003). Although the direct mechanism by which alpha activity exerts functional inhibition is currently unknown, some recent studies have suggested (Mazaheri & Jensen, 2010) and shown that a power increase has a strong inhibitory influence on both spike timing and firing rate of neural activity (Haegens, Nacher, Luna, Romo, & Jensen, 2011).

In addition to alpha power (i.e., the amplitude of the oscillation), alpha phase (i.e., the timing of the oscillation) at stimulus onset also influences perception (Mathewson et al., 2011, 2012; Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010; Busch, Dubois, & VanRullen, 2009; Mathewson, Gratton, Fabiani, Beck, & Ro, 2009) as well as the evoked response (Scheeringa, Mazaheri, Bojak, Norris, & Kleinschmidt, 2011), suggesting that the alpha cycle reflects rhythmically fluctuating states of low and high excitability (Thut, Miniussi, & Gross, 2012; Mathewson et al., 2011; Klimesch et al., 2007). In other words, whereas the amplitude of an alpha oscillation reflects the degree of excitation or inhibition, the phase angle of the alpha oscillation indexes the excitability or inhibitory state of the underlying neural generators within a cycle of the alpha oscillation. This has led to the intriguing possibility that a top–down attentional modulation of the phase of alpha activity could therefore also serve as a mechanism for selection of relevant information on a fast time scale (Bonnefond & Jensen, 2012; Jensen, Bonnefond, & VanRullen, 2012; Mathewson et al., 2011).

However, to date, there has not been a clear demonstration that the phase of the alpha oscillations can be modulated by top–down task demands while accounting for the disturbances occurring because of stimulus evoked responses. The objective of this study was to investigate whether the anticipation of targets and distractors modulated the phase of alpha oscillations via top–down control, without the contamination of sensory evoked responses that would add a waveform with a specific phase to the ongoing alpha activity and subsequently

[1]Academic Medical Center Amsterdam, [2]University of Amsterdam, [3]Netherlands Institute for Neuroscience, [4]University of Birmingham

confounding its phase estimation. Therefore, the phase of the ongoing alpha oscillation was calculated on less frequent, unexpected trials containing no targets ("blank" trials) to measure anticipatory processes not contaminated by sensory evoked responses. These trials were incorporated into three versions of a cross-modal attention task in which top–down modulation of the phase of alpha oscillation would be beneficial for task performance. Brief targets and distractors were presented at regular times, such that their timing was predictable. In the first two versions of the paradigm, a target and distractor in the opposing modality (visual and auditory) were presented together (bimodal experiments). A preceding cue served to signal which modality was the target and which the distractor. In the first experiment, the visual stimulus was always presented 37 msec before the auditory stimulus, whereas in the second task, the target and distractor were presented simultaneously. Our rationale here was that the arrival of a distracting stimulus half cycle before a target might induce a different degree of phase adjustment than when the arrival of distractor and target were simultaneous. In the third "unimodal" version, only targets were presented, either in the visual or auditory domain. Again, cues were presented to help prepare the relevant sensory area for the upcoming to-be-discriminated target. Because no distractors were presented, only anticipatory processes related to target processing would be examined in this version, without the contamination of signals related to inhibition of the distractors.

On the basis of the studies described above, we hypothesized that the modulation of phase would be more precise on a temporal scale and thus more effective than modulation of power to obtain the optimal state of excitability or inhibition. To anticipate our results, examining the degree of intertrial phase-locking as well as phase angle differences between the visual and auditory conditions, we did not find evidence for a cue-induced phase perturbation of alpha activity at the time of expected target/distractor onset across all three experiments.

METHODS

Participants

In total, 30 participants were recruited at the University of Amsterdam and Amsterdam University of Applied Sciences to participate in the experiments. Eighteen (16 women, age range = 18–28 years) participated in Experiments 1 and 3, and 12 (8 women, age range = 19–37 years, one left-handed) participated in Experiment 2. All participants signed informed consent documents before the start of the experiment. Participants reported normal or corrected-to-normal vision, no hearing disabilities, and no history of psychiatric or neurological disorders. Participants were compensated with €10 per hour. This study was approved by the University of Amsterdam's Department of Psychology Ethics Committee.

Apparatus and Procedure

We conducted three variants of a cross-modal attention paradigm previously used in Mazaheri, van Schouwenburg, et al. (2014). All three experiments were run in a dimly lit room. The participants were seated 60 cm from the monitor. Before the start of the experiment, a practice session took place. During the practice session, the percentage of correct responses was shown after every 10 trials so that participants and experimenters were aware of performance levels. The practice session ended after 90 trials or when participants performed above 70% correct. The stimuli were presented using Presentation software (Neurobehavioral Systems, Inc., Albany, CA) on a 24-in. LCD monitor (BenQ XL2420T, Taipei, Taiwan) with a refresh rate of 120 Hz. All three experiments contained 420 trials with a mandatory rest period for every 42 trials.

The visual stimuli, presented centrally for 25 msec (three screen refreshes), consisted of Gabor patches having a visual angle of ~3.8°, a contrast of 50%, and three possible types of orientation: −5°, 0°, and 5° clockwise. The auditory stimuli, presented for 25 msec via speakers, were pure tones with three possible frequencies: 500, 1000, and 2000 Hz (including 5-msec rise and 5-msec fall shaped by a Blackman window).

Experiment 1: Sequential Target Distractor Presentation

In Experiment 1, the visual and auditory stimuli were presented 37 msec apart. A visual cue instructed the participants to what modality they had to perform the target discrimination. A "V" cue (100 msec) instructed the participants to perform spatial judgment on the upcoming visual stimulus while ignoring the auditory stimulus. In contrast, an "inverted V" cue (representing an "A," 100 msec) instructed the participants to make a pitch judgment on the upcoming auditory stimulus, while ignoring the visual stimulus. The participants responded with their right hand using a three-button mouse. A sample trial sequence is conceptualized in Figure 1B. Using a light sensor and sensor custom made by the EEG manufacturer (ANT, Enschede, The Netherlands), we were able to evaluate the synchronization of the visual and auditory stimuli as well the jitter (represented as σ) in times of onset. The standard deviation in onset times of the stimuli was estimated by looking at the distribution time of 100 stimulus onsets. The visual stimuli were presented 1219 msec after cue onset (σ = 5.12 msec), and the auditory stimuli were presented 1256 msec after cue onset (σ = 3.32 msec). Trial duration was 2560 msec. The number of visual and auditory cues was equal. All target orientations and tone frequencies were presented an equal number of times. Importantly, 84 of the 420 trials (20%) did not contain a target and distractor (blank trials). These trials were pseudorandomly intermixed with all the other trials such that no blank trials ever occurred in succession.
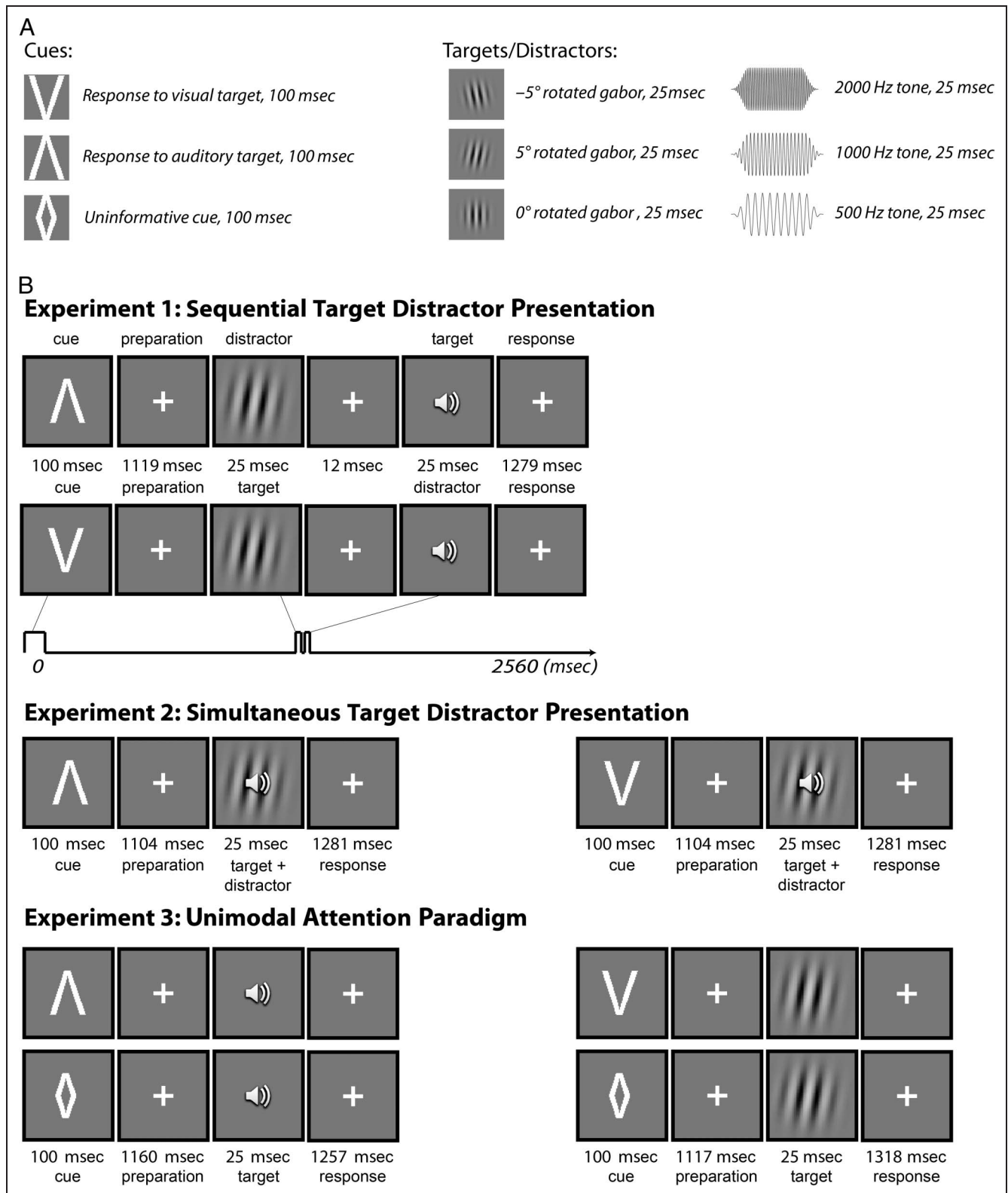
Figure 1. Task figures and example sequences of Experiments 1–3 with stimulus presentation times. A trial started with the presentation of a symbolic cue indicating whether a target in the visual or auditory domain needed to be identified. A "V" cue indicated to identify the rotation of a grating. An "inverted V" cue (representing an "A") indicated to identify the pitch of a tone. The symbolic cue was followed by a constant cue–target interval in which participants were able to prepare for the upcoming target. A target was always presented in the modality indicated by the cue. In Experiments 1 and 3, a distractor in the opposing modality to the target was presented. Participants used their right hand to press a button to choose between three different tones and Gabor gratings.

