A theta rhythm in awake macaque V1 and V4 and its attentional modulation

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Abstract

Theta-rhythmic neuronal synchronization has been described in hippocampus and high-level visual areas. Recent studies suggest that theta in visual areas might originate in V1. We analyzed simultaneous electrocorticographic (ECoG) grid recordings of local field potentials from areas V1 and V4 of two macaque monkeys performing a selective visual attention task. We found a ≈4 Hz theta rhythm, which was strongest at sites showing visually induced gamma-band activity. This theta rhythm was coherent between V1 and V4, with a predominant V1-to-V4 Granger causal influence. Locally, theta phase was correlated with power in a narrow gamma-frequency band. These theta-rhythmic processes were reduced by selective attention to a visual stimulus contralateral to the recorded visual areas. This attentional effect was substantial, particularly compared to other reported effects of attention in area V1. We also investigated, whether microsaccades (MSs) play a role in the generation or attentional modulation of theta. Stratification of MS rate between attention conditions, or elimination of MS-affected data epochs left the main results essentially unchanged. Thus, we find an MS-independent theta rhythm in the visually driven part of V1, which rhythmically modulates local gamma and entrains V4, and which is strongly reduced by attention.

Significance Statement

Theta rhythms, around 3-8 Hz, have been found in many different parts of the brain. They are predominant in the rodent hippocampus, yet have also been described in neocortex, primarily in frontal and parietal areas in relation to executive functions. Here, we show a 4 Hz theta rhythm in awake macaque monkey area V4 and primary visual cortex. This theta rhythm was spatially coextensive with visually induced gamma-band activity, and gamma power was modulated by theta phase. The strength of theta and of theta-rhythmic gamma modulation was markedly reduced by selective attention. Theta rhythmicity has been observed in microsaccade sequences, and microsaccades influence early visual activity. Yet, removing (the effects of) microsaccades did not influence the results.

Introduction

Neuronal activity shows rhythmic structure in several characteristic frequency bands (Buzsáki, 2006). These different rhythms have often been linked to areas and/or functions, in which they predominate (Keitel and Gross, 2016). The theta rhythm has primarily been described in high-level areas of awake mammalian brains in the context of higher cognitive functions. A particularly strong theta rhythm exists in rodent medial temporal lobe (MTL), in particular the hippocampus and entorhinal cortex (O'Keefe and Recce, 1993; Hafting et al., 2008). This theta is found during exploratory behavior, and has been implicated in episodic memory (Skaggs et al., 1996; Dragoi and Buzsáki, 2006; Jezek et al., 2011). A similar theta rhythm also exists in the MTL of non-human and human primates during virtual maze navigation (Kahana et al., 1999) and visual exploration (Killian et al., 2012; Jutras et al., 2013), and has been linked to episodic memory encoding (Rutishauser et al., 2010; Lega et al., 2012; Jutras et al., 2013) and working memory maintenance (Raghavachari et al., 2001; Axmacher et al., 2010).

Hippocampal theta is synchronized with a theta rhythm in prefrontal cortex (PFC) (Siapas et al., 2005; Sirota et al., 2008; Brincat and Miller, 2015). Theta in PFC and strongly connected structures like the anterior cingulate cortex (ACC) and the posterior parietal cortex has been described when subjects exert executive control (Debener et al., 2005; Womelsdorf et al., 2010; Phillips et al., 2014; Voloh et al., 2015; Hawellek et al., 2016; Babapoor-Farrokhran et al., 2017).

The theta rhythm in non-human primate PFC shows long-distance synchronization to a theta rhythm in area V4 (Lee et al., 2005; Liebe et al., 2012). This PFC-V4 theta-band synchronization and the V4 theta rhythm is pronounced during the delay period of a visual working memory task, that is, in the absence of visual stimulation. In inferotemporal cortex, a theta rhythm has been described that is phase-locked to stimulus onset (Rollenhagen and Olson, 2005).

A theta rhythm at 3-5 Hz has also been described in mid-level visual areas V4 and V5/MT during selective visual attention tasks. A study in macaque area MT reported that the power of high-frequency (30-120 Hz) LFP components is modulated by the phase of low-frequency (1-8 Hz) components, and that this modulation is reduced by attention to the visual stimulus activating the recorded neurons (Esghaei et al., 2015). A study in macaque area V4 showed spike-field and spike-spike coherence at 2-4 Hz and straddling the lower end of the spectrum (Fries et al., 2008). This local low-frequency synchronization was enhanced by visual stimulation; furthermore, it was reduced by attention in the absence of visual stimulation. A subsequent study reported that the 4 Hz phase of LFP in macaque V4 modulates the gamma-band synchronization between areas V4 and V1 (Bosman et al., 2012). Also theta-band Granger causality (GC) influences around 4 Hz between V1 and V4 are stronger in the feedforward direction (Bastos et al., 2015b). This suggests that a 4 Hz rhythm might emerge in area V1 and entrain higher areas. Interestingly, a previous study found that microsaccades (MSs) occur at a 3-4 Hz rhythm and lead to evoked responses and perturbations in local synchronization in both, areas V1 and V4 (Bosman et al., 2009). This MS-related V1 4 Hz rhythm temporally structures also the V1-V2 interaction by co-modulating respective gamma power and frequency (Lowet et al., 2016).

Thus, several studies suggest a theta rhythm in V1, by e.g. showing a theta modulation of V1-V4 or V1-V2 interactions. Here, we analyzed simultaneous LFP recordings from awake macaque V1 and V4. We investigated whether the respective LFP power and phase-locking spectra actually show theta peaks, how this is related to visually induced activity, whether local gamma-band power is modulated by theta phase, to which degree these theta-related phenomena are independent of MSs, and whether they are modulated by selective visual attention.

Materials and Methods

Subjects, stimuli and task

Two adult male macaque monkeys participated in this study. All procedures were in accordance with Dutch and European regulations for the protection of animals and were approved by the animal ethics committee of Radboud University Nijmegen (Netherlands). The data analyzed here have been (partially) used in previous studies (Bosman et al., 2012; Brunet et al., 2014a; Brunet et al., 2014b; Pinotsis et al., 2014; Bastos et al., 2015a; Bastos et al., 2015b; Brunet et al., 2015; Richter et al., 2015; Vinck et al., 2015; Lewis et al., 2016).