Experiment 2: Simultaneous Target Distractor Presentation

Experiment 2 was identical to Experiment 1 except that visual and auditory targets were presented simultaneously at 1204 msec after cue onset (visual target: σ = 0.88 msec, auditory target: σ = 3.76 msec). The trial duration of this experiment was 2510 msec.

Experiment 3: Unimodal Attention Paradigm

The purpose of Experiment 3 was twofold. First, to rule out the possibility that electrical fields from the visual and auditory cortices canceled out at the scalp, no distractors were presented together with the targets. Second, to manipulate attention without the need to ignore a distractor, in 60 trials (no blank trials), the informative cue was replaced with an uninformative "diamond" cue (◇). This attention manipulation was possible only in Experiment 3 because, although the cue was not necessary to perform the task correctly, we reasoned that having a cue would facilitate top–down expectation and thus could affect the ongoing phases. The visual cue was presented 1217 msec (σ = 4.18 msec) after cue onset, and the auditory target was presented 1260 msec (σ = 3.07 msec) after cue onset. Trial duration was 2560 msec.

EEG Acquisition and Processing

EEG data were acquired using a WaveGuard 10-5 cap system developed by ANT, with 64 Ag–AgCl electrodes, spanning from frontal, temporal, central, and occipital scalp sites. The EEG was sampled at 1024 Hz with an online average reference and then subsequently imported into MATLAB (Natick, MA) for all further offline analyses. The EOG was recorded between supraorbital and infraorbital sites around the right eye for vertical movement (blinks) and outer canthi of the left and right eyes for possible horizontal eye movements. Impedance was maintained below 100 kΩ. Offline processing and analyses were performed using MATLAB, functions from EEGLAB version 13.1.1b (Delorme & Makeig, 2004), the Fieldtrip software package (Oostenveld, Fries, Maris, & Schoffelen, 2011), and the Circular Statistics Toolbox (Berens, 2009). The EEG data were high-pass filtered at 0.5 Hz and epoched from −1 to +2.5 sec (−1 to +2.45 for Experiment 3), time-locked to cue onset. Trials with substantial muscle artifacts were identified and removed through visual inspection (12.7%, 12.0%, and 15.0% for Experiments 1, 2, and 3, respectively). Bad electrodes were identified and interpolated using the spherical spline interpolation routing in EEGLAB (two participants with two electrodes, two participants with one channel). Ocular artifacts were removed using independent component analysis (infomax algorithm) incorporated as the default "runica" function in EEGLAB 13.1.1b (on average, 1.28,

1.25, and 1.28 components per participant for Experiments 1, 2, and 3, respectively). A PCA was used to reduce dimensionality of the data before performing the independent component analysis. Trials with an RT < 100 msec were considered incorrect and excluded from all data analyses. Participants with exceptional high alpha power values (>3 SDs from mean) were removed from analyses (one participant in Experiment 2).

Time–Frequency Analysis

Time–frequency representations of power and phase were estimated per trial, using sliding Hanning tapers having an adaptive time window of three cycles for each frequency of interest (ΔT = 3/f). Similar approaches were used by Mazaheri, Nieuwenhuis, van Dijk, and Jensen (2009), Jokisch and Jensen (2007), and Osipova et al. (2006). Unless stated otherwise, analyses were performed on every participant at the peak frequency in the alpha band (average across participants: Experiment 1, 11.1 Hz, σ = 1.8; Experiment 2, 10.7 Hz, σ = 2.1; Experiment 3, 10.9, σ = 1.8), which was determined using the 500-msec pretarget interval from all trials.

Phase-locking Factor

To assess whether a preferred phase angle was present for target detection or distractor inhibition, we examined the variability (i.e., clustering or locking) of the phase angle across trials at the time of the expected target arrival. This was done using a measure called the phase-locking factor (PLF), which provides a quantification of intertrial phase-locking (Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1996). The PLF was derived by first unit normalizing the magnitude of the phase angles (obtained in the time–frequency analysis outlined earlier), then averaging (in the complex domain) across the trials, and getting the absolute value of the average. A PLF value close to 0 reflects high variability of phase angles across trials, whereas a PLF value of 1 reflects all trials having the same phase angle. PLFs were calculated for blank trials at the time of visual target/distractor onset. The magnitude of the PLF is dependent on the number of phase observations; thus, an equal number of trials was randomly selected from the condition containing a greater number of trials such that the number was equal for the visual and auditory target conditions.

Intuitively, the PLF might appear a less appropriate measure for our research question than, for example, a difference in phase between the visual and auditory conditions. However, the phase angle of an EEG signal is (at least for tangential dipoles) arbitrary in sign and can vary in its physiological meaning (excitation/inhibition) between participants. PLF is a suitable measure because it expresses whether a phase angle is more prevalent and thus favorable, without retaining information about the actual phase,

and can therefore be averaged over participants with differently positioned dipoles.

Statistical Significance of Intertrial Phase-locking at the Time of Target Presentation

The PLF was estimated exclusively for blank trials as to eliminate contamination by the early sensory responses evoked by the target/distractor onset. Given that the PLF is dependent on the number of observations and the amount of the blank trials surviving artifact rejection varied across participants, we determined the PLF and its significance for each participant separately. We did this using a bootstrapping procedure similar to Jensen, Hari, and Kaila (2002). Accordingly, we generated a random set of n phases, with n being equal to the participant's number of blank trials per condition, repeating this procedure 1,000 times and calculating the PLF value for each set. A significant PLF in the alpha band (at each participant's peak frequency) was defined as being at or above the 95th percentile rank of the randomly generated PLF distribution. The average number of blank trials across participants was 35.6 (σ = 4.2), 34.3 (σ = 4.1), and 30.6 (σ = 3.8; same for the auditory and visual target conditions), resulting in average cutoff values of 0.291 (σ = 0.019), 0.296 (σ = 0.023), and 0.312 (σ = 0.025) for Experiments 1, 2, and 3, respectively.

Differences in the Degree of Intertrial Phase-locking between Time of Target Presentation and Baseline

Across participants, we statistically assessed the difference between the PLFs (in each channel) at baseline and at the time of expected target onset using a two-tailed t test. The baseline was derived from the combined auditory and visual conditions 200 msec before cue onset.