Stimuli and behavior were controlled by the software CORTEX (http://dally.nimh.nih.gov). Stimuli were presented on a CRT monitor at 120 Hz non-interlaced. When the monkey touched a bar, a gray fixation point appeared at the center of the screen. When the monkey brought its gaze into a fixation window around the fixation point (0.85 degree radius in monkey K; 1 deg radius in monkey P), a pre-stimulus baseline of 0.8 s started. If the monkey's gaze left the fixation window at any time, the trial was terminated. The measured eye positions during correct trials used for analysis differed only by an average of 0.03 deg of visual angle between the two attention conditions. After the baseline period, two physically isoluminant patches of drifting sinusoidal grating appeared (diameter= 3 degrees, spatial frequency ≈1 cycles/degree, drift velocity ≈1 degree/s, resulting temporal frequency ≈1 cycle/s, contrast= 100%). The two grating patches chosen for a given recording session always had equal eccentricity, size, contrast, spatial frequency and drift velocity. The two gratings always had orientations that were orthogonal to each other, and they had drift directions that were incompatible with a Chevron pattern moving behind two apertures, to avoid pre-attentive binding. In any given trial, one grating was tinted yellow, the other blue, with the color assigned randomly across trials. The yellow and blue colors were physically equiluminant. After 1-1.5 s (0.8-1.3 s in monkey P), the fixation point changed color to match the color of one of the two gratings, thereby indicating this grating as the relevant stimulus and the other as irrelevant. For each trial, two independent change times for the two stimuli were determined randomly between stimulus onset and 4.5 s after cue onset, according to a slowly rising hazard rate. If the relevant stimulus changed (before or after the irrelevant stimulus changed), and the monkey released the bar within 0.15-0.5 s thereafter, the trial was terminated and a reward was given. If the monkey released the bar at any other time, the trial was terminated without reward. The stimulus changes were small changes in the grating pattern, with the stripes undergoing a gentle bend. During the bend, the outer ends of the grating stripes lagged increasingly behind the center of the stripes, until the lag reached 0.1 degree at 75 ms after the start of the bend. Over the course of another 75 ms, the stripes straightened again.

Several sessions (either separate or after attention-task sessions) were devoted to the mapping of receptive fields (RFs), using 60 patches of moving grating. Receptive field positions were stable across recording sessions (Bosman et al., 2012).

Neurophysiological recordings and signal preprocessing

Neuronal recordings were made from two left hemispheres in two monkeys through a micromachined 252-channel electrocorticographic electrode array (ECoG) implanted subdurally. The details of the production and the electrochemical properties have been described in a separate paper (Rubehn et al., 2009). Briefly, ECoG grids were 10 micron thick polyimide foils with 0.3 micron thick Platinum electrodes and conductive lanes embedded. Electrodes had an exposed surface with a diameter of 1 mm and a center-to-center spacing of 2-3 mm. Electrodes were arranged in lanes, and two neighboring lanes ran parallel on one "finger" of the polyimide foil (Bastos et al., 2015b). The structuring in separate fingers avoided wrinkling of the ECoG on the brain surface and subsequent pressure points. For ECoG implantation, a 6.5x4 cm craniotomy over the left hemisphere in each monkey was performed under aseptic conditions with isoflurane anesthesia. The dura was opened and the ECoG was placed directly onto the brain under visual control. Several high resolution photos were taken before and after placement of the ECoG for later coregistration of ECoG signals with brain regions. After ECoG implantation, both the bone and the dural flap were placed back and secured in place. After a recovery period of approximately three weeks, we started with neuronal recordings.

Signals obtained from the 252-electrode grid were amplified 20 times by eight Plexon headstage amplifiers (Plexon, USA), high-pass filtered at 0.159 Hz, low-pass filtered at 8 kHz and digitized at 32 kHz by a Neuralynx Digital Lynx system (Neuralynx, USA). LFP signals were obtained by low-pass filtering at 200 Hz and downsampling to 1 kHz. Powerline artifacts were removed by digital notch filtering. The actual spectral data analysis included spectral smoothing that rendered the original notch invisible.

Data analysis

General. All analyses were done in MATLAB (The MathWorks, USA) and using FieldTrip (Oostenveld et al., 2011) (http://fieldtrip.fcdonders.nl).

Recording electrodes versus recording sites. During recordings, all ECoG electrodes were referenced against one silver ball implanted epidurally over the other hemisphere. This common reference could lead to artifactual correlations between the signals of separate electrodes. Therefore, all metrics of interaction between distant groups of neurons, that is the pairwise phase consistency (PPC) and Granger causality (GC), were applied after removing the common reference by local bipolar differentiation. That is, the signals from two immediately neighboring electrodes were subtracted from each other. We refer to the ECoG contacts as "electrodes" and to the local bipolar derivations as "recording sites" or just "sites". All analyses of local neuronal activity used directly the signals recorded from the electrodes, to minimize preprocessing and to minimize reduction in theta amplitude due to theta phase alignment between neighboring electrodes.

Selection of electrodes and sites. The ECoG grids provided dense coverage of dorsal V1, the superficial part of dorsal V2, dorsal V4 and posterior TEO (Bosman et al., 2012; Bastos et al., 2015b). For simplicity, we refer to V1 and V2 sites as V1, and to V4 and TEO sites as V4. Monkey K had 45 electrodes on V1, resulting in 40 bipolar sites, and 24 electrodes on V4, resulting in 19 sites. Monkey P had 72 electrodes on V1, resulting in 64 sites, and 26 electrodes on V4, resulting in 21 sites.

Normalization of signals across electrodes and recording sessions. Signal amplitude could vary across electrodes because several separate headstages were used. Furthermore, signal amplitude of a given electrode could vary across sessions, probably due to variable quality of contact to the cortical surface. To equalize the contribution of different electrodes and sessions, we applied a z-transform: For each electrode and session, the raw LFP signal was demeaned and divided by its standard deviation.

Segmenting data into epochs. Each successfully completed trial contained three periods: The pre-stimulus, the pre-cue and the post-cue period. The pre-stimulus period was the time between fixation onset and stimulus onset. During the pre-stimulus period, monkeys fixated on a fixation point on a gray screen, and there was no stimulus presented and no cue had been nor was presented during that time. The pre-cue period was the time between stimulus onset and cue onset. During the pre-cue period, monkeys kept fixation, the stimuli were continuously present, one tinted yellow the other blue, chosen randomly, and the fixation point had not yet assumed a color, and thereby the attentional cue had not been given. The post-cue period was the time between cue onset and target change. During the post-cue period, monkeys kept fixation, the stimuli were continuously present with their tints and the fixation point was tinted in one of these colors, thereby providing the attentional cue. On approximately half of the trials, the post-cue period contained a distracter change, and the data immediately following this event were excluded as explained below. The pre-stimulus, pre-cue and post-cue periods all were of variable length across trials. The spectral analysis was based on epochs of fixed lengths. Therefore, the described task periods were cut into non-overlapping epochs. We aimed at excluding data soon after events, like stimulus onset, cue onset and distracter change, to minimize effects of post-event transients and non-stationarities on the metrics of rhythmicity and synchronization. Therefore, periods were cut into non-overlapping epochs, starting from the end of the period and stopping, before an epoch would have included data less than 0.5 s after those events. In general, we cut epochs of 1 s length, to achieve a fundamental spectral resolution (Rayleigh frequency) of one Hertz. This was used for the analysis of PPC, GC and phase-amplitude coupling (PAC). The PAC analysis required the prior estimation of the power time course, for which we employed window lengths of ±2.5 cycles per frequency. In this case, epochs were cut such that the power estimation windows excluded data less than 0.5 s after events. The estimation of power spectra was based on 1.6 s epochs, because theta peaks were visible but less conspicuous when 1 s epochs were used.

Spectral estimation. Epochs were Hann tapered and Fourier transformed. For the PAC analysis, the ±2.5 cycle long windows were also treated in this way. For the analysis of the spatial correlation between theta power and stimulus induced gamma power, the gamma-power estimation used multitaper spectral estimation with seven tapers taken from the discrete prolate spheroidal sequence, defined on 0.5 s long epochs (Mitra and Pesaran, 1999).