Phase Angle Differences between Visual and Auditory Target Conditions

Previous work suggests having different phase distributions (i.e., preferred phase angle) between conditions without differences in PLF values. Thus, we also examined the (average) phase bifurcation index (PBI; Busch et al., 2009), which quantifies intertrial phase angle differences between conditions. The following formula was used:

$$\left(PLF_{\text{Visual}} - PLF_{\text{Visual+auditory}}\right) \\ \times \left(PLF_{\text{auditory}} - PLF_{\text{visual+auditory}}\right)$$

When phases are phase-locked toward a different angle for the visual and auditory target conditions, the bifurcation index will take a positive value. When a random phase distribution is present for both conditions, the index will be close to 0. When only one condition exhibits intertrial phase-locking, the PBI will take a negative value.

The significance level of PBI values was obtained using a bootstrapping procedure consisting of the following two steps: First, for each participant, trials from the visual and auditory cue conditions were pooled. Two random samples were drawn from the pool, and a "pseudo" PBI was calculated. This procedure was repeated 500 times per participant to create a random distribution of values that fall under the null hypothesis. Second, for each participant, a pseudo PBI value was randomly selected from this distribution, after which the average over participants was calculated. This was repeated 100,000 times. For each channel, the level of significance was determined as the proportion of average pseudo PBI values exceeding the average observed PBI.

Oscillatory Power Analysis

In addition to our phase analyses, we also examined the effect of the attentional cues on the power of the ongoing alpha activity. To ensure our results in the current study were consistent with those of previous literature showing attention-modulated suppression of alpha power (Mazaheri, Fassbender, et al., 2014; Mazaheri, van Schouwenburg, et al., 2014; Haegens et al., 2012; Haegens, Handel, et al., 2011; Kerlin et al., 2011; Hanslmayr et al., 2007; Jokisch & Jensen, 2007; Medendorp et al., 2007; Rihs et al., 2007; Sauseng et al., 2005; Thut et al., 2003), here, we did a correction for multiple comparisons. Cue-induced power differences for the alpha peak frequency were examined for every time point between cue and target presentation using a nonparametric randomization test (as described in Maris & Oostenveld, 2007) using alpha power from every participant's peak frequency. Monte Carlo p values were calculated on 1,000 random partitions in which the visual and auditory labels of power estimates were shuffled. Type 1 errors because of multiple comparisons are reduced by clustering neighboring electrodes that show a similar effect. The cluster-level test statistics (p = .05, two sided) reported in the Results section are calculated by averaging t values for electrodes in a given cluster. For this analysis, the following number of trials were available for the auditory condition and visual condition, respectively: 122.0556 (σ = 23.2416), 104.9091 (σ = 21.5845), and 115.5000 (σ = 14.4924) and 138.1111 (σ = 17.1323), 130.6364 (σ = 20.9775), and 124.7222 (σ = 14.4010).

RESULTS

Behavioral Data

In Experiment 1, participants were better at discrimination of visual targets than auditory targets (96% vs. 88%, $t(17)$ = 7.20, p = .000001). This was also reflected in RTs, which were faster for visual discrimination than auditory discrimination (630 vs. 728 msec, $t(17)$ = −4.26, p = .0004). In

Experiment 2, similar to the first experiment, the percentage of correct response was higher for visual than auditory targets (96% vs. 81%, $t(10) = 89.36$, $p = .000003$). In line with that RTs were faster for trials with a visual target than for trials with an auditory target (639 vs. 748 msec, $t(10) = 9.36$, $p = .000002$). Also in Experiment 3, the unimodal experiment, visual targets were identified faster (606 vs. 697 msec, $t(17) = -7.12$, $p = .000002$) and more often (98% vs. 95%, $t(17) = 3.24$, $p = .005$) compared with auditory cues.

Because of the absence of distractors in Experiment 3, the attentional cues were not essential to perform the task correctly. However, participants nevertheless demonstrated significant benefits from the cuing: RTs for auditory targets decreased from 748 msec for uninformative cues to 697 msec for informative cues ($t(17) = -5.10, p = .00008$). For visual targets, the average RT decreased from 642 msec for uninformative cues to 606 msec for informative cues ($t(17) = -5.91$, $p = .00002$). These behavioral results demonstrate that the attentional cues in the experiment were indeed used by the participants, suggesting that top–down processes facilitated target processing.

To test whether the distraction in the Experiment 1 influenced RTs (i.e., there was a distraction cost), we compared RTs from Experiment 1 (bimodal) with Experiment 3 (unimodal). For auditory targets, presentation of a distractor slowed RTs by an average of 31 msec ($t(17) = -3.77, p = .001$). For visual targets, presentation of a distractor slowed RTs by 24 msec ($t(17) = -3.29, p = .004$). These results suggest that the presence of the distractor was detrimental to performing the task. A mechanism for active inhibition of the distractor could be beneficial during this task.

The attentional cues did not have any influence on the participant's accuracy in the task, which we speculated to be because of a ceiling effect in performance. Auditory targets were identified in 93% of the trials with an uninformative cue and in 95% with an informative cue ($t(17) = -1.48, p = .16$). Visual targets were identified in 98% of the trials with both informative and uninformative cues ($t(17) = -0.15, p = .917$).

EEG Results

The onset of visual stimuli (i.e., cues and targets) evoked a transient increase in power (Figure 2) in the theta band and an increase in PLF in the theta and alpha bands (Figure 3) in electrodes located over the occipital cortex, consistent with results shown in previous literature (e.g., Mazaheri & Jensen, 2006; Makeig et al., 2002). Moreover, before target presentation, alpha power was highest in occipital electrodes. Given that alpha activity from the auditory cortex has been found difficult to measure using scalp EEG, because of the anatomical location of the auditory cortex (Mazaheri, van Schouwenburg, et al., 2014; Bastiaansen & Brunia, 2001), we focused in part of our subsequent analyses on the average values of electrodes located over the occipital cortex (Oz, O1, and O2).

Absence of Significant PLF at Expected Arrival of Targets

We found an absence of robust PLF at the time of expected target presentation in most participants across all three experiments. Participants showed an average of 2.1 ($\sigma = 4.3$), 3.4 ($\sigma = 4.9$), and 2.8 ($\sigma = 5.6$) electrodes with a significant PLF during the visual condition and 2.8333 ($\sigma = 3.0147$), 3.9167 ($\sigma = 6.5569$), and 3.7222 ($\sigma = 5.1542$) electrodes during the auditory condition. However, these electrodes were not neighboring one another, suggesting that the phase-locking was spurious. The absence of a consistent pattern (Figure 4), even with the liberal statistical threshold employed, suggests that the attentional cues did not induce a significant degree of phase-locking at the time of expected target onset.

Intertrial Phase-locking at Target Onset Was Not Significantly Different from Baseline

We assessed if the PLF at the time of target onset was significantly greater than baseline values across participants. We found that PLF values at the time of expected target arrival were not increased in any channel in Experiments 1 (sequential target distractor presentation) and 3 (unimodal stimulus presentation). In Experiment 2 (simultaneous target distractor presentation), one channel showed an increase in PLF in the parietal cortex when a visual target was expected, and two electrodes showed an increase in the right temporal cortex (not adjacent) when an auditory target was expected. However, as can be seen from the topographic maps of the t values, there was no clear pattern of increases and decreases of PLF at the time of expected target onset compared with the baseline period (Figure 5).

No Phase Angle Differences between Visual and Auditory Target Conditions

We investigated if there were any phase angle differences between visual target and auditory target (visual distractor) conditions using the PBI. Figure 6 shows a topographic representation of average PBI values over participants, including marked electrodes that showed a significant PBI from 0 calculated using a resampling procedure. We were unable to find any clusters of electrodes showing a significant clear phase difference present between visual and auditory target trials at the time of expected target presentation.