Robust regression. We reduced the $1/f^n$ background in power spectra by estimating the $1/f^n$ component and subtracting it. Specifically, for each electrode separately, we pooled attention conditions and fitted a line to the log-log power plot between 0.625 and 10 Hz, using robust regression as implemented in the MATLAB "robustfit" function with default settings. Robust regression uses an iterative procedure that lends less weight to data that are far from the fitted function. Subsequently, the fitted line was subtracted to obtain the power residuals.

Pairwise phase consistency (PPC) and Phase-amplitude coupling (PAC). Phase locking was quantified with the pairwise phase consistency (PPC) metric (Vinck et al., 2010). We used PPC both to quantify the locking between LFPs recorded from separate sites, and to quantify the locking between the LFP phase and its amplitude fluctuations, that is, the PAC (phase-amplitude coupling) (Scheffer-Teixeira and Tort, 2016). PPC is not biased by the number of epochs, whereas the more conventional coherence metric has that bias. Essentially, the PPC calculation proceeds in two steps. First, phases are estimated for the multiple epochs of the two signals, and the relative phases are calculated. The second step is the crucial step: In conventional coherence calculation, those relative phases are averaged, which leads to the bias by epoch number; in PPC calculation, all possible pairs of relative phases are formed, the cosines between those relative phases are determined and those cosine values are averaged.

To quantify PAC, we computed the PPC between the LFP at lower frequencies, the "phase-frequencies", and the time-varying power at higher frequencies, the "amplitude-frequencies". One-second long epochs of the raw LFP and of its time-varying power were Fourier transformed, and locking among the phase estimates at the phase-frequencies was quantified as the PPC across all available epochs. PAC can in general only be estimated for pairs of phase- and amplitude-frequencies, for which the amplitude frequency is higher than the phase frequency. In addition, the estimation of time-varying power entails low-pass filtering, and PAC can only be estimated for pairs of phase- and amplitude-frequencies, for which this low-pass frequency is above the phase frequency. Power is estimated on the basis of epochs and tapers of finite length. As described above, we chose epochs of ±2.5 cycle length per frequency. In order to assess the resulting low-pass filtering, we applied the power estimation 10000 times to a random Gaussian process of the same length as the data epochs, and determined the frequency, at which this low-pass filtering reduced the average power to less than 70% of the power in the passband. For example, for 50 Hz, this cutoff frequency was 7.7 Hz. This procedure was applied for each amplitude frequency, and the PAC for this amplitude frequency was only considered up to the respective phase frequency. The excluded combinations of phase-frequencies and amplitude-frequencies are masked with black in the figures. The PAC results shown here use phase and power estimates from the same electrode.

We also calculated PAC by combining phase estimates from one electrode with power estimates of neighboring electrodes, and this left the results essentially unchanged.

Granger causality. We used the non-parametric estimation of Granger causality (Dhamala et al., 2008). For this, Fourier spectra were estimated as described above and entered into a non-parametric spectral matrix factorization (NPSF) as implemented in the FieldTrip toolbox.

Statistical testing. The confidence intervals shown for power and PPC spectra in Figure 1 were estimated with a bootstrap procedure (1000 bootstrap replications for power, 500 for PPC) (Efron and Tibshirani, 1994): Spectra were first averaged across electrodes (for power) or site pairs (for PPC), and subsequently, the bootstrap was performed across epochs. All statistical comparisons were based on non-parametric permutation and included corrections for the multiple comparisons made across frequencies. We illustrate the procedure for the comparison of power between the two attention conditions. The power difference between the attention conditions was first averaged over all electrodes per monkey and then over the two animals, giving the observed power difference per frequency. Subsequently, the following procedure was done 1000 times: 1) The attention conditions were randomly exchanged between epochs, keeping the original number of epochs per attention conditions constant; 2) The average power difference was calculated as described for the observed data; 3) The maximal (minimal) difference across all frequencies was placed into the randomization distribution of maximal (minimal) values; 4) The 2.5^{th} percentile of the minimal values and the 97.5^{th} percentile of the maximal values were taken as statistical thresholds. The observed differences were compared to those thresholds. This procedure implements a non-parametric version of a two-sided test with multiple comparison correction (Nichols and Holmes, 2002). The same procedure was used for comparing power, PPC, GC and PAC values between attention conditions; for power and PAC, we used 1000 permutations, for PPC and GC 500 permutations.

The spatial correlation coefficients and the PAC values were tested in two ways: They were compared between attention conditions as described, and they were additionally tested for the presence of significant correlation or PAC. In the case of PAC, the comparison was done between the observed values and a randomization distribution obtained by randomly pairing raw LFP epochs and power time courses 1000 times. After each random pairing and recalculation of PAC, maximal and minimal values across all frequency-frequency pairs were placed into the respective randomization distribution, and further testing proceeded as described. In the case of the spatial correlations, the comparison was done between the observed values and zero, because the Spearman rank correlation has no bias; the randomization was done by randomly pairing electrodes between the theta power residuals and the stimulus induced gamma. After each randomization, maximal and minimal correlation values across all tested frequencies were placed into the respective randomization distribution, and further testing proceeded as described.

Microsaccade detection. Raw vertical and horizontal eye position signals were low-pass filtered by replacing each value with the average over itself ±15 samples (at 1 kHz sampling rate). Signals were then differentiated in time to obtain the vertical and horizontal velocities. Those are combined to obtain the eye speed irrespective of the direction of eye movement. Per trial, the standard deviation of eye speed was determined, and any deviation larger than 5 SDs and lasting for at least 30 ms was considered a saccadic eye movement. Saccadic eye movements that remained within the fixation window were considered microsaccades (MSs).

Stratification. We intended to test, whether some of the observed differences in power, PPC or PAC between attention conditions were due to differences in the rate of MSs or in the power of theta, which existed between attention conditions. To this end, we used a stratification approach, that is, we randomly subsampled the available data to equate as well as possible the distributions of MS rates or theta power (Schoffelen et al., 2005). For MS stratification, we first calculated MS density by convolving the MS sequence with a Gaussian kernel with an SD of 150 ms (truncated at ±500 ms). For each epoch, we calculated the average MS density, which was then used for stratification. Stratification for theta power was applied after removing the $1/f^n$ component estimated by robust regression. Stratification for a given parameter (MS density or theta power) proceeded as follows: The parameter distributions were compiled for the two attention conditions and binned into 40 equally spaced bins. For each bin, the number of entries for the two attention conditions was equated by random subsampling with a procedure that aims at equating the parameter averages between the conditions as well as possible. This procedure is applied to the distributions per bin: 1) The condition with more entries is defined as the larger condition, the other as the smaller condition; 2) The mean of the parameter for the smaller condition is calculated and taken as target value; 3) The larger condition is randomly subsampled, by first drawing one entry at random, and then proceeding as follows: a) A further entry is randomly drawn; b) If the mean of the current bin entries (or the starter entry) is smaller (larger) than the target value, the new entry is added if it is larger (smaller), otherwise it is discarded and a new random draw is performed. This latter step aims at equating means; if no such entry is present, a randomly drawn entry is accepted.

Results

Macaque areas V1 and V4 show a theta rhythm

We first calculated power spectra averaged over all electrodes on V1 and V4 from periods, during which the monkey fixated and covertly monitored one of two simultaneously presented drifting grating stimuli (see Materials and Methods for the definition of "electrodes" versus "sites" and the attribution of electrodes and sites to areas). Those average power spectra exhibited clear peaks in the gamma and the beta range, with peak frequencies specific to each monkey; however, they did not exhibit clear peaks in the theta-frequency range (Fig. 1A,B). We have previously found that power spectra can fail to reveal rhythms that are nevertheless unequivocally detectable with metrics of phase locking (Vinck et al., 2013;

Brunet et al., 2014a). Here, we quantified phase locking by means of the pairwise phase consistency metric (PPC, see Materials and Methods). We calculated PPC spectra averaged over all possible pairs of sites within and between V1 and V4. The average PPC spectra confirmed the gamma and beta peaks and in addition revealed clear theta peaks around 4 Hz (Fig. 1C,D). Thus, awake macaque visual cortex shows a distinct theta rhythm, when activated by a visual stimulus.

Selective attention reduces theta

Previous studies reported similar theta or low-frequency rhythms in awake macaque areas V4 and MT, which were reduced by selective attention (Fries et al., 2001; Esghaei et al., 2015). Theta might be generated in those extrastriate areas, or it might alternatively emerge already at earlier stages of the visual system. A previous study has found that Granger-causality between visual areas in the theta band is stronger in the feedforward than feedback direction (Bastos et al., 2015b). Thus, theta in extrastriate cortex might actually be driven by theta in primary visual cortex. Therefore, we investigated the theta rhythm separately in areas V1 and V4, and we tested if it was affected by selective attention. Raw power spectra averaged over all V1 electrodes showed a shallow bump around 4 Hz (Fig. 2A). This V1 theta rhythm was reduced when attention was directed to the contralateral visual stimulus, which was driving part of the V1 electrodes. A similar pattern was found in V4: There was a very shallow bump with an attentional reduction close to 4 Hz (Fig. 2B).

To reduce the $1/f^n$ component of the power spectrum, we estimated it by robust regression and subtracted it from the total power (Manning et al., 2009). We followed this approach and found that in the absence of attention, there were distinct peaks around 4 Hz in both V1 and V4 (Fig. 2C,D). Those peaks were reduced when attention was directed to the contralateral hemifield.

We also calculated low-frequency phase-locking (PPC) spectra separately for pairs of sites within V1 or V4 and between V1 and V4, and we investigated whether this phase locking is affected by selective attention. The PPC spectra showed theta peaks for pairs of sites within and between V1 and V4, and this theta-band PPC was reduced by attention (Fig. 3).

Theta is spatially coextensive with visually induced gamma

Because theta was modulated by attention, while attention was directed to visual stimuli, we next investigated whether theta was related to visually induced activity. The ECoG covered large parts of V1, corresponding to large parts of the representation of the lower right visual quadrant, from the fovea out to about six degrees of visual angle. This allowed us to test whether theta was coextensive with visually driven activity. A given ECoG electrode does not provide conventional spike recordings, yet it does provide gamma power enhancements selectively for particular stimulus positions, that is, gamma power enhancements with circumscribed receptive fields (RFs) (Bosman et al., 2012; Lewis et al., 2016). The electrodes over V1 had varying overlap with the employed grating patch, which resulted in a topographic

map of visually induced gamma-band power with a clear peak at the representation of the stimulus (Fig. 4A). When we calculated a corresponding topographic map of theta power (after robust regression of the $1/f^n$ component and its removal), it also showed a clear spatial peak (Fig. 4B). We calculated the spatial correlation (Spearman rank correlation) between low-frequency components (power residuals) and visually induced gamma power, across electrodes, separately for V1 and V4, for each attention condition, and for each of the low frequency components up to 10 Hz. The resulting correlation spectra reveal that across the spatial extension of both V1 and V4, visually induced gamma is positively correlated with theta when attention is ipsilateral (Fig. 4C,D, blue lines). In addition, visually induced gamma is negatively correlated with power around 1-4 Hz when attention is contralateral, and in V4 also when attention is ipsilateral (Fig. 4C,D). To ensure that the correlations shown in Figure 4C, D are not due to broadband power correlations, the analyses used gamma from the pre-cue period and theta power from the post-cue period (both with visual stimulation), that is, from non-overlapping trial epochs. Results are essentially the same if the post-cue period is used for both (data not shown).

Theta-band Granger causality is stronger in the feedforward direction and reduced by attention

The PPC analysis revealed clear theta peaks for the visually driven sites, and a previous study found theta-band GC between visual areas to be generally stronger in the feedforward direction (Bastos et al., 2015b). Therefore, we next investigated in detail the GC between V1 and V4 in the low-frequency range and separately for the two attention conditions. Figure 5A shows the GC spectra averaged over all V1-V4 site pairs, pooled across both attention conditions, and separately for the feedforward (V1-to-V4; green line) and feedback (V4-to-V1; black line) directions. These GC spectra reveal clear theta peaks, and they confirm that GC is stronger in the feedforward than feedback direction. Figure 5B shows the feedforward GC spectra separately for the two attention conditions. It reveals that feedforward GC in the theta band is enhanced when attention is to the ipsilateral stimulus. Figure 5C shows that the same pattern of attention effects exists for the feedback GC.

Theta-gamma phase-amplitude coupling and its attentional modulation

Several previous studies have found that the theta phase modulates gamma power, that is, there is theta-gamma phase-amplitude coupling, or PAC (Bragin et al., 1995; Sirota et al., 2008; Axmacher et al., 2010; Voloh et al., 2015). One of those studies also reported that theta-gamma PAC in area MT is decreased with attention to the activating stimulus (Esghaei et al., 2015). We investigated whether the theta rhythm described above for V1 and V4 modulates gamma power, and whether this is affected by selective attention. As described above, we found that theta is spatially coextensive with visually induced gamma and reduced by attention. Therefore, to explore whether theta phase modulates gamma amplitude, we first selected conditions with maximal theta strength, that is, visual stimulation with a non-attended stimulus. Figure 6A shows for one example electrode the raw spectral power as a function of time relative to the theta trough. This reveals that the amplitude of visually

induced gamma-band power is modulated systematically by theta phase. Figure 6B shows the resulting PAC, averaged over all electrodes in V1 and V4, and over both attentional conditions. It reveals a distinct peak of PAC between theta phase and gamma power. We note that the theta-rhythmic modulation of gamma was most pronounced for the high-frequency end of the gamma band. In addition, this analysis reveals PAC between the phase around 1 Hz and power in several frequency bands; this 1 Hz component is likely related to the temporal frequency of the drifting gratings (see Materials and Methods).

Figure 7 shows PAC separately for areas V1 and V4 and for the two attention conditions. In V1, there was a PAC peak for phase-frequencies around 4 Hz (Fig. 7A,B). This theta-gamma PAC was strongly reduced by attention (Fig. 7C). There were additional significant PAC components at lower phase frequencies, which partly also showed significant attentional effects. As mentioned above, these slower components are likely related to the temporal frequency of the drifting gratings. In contrast to V1, V4 did not show significant theta-gamma PAC, and also no significant PAC difference between attention conditions (Fig. 7D-F).