The Attentional Cue-induced Modality-specific Modulation of Alpha Power in Anticipation of Target Presentation

In Experiment 1, alpha power over occipital/parietal areas was greater before the presentation of the auditory target

Figure 2. Grand mean time–frequency representations of power per condition for trials with target (top rows) and blank (bottom rows) trials. Values are averaged across electrodes located over the occipital cortex (electrodes Oz, O1, and O2) and not baseline corrected. The dark blue color indicates power of 0 μV². The first two dotted vertical lines represent the time interval of cue presentation. The second set of vertical dotted lines represents the presentation interval of targets. The expected time of target onset for blank trials is indicated with a single dotted line. (Left) Trials containing an auditory target (i.e., visual distractor in Experiments 1 and 3), showing an increase in alpha power before and during presentation of a visual distractor. (Right) Trials with a visual target, showing a decrease in alpha power during preparation and target presentation.
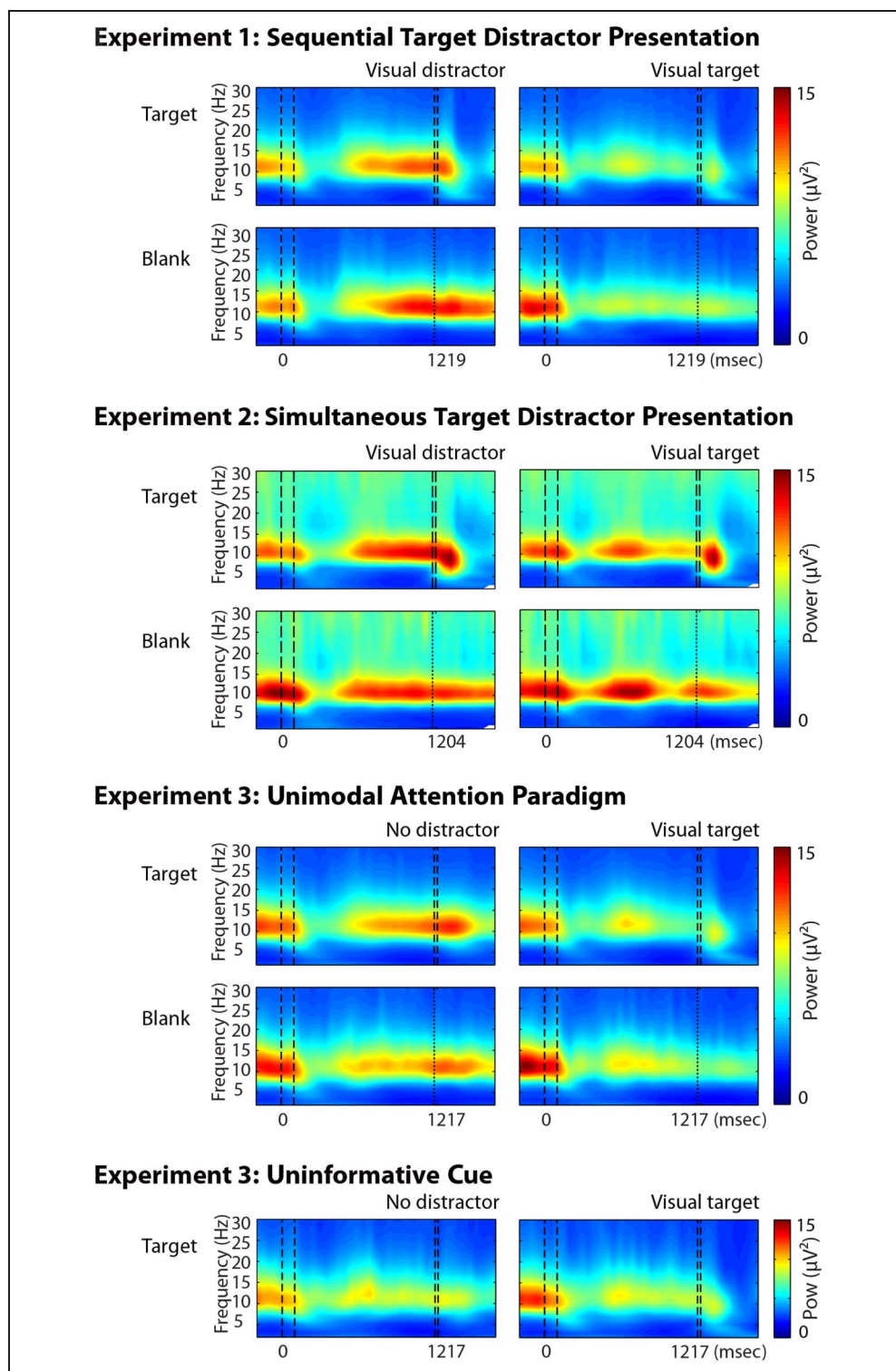
compared with the presentation of a visual target. This difference started in electrodes located over the parietal cortex and spread toward occipital and frontal electrodes. For the trials containing a target, the difference was present 550 msec after cue onset until target presentation ($t = -182.42$, $p = .0001$, Monte Carlo p value, corrected for multiple comparisons). For blank trials, the difference was present from 600 msec after cue onset until target

presentation ($t = -123.74$, $p = .003$, Monte Carlo p value, corrected for multiple comparisons; Figure 7).

The same pattern of results was observed in Experiment 2 where, at 700 msec postcue until target presentation, electrodes over the occipital cortex had greater alpha power before an expected auditory target than expected visual target ($t = -11.59$, $p = .049$, Monte Carlo p value, corrected for multiple comparisons).

These results are consistent with previous studies indicating that cues signaling the preparation for visual discrimination (relative to pitch discrimination) resulted in a decrease of alpha power (9–11 Hz) in the early visual cortex (Mazaheri, van Schouwenburg, et al., 2014; Mazaheri et al., 2010).

Finally, the informative cues in Experiment 3 also modulated alpha activity even when a target was presented without a distractor. Alpha power was higher when an auditory target had to be identified compared with when a visual target had to be identified. For correct trials, the difference started in frontal electrodes at 650 msec after cue onset ($t = -68.86$, $p = .006$, Monte Carlo p value, corrected for multiple comparisons) and 750 msec after cue onset also in electrodes located over the occipital cortex ($t = -56.04$, $p = .008$, Monte Carlo p value, corrected for multiple comparisons). In blank trials, the dif-ferences originated 950 msec after cue presentation in left occipital electrodes and spread toward frontal electrodes ($t = -16.75$, $p = .028$, Monte Carlo p value, corrected for multiple comparisons).

Taken together, all three experiments showed modulated pretarget alpha power depending on informative cue presentation, such that power was higher before identification of a visual target compared with an auditory target. This difference was most pronounced in electrodes located over parietal cortex.

Modality-specific Alpha Modulation Restricted to Only Attentional Cues

We found that, in trials with an uninformative cue in Experiment 3, no difference in alpha power was present