Control for microsaccades

It has previously been shown that theta-band rhythmicity is present in the sequence of microsaccades (MSs) (Bosman et al., 2009; Lowet et al., 2016). MSs cause a movement of the retinal image and an MS-related response in the LFP and the multi-unit activity (Bosman et al., 2009). MSs also modulate the strength of gamma-band activity (Bosman et al., 2009; Lowet et al., 2016). Thus, the MS rhythm may underlie both the theta rhythm and the theta-gamma PAC observed here. To investigate this, we detected MSs and excluded data recorded between MS onset and 0.5 s thereafter. This substantially reduced the amount of available data. Nevertheless, the main results remained essentially unchanged (Fig. 8): Low-frequency power spectra (after robust regression of $1/f^n$ and removal) show theta peaks for attention ipsilateral, which are reduced by attention to the contralateral stimulus (Fig. 8A,B); PPC spectra show theta peaks for all cases (Fig. 8C-E), and significant attentional reduction; PAC in area V1 shows a peak for theta-band phase frequencies and gamma-band amplitude frequencies only when attention is directed to the ipsilateral stimulus (Fig. 8F,G,H). Note that excluding MSs eliminated PAC components with phase frequencies at the temporal frequency of the drifting gratings. This suggests that those components were due to entrainment of MSs to the grating cycle.

Control for microsaccade rate

In addition, we performed an alternative control, by equating the MS rate, that is, the MS temporal density, between attention conditions. This specifically controls for potential MS rate differences between attention conditions. Figure 9A shows the cumulative distribution of MS rate over the respective number of data epochs (see Materials and Methods for MS rate estimation). MS rate actually differed between attention conditions. We therefore stratified the data (see Materials and Methods) to arrive at two equally sized sets of epochs

with an essentially equal distribution of MS rates (dashed lines in Fig. 9A). After stratification, all main results remained essentially unchanged (Fig. 9B-G).

Control for theta power

Finally, we controlled for the possibility that the effects of attention on theta-gamma PAC were fully explained by the effects of attention on theta power. Specifically, theta power was enhanced with ipsilateral attention, which might enhance the sensitivity of theta-gamma PAC quantification, which might in turn fully explain the enhanced theta-gamma PAC with ipsilateral attention. To investigate this possibility, we stratified for theta power. Figure 10A illustrates the stratification for one example electrode. Figure 10 B shows the average V1 PAC difference between attention conditions after stratification, and demonstrates that the attentional reduction of theta-gamma PAC in V1 is not due to attention effects on theta power. Figure 10 C shows the same control analysis for V4, confirming the absence of an attention effect for the combination of theta-band phase frequencies and gamma-band amplitude frequencies. Both V1 and V4 show some attention effects for phase frequencies at the temporal frequency of the drifting gratings and for a few scattered combinations of phase and amplitude frequencies. Note that multiple comparison correction across phase- and amplitude frequencies was less stringent due to power stratification. The other attention contrasts, without power stratification, randomly assign an attention condition per trial, for all electrodes together. Stratification was done for each electrode separately, which required the random assignment of attention condition to be done also per electrode, which then leads to a less stringent multiple comparison correction. This likely explains some of the scattered significant PAC points.

Discussion

We demonstrate the presence of a ≈4 Hz theta rhythm in awake macaque V4 and V1. This theta rhythm is present selectively in sites driven by the visual stimulus, such that the spatial map of theta co-extends with the map of visually induced gamma-band activity. In V1, theta rhythmically modulates local gamma-band activity and thereby most likely the gamma-associated local processing of visual information. Theta rhythms in V1 and V4 synchronize, and an analysis of GC reveals a predominant feedforward influence. Both, local and inter-areal theta-rhythmic synchronization are substantially reduced by selective attention to a visual stimulus contralateral to the recorded areas. While previous studies have described that MSs can occur at a similar rhythm and influence V1, V2 and V4, we found that exclusion of MS effects leaves all main theta-related observations essentially unchanged.

We were somewhat surprised to find that theta shows a clear spatial correlation or coextension with visually induced gamma-band power. There were reasons to assume that a putative theta rhythm might be global across visual cortex. Hippocampal recordings suggest that theta is global in this structure, travelling as a wave from dorsal to ventral parts (Lubenov and Siapas, 2009; Patel et al., 2012). Also, there is the general notion that slower rhythms are more global than faster rhythms (von Stein and Sarnthein, 2000; Buzsáki and Draguhn, 2004).

Yet, our finding of a spatially specific theta, which is coupled to gamma by spatial extension and also through PAC, is also in agreement with one previous study: Inter-areal GC influences in both theta and gamma are typically stronger in the anatomically defined feedforward than feedback direction (Bastos et al., 2015b).

The theta rhythms in V1 and V4 are reduced by selective attention to a contralateral stimulus. Attention effects are typically smaller in V1 than in higher visual areas (for otherwise comparable conditions). This holds for firing rates (Luck et al., 1997; Buffalo et al., 2010) and gamma-band synchronization (Buffalo et al., 2011). In fact, different studies in V1 have reported attentional increases (Buffalo et al., 2011), decreases (Chalk et al., 2010) or the absence of an effect (Bosman et al., 2012) on gamma-band synchronization. By contrast, the attentional effects on theta appeared to be of similar strength in V4 and V1, entailing an unusually strong attention effect for V1.

The PAC analysis showed theta-gamma coupling that peaked for an amplitude-frequency at the high-frequency end of the visually induced gamma band activity. Thus, theta-rhythmic modulation is most apparent for this high-frequency part of the overall gamma peak. This might reflect a physiological asymmetry or be related to signal-to-noise ratio. Physiologically, it is conceivable that the modulation is in fact stronger at the upper flank of the gamma peak than at the lower flank, which would be equivalent to an asymmetric broadening of the gamma peak towards higher frequencies. Alternatively, the gamma-band peak is modulated in its entirety, yet the PAC metric ends up larger for the upper than the lower flank, e.g. because the gamma peak is superimposed on unmodulated (or less modulated) $1/f^n$ power. If we consider the $1/f^n$ component of the power spectrum as noise, this noise is larger for the lower than the upper flank.

Similarly, it is interesting to investigate the precise frequency of the observed theta rhythm. The basic spectra of power (residuals) and phase locking show peaks close to 4 Hz. The analysis of spatial correlation between theta power and visually-induced gamma power shows a broader peak that includes 4 Hz, yet extends up to 8 Hz. This suggests that the underlying phenomenon might actually occupy this broader frequency range, with theta merely peaking at 4 Hz for the particular stimulus and task conditions used here. Whether other stimuli or tasks make theta in V1 and/or V4 shift in frequency is an interesting topic for further study. In any case, the 4-8 Hz range found in the spatial correlation analysis is an interesting link to the classical hippocampal theta, which occupies this range. Hippocampal theta in fact shifts in frequency, e.g. depending on running speed (Shin and Talnov, 2001; Geisler et al., 2007).

The mechanisms behind the observed visual cortical theta rhythm and its attentional modulation are not yet clear. The mechanisms underlying hippocampal theta have been studied in great detail (Colgin, 2013), and hippocampal theta is partly synchronized to neocortex, e.g. to entorhinal and prefrontal areas. It is conceivable that this theta synchronizes further to intermediate and lower visual areas, yet we deem it unlikely that this is the source of the theta observed here. Such a mechanism would most likely not generate

the spatial coextension between theta and gamma, and the predominant GC direction from V1 to V4, which we observed here. The present results place further constraints on potential mechanisms: The fact that removing MSs left the main results essentially unchanged suggests that theta in visual cortex does not merely reflect theta-rhythmic MSs. Rather, the clear spatial co-extension between theta power and visually induced gamma suggests a role for visually driven activity in theta generation.

Recent studies have shown that attention samples visual stimuli at a theta rhythm. When human subjects have to detect the appearance of a faint stimulus at a peripheral location, their detection performance is modulated by the phase of a 7-8 Hz rhythm with a maximum over frontal cortex (Busch and VanRullen, 2010). This might reflect an ≈8 Hz rhythmic attentional sampling. In support of this, three subsequent studies show that two simultaneously monitored stimuli are attentionally sampled in alternation, each at ≈4 Hz (Landau and Fries, 2012; Fiebelkorn et al., 2013; Landau et al., 2015). A further study estimated the temporal sampling frequency of attention, and found it to be around 7 Hz for a single attended stimulus, 4 Hz for two and 2.6 Hz for three (Holcombe and Chen, 2013). These numbers are consistent with a single attentional sampling mechanism that is multiplexed over the to-be-attended stimuli. Such a scenario would also explain theta-rhythmic modulations of firing rates in inferotemporal (IT) cortex during the presentation of two stimuli (Rollenhagen and Olson, 2005). When IT neurons respond to one stimulus, and a second stimulus is added onto the screen, firing rates start oscillating at ≈4 Hz in a way that suggests that attention is drawn to the newly presented stimulus and subsequently alternates between the two stimuli. At first glance, these results might seem to suggest that visual cortical theta should be stronger for the attended stimulus, in contrast to our findings. Yet, the fact that divided attention tasks reveal theta-rhythmic sampling does not mean that attended stimuli are affected by stronger theta-rhythmic modulation than non-attended stimuli. The mentioned recordings in IT showed strong theta rhythmicity when two stimuli were presented, but weaker theta rhythmicity when a single stimulus was presented and thereby received full attention. Based on these and the present results, we propose that attention is more sustained, yet still weakly theta rhythmic, at the attended location, and that it theta-rhythmically scans the space around it, to explore other stimuli. As a consequence, non-attended stimuli receive attentional processing benefits only when they are attentionally scanned, leading to relatively strong theta rhythmicity. This scanning hypothesis is consistent with theta-rhythmic modulations of detection performance when one location on an extended stimulus is attended, while another location on the same object is not attended: The non-attended location is consistently sampled at an 8 Hz rhythm, yet 90 degrees later in the 8 Hz cycle than the attended location (Fiebelkorn et al., 2013).

Future studies will need to investigate whether attentional control structures show an ≈8 Hz sampling rhythm that is coherent to the sampled stimulus representations in visual cortex. As mentioned above, the ≈8 Hz EEG component, whose phase predicts human detection performance, is strongest over frontal areas (Busch and VanRullen, 2010). Also, spike and LFP

563 recordings in macaque parietal cortex have recently revealed a similar theta rhythm (Phillips
564 et al., 2014; Hawellek et al., 2016). If such theta-rhythmic top-down influences were to be
565 found, it will be interesting to understand how they fit with the predominantly bottom-up
566 directed theta influences observed between visual areas (Bastos et al., 2015b). One possibility
567 is that control structures exert a theta-rhythmic perturbation on early and even primary visual
568 cortex, which then percolates up through the hierarchy of visual areas.

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Legends

Figure 1. Average power and phase locking spectra for the two macaques. ***A***, Average power spectrum of the ECoG LFP in V1 and V4, for monkey K, during attentional monitoring of a drifting grating. Data around the 50 Hz line-noise frequency and harmonics is not shown. ***B***, Same as ***A***, but for monkey P. ***C***, Average phase locking (PPC) spectrum across all possible site pairs within and between V1 and V4, for monkey K. The shading (hardly visible behind the lines) shows the 95% confidence interval based on a bootstrap procedure across trials. ***D***, Same as ***C***, but for monkey P.

Figure 2. Average low-frequency LFP power spectra and their modulation by selective attention. ***A***, Average LFP power spectra in area V1 with attention toward (red) and away (blue) from the activating stimulus. The gray-shaded region indicates frequencies with a significant difference between attention conditions ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). ***B***, Same as ***A***, but for area V4. ***C***, Same as ***A***, but showing the power residuals after removing the $1/f^n$ component of the power spectrum through robust regression (see Materials and Methods). ***D***, Same as ***C***, but for area V4.

Figure 3. Average low-frequency LFP phase-locking (PPC) spectra and their modulation by selective attention. ***A***, Average LFP phase locking between sites within area V1 with attention toward (red) and away from (blue) the activating stimulus. The gray-shaded region indicates frequencies with a significant difference between attention conditions ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). ***B***, Same as ***A***, but between sites within area V4. ***C***, Same as ***A***, but between sites in area V1 and sites in area V4.

Figure 4. The theta rhythm coextends with the visually induced gamma rhythm. ***A***, Visually induced LFP gamma-band power, as a function of spatial location in V1 (indicated by blue outline) and V4 (indicated by green outline). ***B***, Same as ***A***, but showing LFP theta-band power after removing the $1/f^n$ component. ***C***, Correlation between 1) visually induced gamma-band power and 2) the power ($1/f^n$ removed) at the frequency indicated on the x-axis, across recording sites in area V1. Colored lines on the bottom indicate frequencies with significant correlations with attention toward (red) or away from (blue) the activating stimulus ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). The gray line on the bottom indicates frequencies with a significant difference in correlation between the attention conditions (same test). ***D***, Same as ***C***, but for area V4.

Figure 5. Average low-frequency Granger causality (GC) spectra between V1 and V4 sites. ***A***, Average GC-influence spectra between V1 and V4 in the feedforward (green) and feedback directions (black). The gray-shaded regions indicate frequencies with a significant difference between bottom-up and top-down ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). ***B***, Average GC-influence spectra between V1 and V4 in the feedforward direction, with attention toward (red) and away from (blue) the

activating stimulus. The gray-shaded regions indicate frequencies with a significant difference between attention conditions ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). Frequency regions with significant positive and negative attention effects were directly abutting to each other, and therefore the gray region is continuous. ***C,*** Same as ***B,*** but for the feedback direction.

Figure 6. Theta-gamma phase-amplitude coupling (PAC) in visual cortex. ***A***, LFP power of one example site in the 50-150 Hz range (y-axis) as a function of time relative to the theta trough (x-axis). ***B***, Grand-average PAC as a function of the frequency defining the power (y-axis) and the frequency defining the phase (x-axis). The semitransparent gray mask indicates frequency pairs with non-significant PAC ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequency pairs). The black area indicates frequency pairs excluded from the analysis (see Materials and Methods).