Figure 3. Grand mean time–frequency representations of PLF per condition for trials with a target (top rows) and blank (bottom rows) trials. Values are averaged across electrodes located over the occipital cortex (electrodes Oz, O1, and O2). (Top) Trials in which a target was shown. (Bottom) Trials in which a target was expected but not shown. An increase in PLF occurs after presentation of a stimulus (cue or target); however, there was no (significant) PLF observed during the preparation for an upcoming target or at the time of expected target presentation.
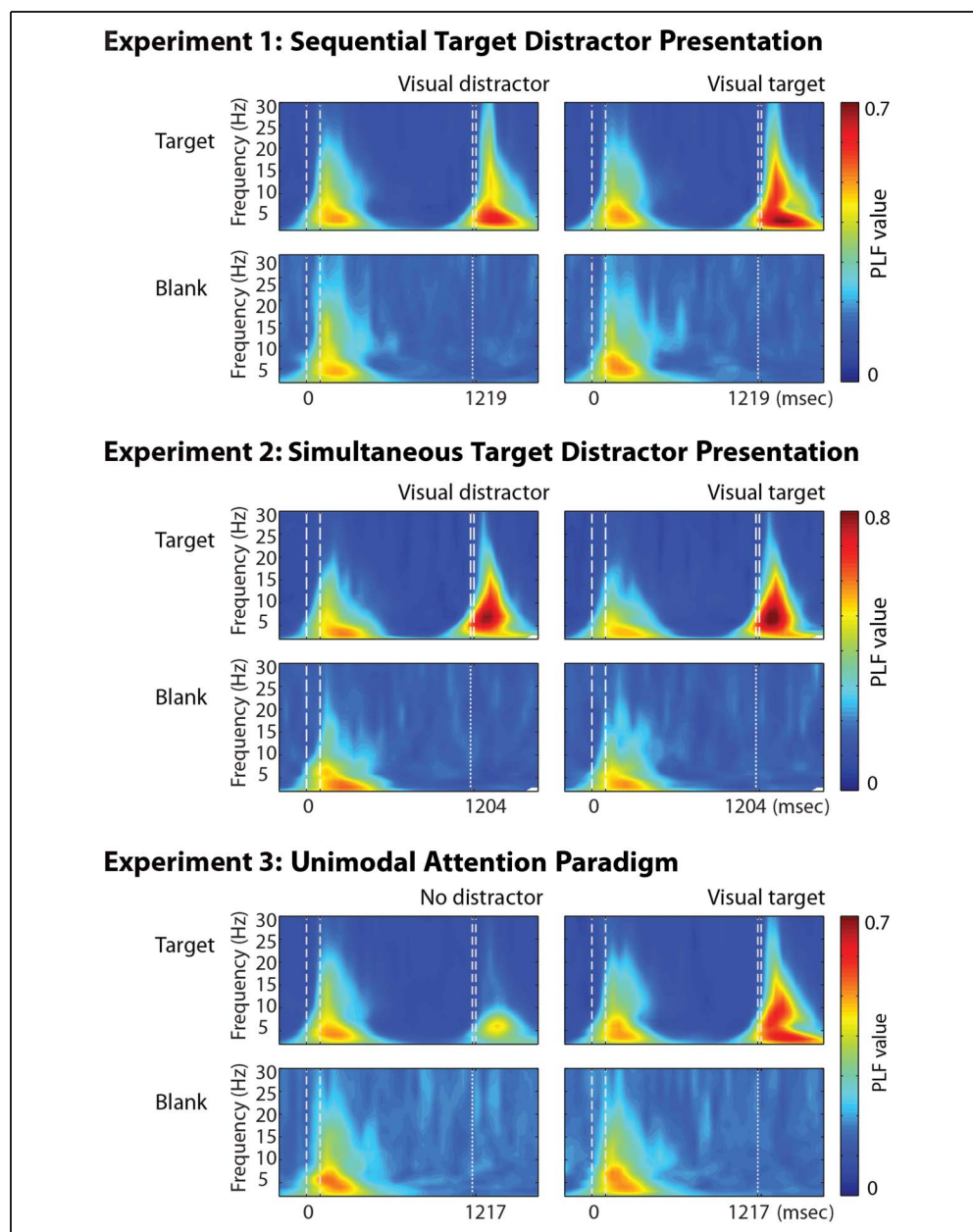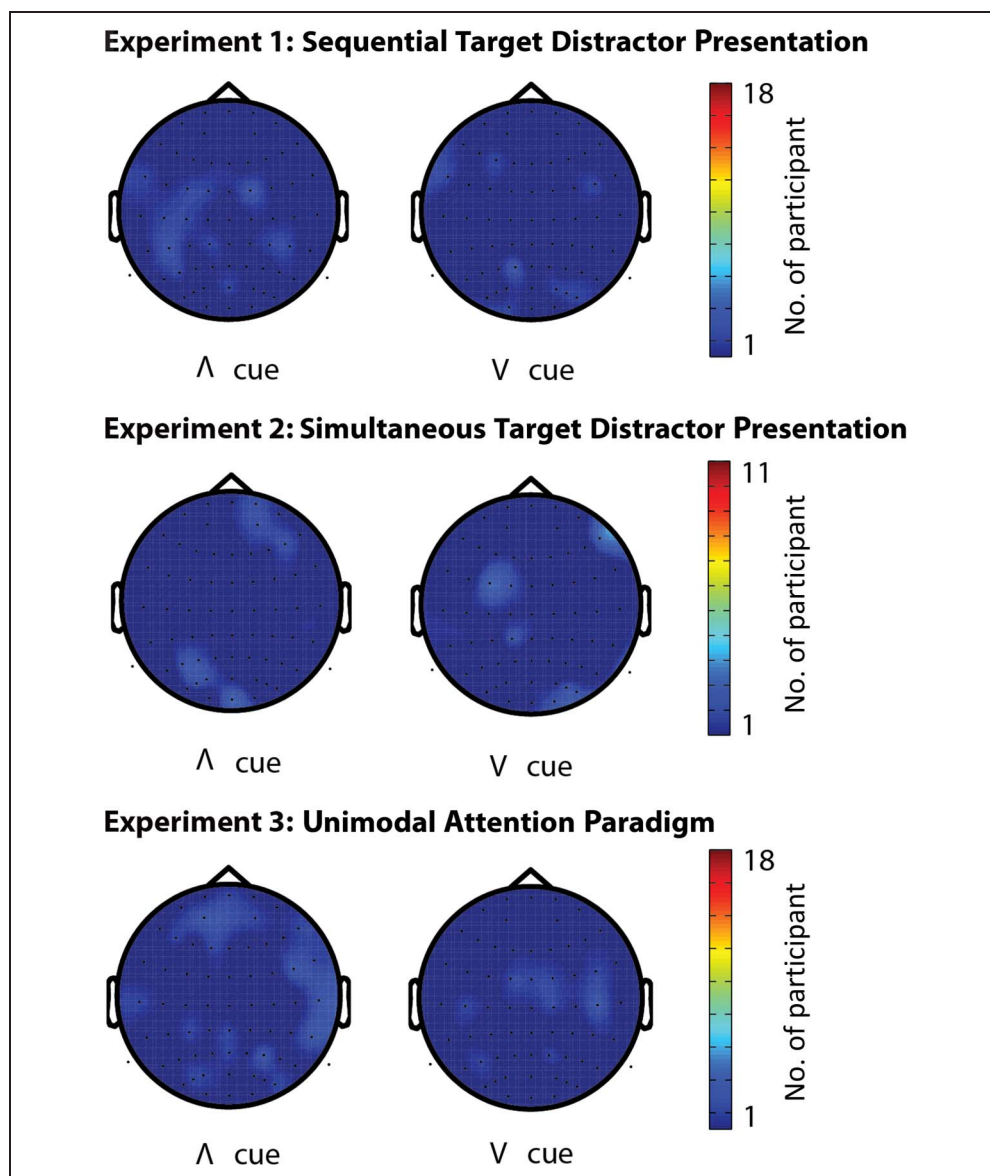
Figure 4. Topographic maps of PLF at the time of expected target presentation. Color scaling specifies the number of participants that show significant PLF, per channel. Left images refer to PLF over trials with an "inverted V" cue, indicating to respond to an auditory target. Right images refer to significant PLF over trials with a "V" cue, indicating to respond to a visual target. The maximum number of participants showing significant PLF values in the same channel was 3.

Experiment 1: Sequential Target Distractor Presentation

∧ cue   V cue

Experiment 2: Simultaneous Target Distractor Presentation

∧ cue   V cue

Experiment 3: Unimodal Attention Paradigm

∧ cue   V cue

No. of participant

before presentation of the targets (when a separate analysis was done on every time point between cue and target presentation as well as when activity was averaged over 450-msec pretarget interval [interval based on time interval in which the difference was found for informative cues]). These results suggest that the modulation of the power of the alpha activity was because of top–down attentional factors, rather than simply the physical onset of the cues.

DISCUSSION

In the current study, we investigated whether the phase of an alpha oscillation could be modulated by top–down control. We utilized a series of attentional cuing paradigms with temporally predictable targets and distractors that also contained "blank" trials with no targets/distractors. These blank trials afforded us the opportunity to in-

vestigate the phase property of the alpha oscillations at the time of expected target or distractor arrival without contamination from sensory evoked responses. We found that the distribution of the phase angles across trials at the time of expected target and distractor arrival was uniform and did not significantly differ from a precue baseline period. These results argue against top–down modulation of phase as a (general) mechanism for selection of relevant information.

Our results appear inconsistent with recent suggestions that the prioritization of information in a stimulus stream occurs through the top–down modulation of alpha phase (Bonnefond & Jensen, 2012; Jensen et al., 2012). Although we find this idea quite intriguing, we argue that the estimates used to support evidence for phase modulation were not fully disentangled from the sensory evoked responses of the targets and distractors. Another explanation for the discrepancy could be that