Figure 7. Modulation of PAC by selective attention. ***A***, ***B,*** Average PAC in area V1 with attention toward (***A***) and away from (***B***) the activating stimulus. ***C***, Average PAC difference in area V1 between the two attention conditions shown in ***A*** and ***B***. The semitransparent gray mask indicates frequency pairs with non-significant PAC ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequency pairs). The black area indicates frequency pairs excluded from the analysis (see Materials and Methods). ***D***, ***E***, ***F***, Same as ***A***, ***B***, ***C***, but for area V4.

Figure 8. Attention contrast, excluding epochs with microsaccades. ***A***, Average LFP power spectra in area V1 after removing the $1/f^n$ component, with attention toward (red) and away (blue) from the activating stimulus. ***B***, Same as ***A***, but for area V4. ***C***, Average LFP phase locking between sites in area V1 and sites in area V4, with attention toward (red) and away from (blue) the activating stimulus. ***D***, ***E*** Same as ***C***, but for pairs of sites within area V1 (***D***) and area V4 (***E***). ***A***-***E,*** The gray-shaded region indicates frequencies with a significant difference between attention conditions ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). ***F***, ***G***, Average PAC in area V1 with attention toward (***F***) and away from (***G***) the activating stimulus. ***H***, Average PAC difference in area V1 between the two attention conditions. ***F***-***H***, The semitransparent gray mask indicates frequency pairs with non-significant PAC ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequency pairs). The black area indicates frequency pairs excluded from the analysis (see Materials and Methods).

Figure 9. Attention contrast, controlled for microsaccade (MS) rate. Same analyses as shown in Figure 8, but after equating the MS rate. ***A***, Cumulative distribution of MS rate with attention toward (red) and away (blue) from the activating stimulus. Solid lines show data before stratification; dashed lines show data after stratification. Note that after stratification, the lines for the two attention conditions overlap essentially perfectly. ***B***, Average LFP power spectra in area V1 after removing the $1/f^n$ component, with attention toward (red) and away (blue) from the activating stimulus. ***C***, Same as ***B***, but for area V4. ***D***, Average LFP phase locking

between sites in area V1 and sites in area V4, with attention toward (red) and away from (blue) the activating stimulus. ***E***, ***F***, Same as ***D***, but for pairs of sites within area V1 (***E***) and area V4 (***F***). ***B***-***F,*** The gray-shaded region indicates frequencies with a significant difference between attention conditions ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). ***G***, Average PAC difference in area V1 between the two attention conditions. The semitransparent gray mask indicates frequency pairs with non-significant PAC ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequency pairs). The black area indicates frequency pairs excluded from the analysis (see Materials and Methods).

Figure 10. Attention contrast, controlled for theta power. ***A***, Example V1 LFP power spectrum with attention toward (red) and away from (blue) the activating stimulus. Solid lines show data before stratification; dashed lines show data after stratification. The gray bar at the bottom indicates statistical significance between the stratified spectra ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequencies). ***B***, Average PAC difference in area V1 between the two attention conditions. The semitransparent gray mask indicates frequency pairs with non-significant PAC ($p<0.05$; non-parametric permutation test with correction for multiple comparisons across frequency pairs). The black area indicates frequency pairs excluded from the analysis (see Materials and Methods). ***C***, Same as ***B***, but for area V4.

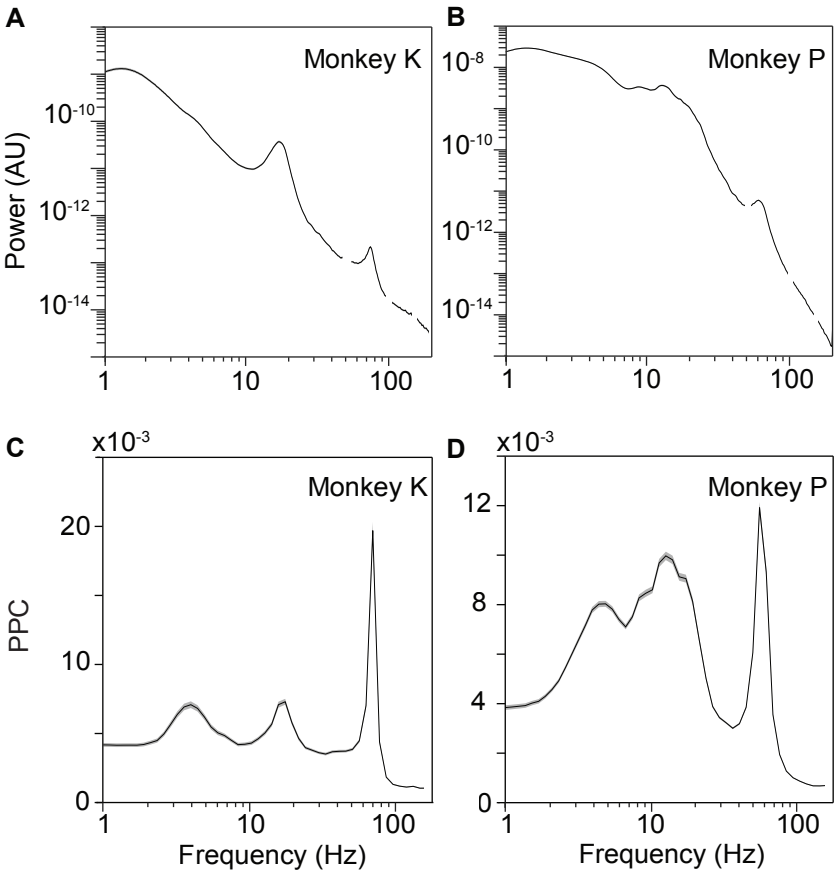

Figure 1
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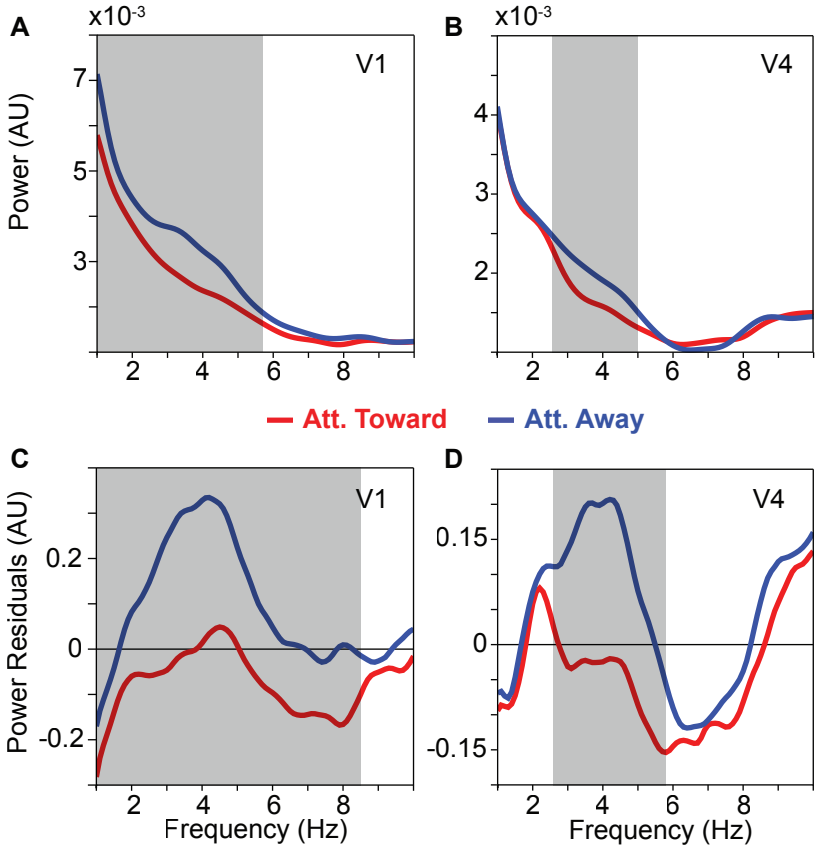

Figure 2
Spyropoulos et al.