Figure 5. Scalp topographic maps of PLF difference (*t* value) of *t* test between baseline and time of expected target/distractor presentation. The *t* values are positive (red color) when PLF values are higher at the expected target presentation than baseline. The range of the color bar was chosen such that the upper values correspond to the critical significant values of the *t* distribution. Left images refer to PLF over trials with an "inverted V" cue, indicating to respond to an auditory target. Right images refer to significant PLF over trials with a "V" cue, indicating to respond to a visual target. White dots indicate electrodes with a *t* value that exceeded the statistical threshold of $p < .05$ (no correction for multiple comparisons). No clusters (number of neighboring electrodes > 1) were found in which PLF significantly increased compared with baseline.
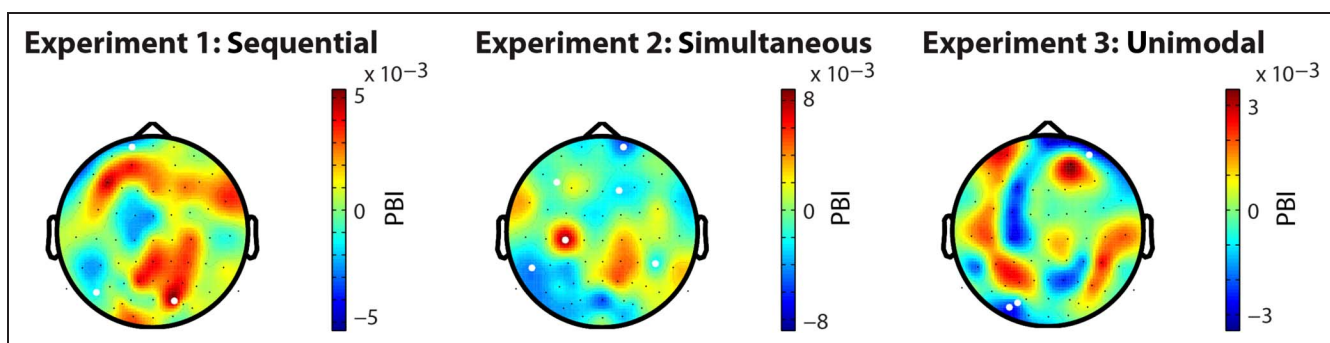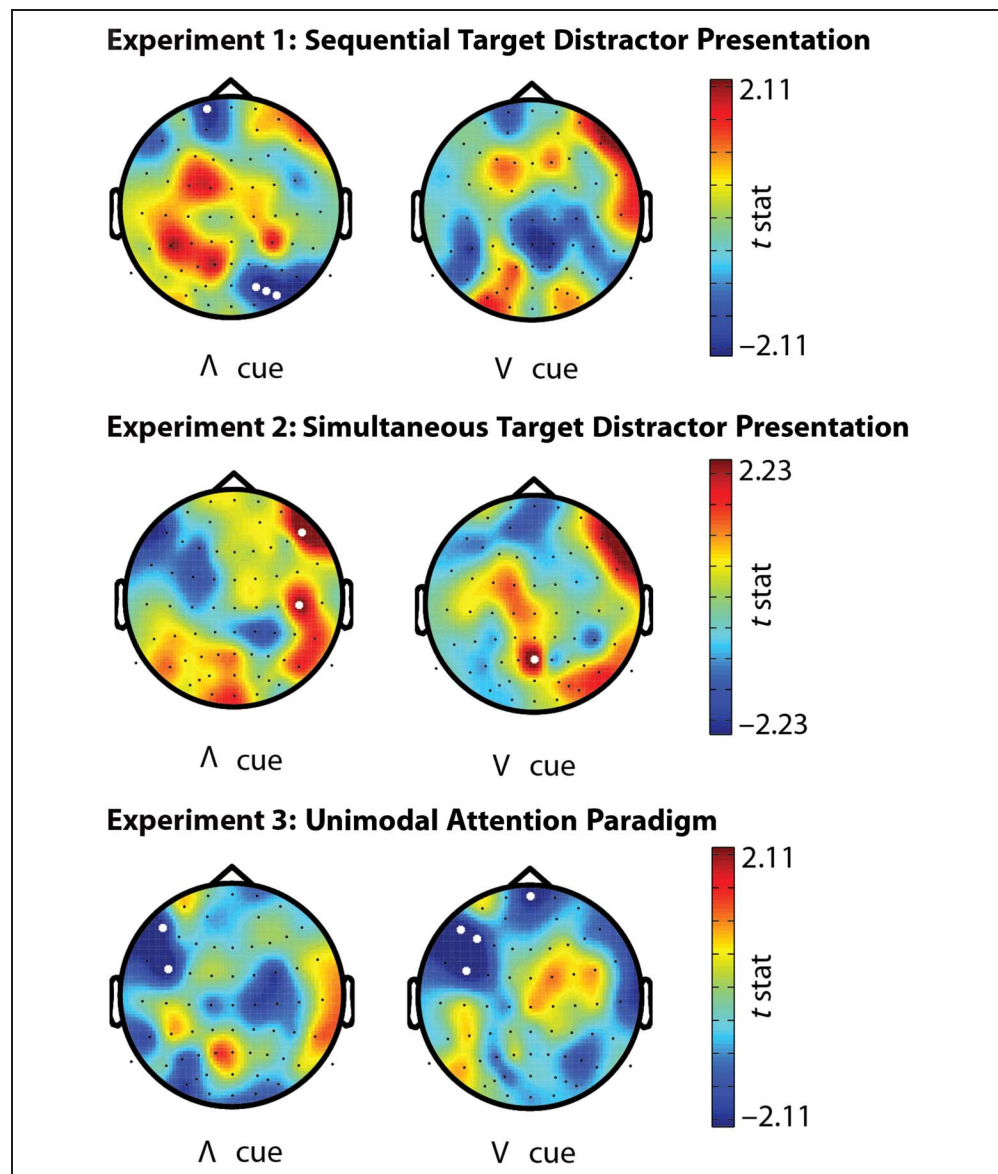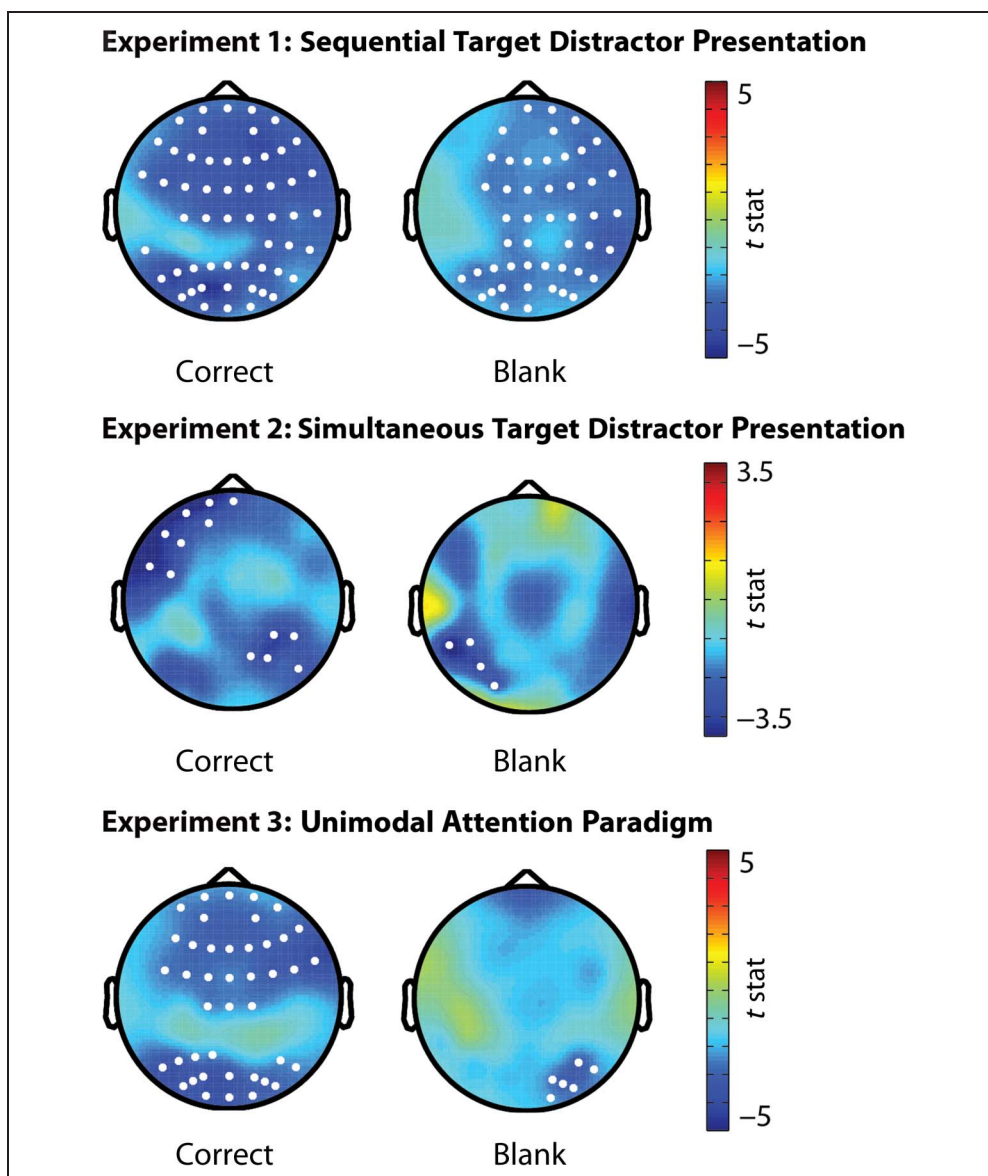

Experiment 1: Sequential Target Distractor Presentation

Λ cue   V cue

Experiment 2: Simultaneous Target Distractor Presentation

Λ cue   V cue

Experiment 3: Unimodal Attention Paradigm

Λ cue   V cue

Experiment 1: Sequential x 10−3

Experiment 2: Simultaneous x 10−3

Experiment 3: Unimodal x 10−3

Figure 6. Topographic representations of average PBI over participants. White dots mark electrodes with a significant PBI assessed using a bootstrapping procedure. A significant positive PBI is observed when the visual and auditory target conditions show a difference in preferred phase angle. A negative PBI is found when a difference in PLF is present between conditions. Because the overall PLF is based on a larger amount of trials than the auditory and visual conditions, the PBI is biased toward positive values, and an absence of any effect (in PLF or phase angle) is represented as a value just above zero. None of the three experiments revealed a cluster of significant PBI values, indicating that no significant difference in phase angle or PLF is present in preparation for a visual or an auditory target.

Figure 7. Topographic representation of alpha power in relation to the cues across the three experiments. The electrodes showing a significant decrease in alpha activity in preparation for a target compared with an auditory target are marked with white dots. Across all three experiments, we found that cues signalling an upcoming visual target induced a pretarget suppression in alpha power over occipital electrodes.

Experiment 1: Sequential Target Distractor Presentation

Correct — Blank

Experiment 2: Simultaneous Target Distractor Presentation

Correct — Blank

Experiment 3: Unimodal Attention Paradigm

Correct — Blank

the study finding the strongest support for top–down control of alpha-phase modulation utilized a working memory paradigm rather than a cross-modal attention task (Bonnefond & Jensen, 2012). It could be that the suppression of distractors during maintenance in working memory is mediated through different mechanisms than suppression of a distracting modality stream. In addition, the cadence of stimulus presentation of their working memory task might have been different, possibly helping the intrinsic time estimation and thus the anticipatory phase estimate. Finally, measurements for current experiment are done with EEG, whereas Bonnefond and Jensen (2012) used MEG for the working memory task. Because EEG is more prone to blurring of signals from several sources, phase estimates in the current paradigm could have been distorted to a larger extent.

In contrast to the PLF results, we did find cue-related differences in alpha power in occipital electrodes. The power of alpha oscillations was larger after presentation of an auditory cue compared with a visual cue, consistent with previous visual-audio cross-modal attention studies (Mazaheri, van Schouwenburg et al., 2014). In the experiments performed in this study, the presentation of a visual cue was meant to facilitate the processing of upcoming stimulus, whereas presentation of the auditory cue indicates that the upcoming visual stimulus needs to be ignored. The absence of a pretarget difference in alpha power after presentation of uninformative cues, together with the slower responses in this condition, indicates that participants used top–down modulation of alpha power as a mechanism to prepare for an upcoming target. A number of previous studies have found that a top–down increase in the power alpha oscillations in task-irrelevant regions serves as a mechanism to actively ignore distracting information (Bauer, Kennett, et al., 2012; Bauer, Kluge, et al., 2012; Haegens et al., 2012; Haegens, Handel, et al., 2011;

Jokisch & Jensen, 2007; Medendorp et al., 2007; Rihs et al., 2007; Sauseng et al., 2005; Thut et al., 2003) through its suppressive influence on spike timing and firing rate of neural activity (Haegens, Nacher, et al., 2011; Mazaheri & Jensen, 2010).

The absence of phase adjustment during processing of the visual target is in line with previous research showing no influence of phase on detection rates during low alpha power (Mathewson et al., 2009, 2011). A decrease in alpha power can induce constant vigilance for detection of (unpredictable) events. The relative decrease in alpha in the occipital cortex after presentation of a visual cue is sufficient to reach a state of high excitability. On the other hand, given that inhibitory influence of high power alpha activity is found to be pulsed instead of continuous (Mathewson et al., 2010, 2011, 2012), a phase modulation would allow for a temporally more precise inhibition than only a power modulation. Interestingly, Mathewson et al. (2011) have proposed that the rhythmicity between excitation and inhibition phases of alpha activity could be beneficial because it would allow for unattended (yet valuable) information from the external environment to filter through analogous to an "…anti-lock brake (ABS) system of a car, in which some level of contacts with the road surface (in our case, the external environment) is maintained by applying pulses of braking rather than by braking continuously."

A handful of studies have found evidence for phase modulation in tasks using rhythmic stimulation, including behavioral effects. For instance, phase entrainment of low-frequency oscillations to temporally regular presented stimulation can enhance contrast sensitivity (Cravo, Rohenkohl, Wyart, & Nobre, 2013). Rhythmic visual stimulation in the alpha range entrains activity and, at the same time, entrains visual awareness (Mathewson et al., 2010). Entrainment is also found when temporally expected events need to be inhibited. Besle and colleagues (2011) found electrodes for which low-frequency oscillations were entrained to stimulus presentation but were phase-shifted for an unattended stream of stimuli compared with an attended stream. Because no trial-by-trial control or shifts of attention are required during these tasks, it is possible that this phenomenon is not realized by top–down attentional control but rather bottom–up processes. In the current experiments, we explicitly searched for phase adjustment in the absence of entrainment. This was realized by the use of tasks with predictable targets in which attentional shifting was needed between trials instead of blocks. The absence of a phase modulation during these tasks argues (with more confidence) against top–down phase modulation as mechanism for inhibition or attention.

We believe that top–down modulation of the phase of alpha oscillations is not necessary. It could be beneficial for (single) temporally predictable events that need to be inhibited. Apart from rhythmic stimulation, such temporally predictable events are uncommon in the natural en-

vironment. Common predictable events, such as speech, can be processed or ignored more efficiently using entrainment (Calderone, Lakatos, Butler, & Castellanos, 2014; Henry & Obleser, 2012). We suggest that top–down modulation of phase of alpha oscillations is an unnecessary mechanism for selection of information when only a temporally brief stimulus is presented.

Caveats

Several task parameters could explain the absence of alpha phase modulation in our series of experiments, leaving open the possibility of phase modulation in other situations. First, a phase modulation is especially effective for near-threshold stimuli (Mathewson et al., 2011; Womelsdorf, Fries, Mitra, & Desimone, 2006). Targets presented in our design were detectable far above threshold, such that the percentage of correct responses was fairly high. The advantage of high task performance is that a higher percentage of blank trials contain correct anticipatory processes instead of mistakes. However, we cannot completely discount the possibility that easiness of the task made that phase adjustment was not essential to perform the task correctly. On the other hand, we believe that it is rather surprising if there were two mechanisms for distraction suppression, one for when target detection is easy and one for when it is difficult.

Another limitation of our task could be the length of the ISI between cue and target. A certain amount of time may be needed to adjust a phase, which would argue for a long cue–target interval. However, interval timing becomes less precise when the interval becomes longer (Buhusi & Meck, 2005), making the estimation of target arrival not precise enough to adjust the phase properly. The time interval between cue and target should be varied to find out whether an ISI exists in which both conditions are met.

Furthermore, we did not localize the anticipatory increase in alpha oscillations before presentation of a visual distractor, which means that the designation of the occipital cortex as source of the inhibitory activity is only speculative.

Conclusion

In summary, in our tasks, attentional cues led to both behavioral and neural changes. RTs to targets were faster when informative cues were presented. The neural changes involved a modulation of the power of ongoing oscillatory activity in the alpha band. However, no sign of a trial-by-trial phase modulation in the alpha band was found. A modulation of phase rather than power of an ongoing oscillation was expected because it might be a more instantaneous and more efficient mechanism (Pilovsky, Rosenblum, & Kurths, 2001). We presented several task parameters that could explain the absence of a phase modulation. Before the start of the experiment,

we hypothesized that a predictable target presentation would be the only requirement for a phase modulation to occur. The increase in number of conditions that might need to be met before a phase modulation can take place makes it less likely that such a modulation is biologically relevant. Our conclusion is, therefore, that the phase of the alpha oscillation is not likely under top–down control.

REFERENCES

Bastiaansen, M. C., & Brunia, C. H. (2001). Anticipatory attention: An event-related desynchronization approach. *International Journal of Psychophysiology, 43,* 91–107.

Bauer, M., Kennett, S., & Driver, J. (2012). Attentional selection of location and modality in vision and touch modulates low-frequency activity in associated sensory cortices. *Journal of Neurophysiology, 107,* 2342–2351.

Bauer, M., Kluge, C., Bach, D., Bradbury, D., Heinze, H. J., Dolan, R. J., et al. (2012). Cholinergic enhancement of visual attention and neural oscillations in the human brain. *Current Biology, 22,* 397–402.

Berens, P. (2009). CircStat: A Matlab toolbox for circular statistics. *Journal of Statistical Software, 31,* 1–21.

Besle, J., Schevon, C. A., Mehta, A. D., Lakatos, P., Goodman, R. R., McKhann, G. M., et al. (2011). Tuning of the human neocortex to the temporal dynamics of attended events. *Journal of Neuroscience, 31,* 3176–3185.

Bonnefond, M., & Jensen, O. (2012). Alpha oscillations serve to protect working memory maintenance against anticipated distractors. *Current Biology, 22,* 1969–1974.

Buhusi, C. V., & Meck, W. H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews Neuroscience, 6,* 755–765.

Busch, N. A., Dubois, J., & VanRullen, R. (2009). The phase of ongoing EEG oscillations predicts visual perception. *Journal of Neuroscience, 29,* 7869–7876.

Calderone, D. J., Lakatos, P., Butler, P. D., & Castellanos, F. X. (2014). Entrainment of neural oscillations as a modifiable substrate of attention. *Trends in Cognitive Sciences, 18,* 300–309.

Cravo, A. M., Rohenkohl, G., Wyart, V., & Nobre, A. C. (2013). Temporal expectation enhances contrast sensitivity by phase entrainment of low-frequency oscillations in visual cortex. *Journal of Neuroscience, 33,* 4002–4010.

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,* 9–21.

Fu, K. M. G., Foxe, J. J., Murray, M. M., Higgins, B. A., Javitt, D. C., & Schroeder, C. E. (2001). Attention-dependent suppression of distractor visual input can be cross-modally cued as indexed by anticipatory parieto-occipital alpha-band oscillations. *Cognitive Brain Research, 12,* 145–152.

Haegens, S., Handel, B. F., & Jensen, O. (2011). Top–down controlled alpha band activity in somatosensory areas determines behavioral performance in a discrimination task. *Journal of Neuroscience, 31,* 5197–5204.

Haegens, S., Luther, L., & Jensen, O. (2012). Somatosensory anticipatory alpha activity increases to suppress distracting input. *Journal of Cognitive Neuroscience, 24,* 677–685.

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, U.S.A., 108,* 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 participants. *NeuroImage, 37,* 1465–1473.

Henry, M. J., & Obleser, J. (2012). Frequency modulation entrains slow neural oscillations and optimizes human listening behavior. *Proceedings of the National Academy of Sciences, U.S.A., 109,* 20095–20100.

Jensen, O., Bonnefond, M., & VanRullen, R. (2012). An oscillatory mechanism for prioritizing salient unattended stimuli. *Trends in Cognitive Sciences, 16,* 200–206.

Jensen, O., Hari, R., & Kaila, K. (2002). Visually evoked gamma responses in the human brain are enhanced during voluntary hyperventilation. *NeuroImage, 15,* 575–586.

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: Gating by inhibition. *Frontiers in Human Neuroscience, 4,* 186.

Jokisch, D., & Jensen, O. (2007). Modulation of gamma and alpha activity during a working memory task engaging the dorsal or ventral stream. *Journal of Neuroscience, 27,* 3244–3251.

Kerlin, J. R., Shahin, A. J., & Miller, L. M. (2011). Attentional gain control of ongoing cortical speech representations in a cocktail party. *Journal of Neuroscience, 30,* 620–628.

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews, 53,* 63–88.

Makeig, S., Westerfield, M., Jung, T. P., Enghoff, S., Townsend, J., Courchesne, E., et al. (2002). Dynamic brain sources of visual evoked responses. *Science, 295,* 690–694.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164,* 177–190.

Mathewson, K. E., Fabiani, M., Gratton, G., Beck, D. M., & Lleras, A. (2010). Rescuing stimuli from invisibility: Inducing a momentary release from visual masking with pre-target entrainment. *Cognition, 115,* 186–191.

Mathewson, K. E., Gratton, G., Fabiani, M., Beck, D. M., & Ro, T. (2009). To see or not to see: Prestimulus alpha phase predicts visual awareness. *Journal of Neuroscience, 29,* 2725–2732.

Mathewson, K. E., Lleras, A., Beck, D. M., Fabiani, M., Ro, T., & Gratton, G. (2011). Pulsed out of awareness: EEG alpha oscillations represent a pulsed-inhibition of ongoing cortical processing. *Frontiers in Psychology, 2,* 99.

Mathewson, K. E., Prudhomme, C., Fabiani, M., Beck, D. M., Lleras, A., & Gratton, G. (2012). Making waves in the stream of consciousness: Entraining oscillations in EEG alpha and fluctuations in visual awareness with rhythmic visual stimulation. *Journal of Cognitive Neuroscience, 24,* 2321–2333.

Mazaheri, A., Coffery-Corina, S., Mangun, G. R., Bekker, E. M., Berry, A., & Corbett, B. A. (2010). Functional disconnection of frontal cortex and visual cortex in attention deficit hyperactivity disorder. *Biological Psychiatry, 67,* 617–623.

Mazaheri, A., Fassbender, C., Coffey-Corina, S., Hartanto, T. A., Schweitzer, J. B., & Mangun, G. R. (2014). Differential oscillatory electroencephalogram between attention-deficit/hyperactivity disorder subtypes and typically developing adolescents. *Biological Psychiatry, 76,* 422–429.

Mazaheri, A., & Jensen, O. (2006). Posterior alpha activity is not phase-reset by visual stimuli. *Proceedings of the National Academy of Sciences, U.S.A., 103,* 2948–2952.

Mazaheri, A., & Jensen, O. (2010). Rhythmic pulsing: Linking ongoing brain activity with evoked responses. *Frontiers in Human Neuroscience, 4,* 177.

Mazaheri, A., Nieuwenhuis, I. L. C., van Dijk, H., & Jensen, O. (2009). Prestimulus alpha and mu activity predicts failure to inhibit motor responses. *Human Brain Mapping, 30,* 1791–1800.

Mazaheri, A., van Schouwenburg, M. R., Dimitrijevic, A., Denys, D., Cools, R., & Jensen, O. (2014). Region-specific modulations in oscillatory alpha activity serve to facilitate processing in the visual and auditory modalities. *NeuroImage, 87,* 356–362.

Medendorp, W. P., Kramer, G. F. I., Jensen, O., Oosterveld, R., Schoffelen, J. M., & Fries, P. (2007). Oscillatory activity in human parietal and occipital cortex shows hemispheric lateralization and memory effects in a delayed double-step saccade task. *Cerebral Cortex, 17,* 2364–2374.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience, 2011,* 156869.

Osipova, D., Takashima, A., Oostenveld, R., Fernandez, G., Maris, E., & Jensen, O. (2006). Theta and gamma oscillations predict encoding and retrieval of declarative memory. *Journal of Neuroscience, 26,* 7523–7531.

Pilovsky, A. S., Rosenblum, M. G., & Kurths, J. (2001). *Synchronization: A universal concept in nonlinear sciences.* Cambridge: Cambridge University Press.

Rihs, T. A., Michel, C. M., & Thut, G. (2007). Mechanisms of selective inhibition in visual spatial attention are indexed by alpha-band EEG synchronization. *European Journal of Neuroscience, 25,* 603–610.

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. *European Journal of Neuroscience, 22,* 2917–2926.

Scheeringa, R., Mazaheri, A., Bojak, I., Norris, D. G., & Kleinschmidt, A. (2011). Modulation of visually evoked cortical fMRI responses by phase of ongoing occipital alpha oscillations. *Journal of Neuroscience, 31,* 3813–3820.

Tallon-Baudry, C., Bertrand, O., Delpuech, C., & Pernier, J. (1996). Stimulus specificity of phase-locked and non-phase-locked 40 Hz visual responses in human. *Journal of Neuroscience, 16,* 4240–4249.

Thut, G., Miniussi, C., & Gross, J. (2012). The functional importance of rhythmic activity in the brain. *Current Biology, 22,* R658–R663.

Thut, G., Theoret, H., Pfennig, A., Ives, J., Kampmann, F., Northoff, G., et al. (2003). Differential effects of low-frequency rTMS at the occipital pole on visual-induced alpha de synchronization and visual-evoked potentials. *NeuroImage, 18,* 334–347.

Womelsdorf, T., Fries, P., Mitra, P. P., & Desimone, R. (2006). Gamma-band synchronization in visual cortex predicts speed of change detection. *Nature, 439,* 733–736.