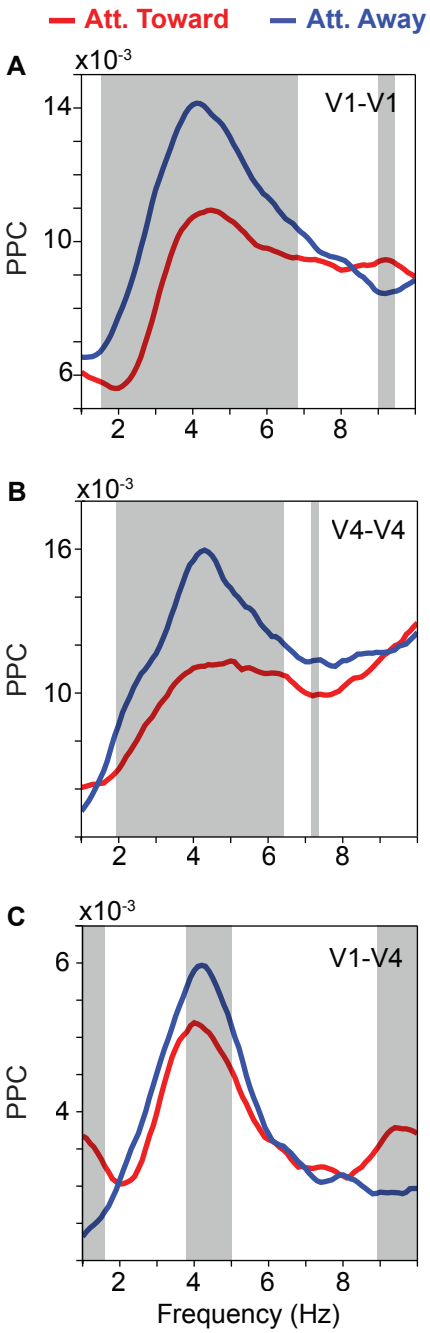

Figure 3
Spyropoulos et al.

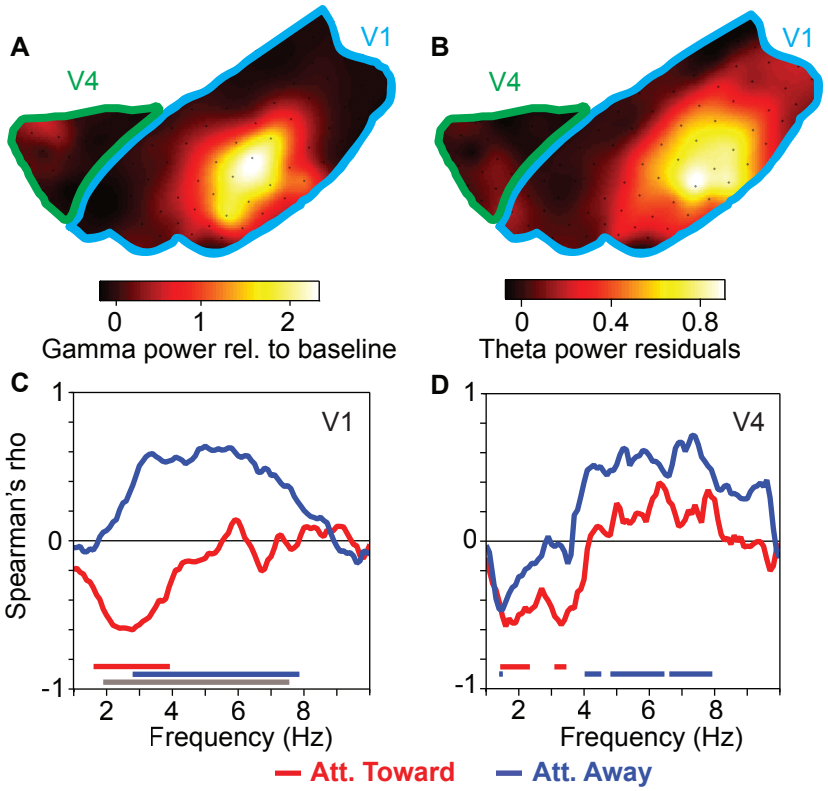

Figure 4

Spyropoulos et al.

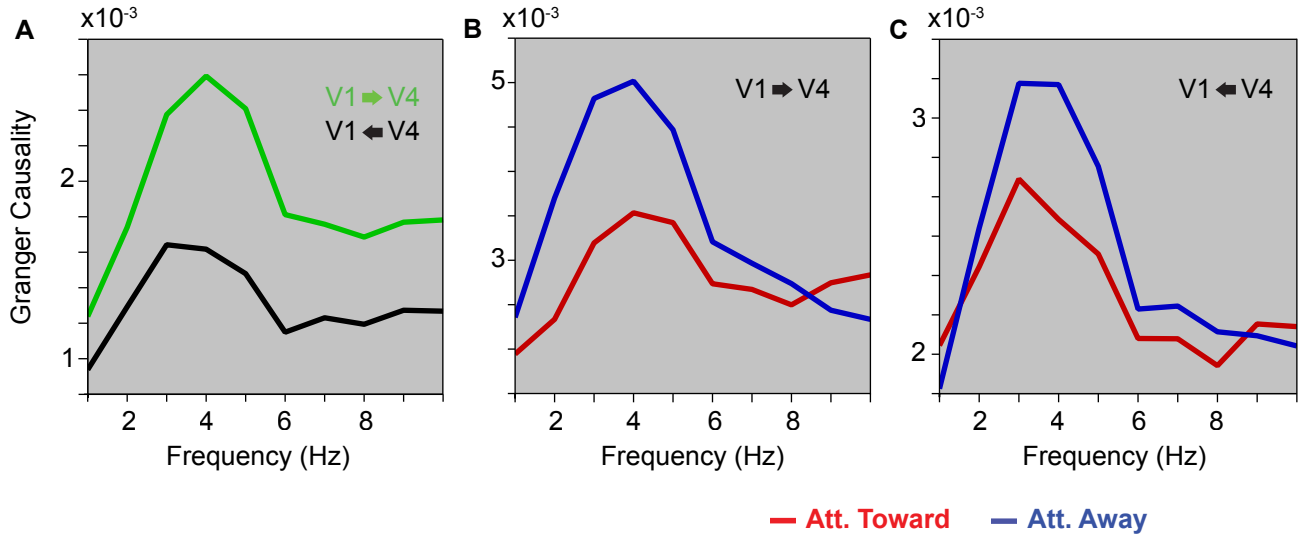

Figure 5
Spyropoulos et al.

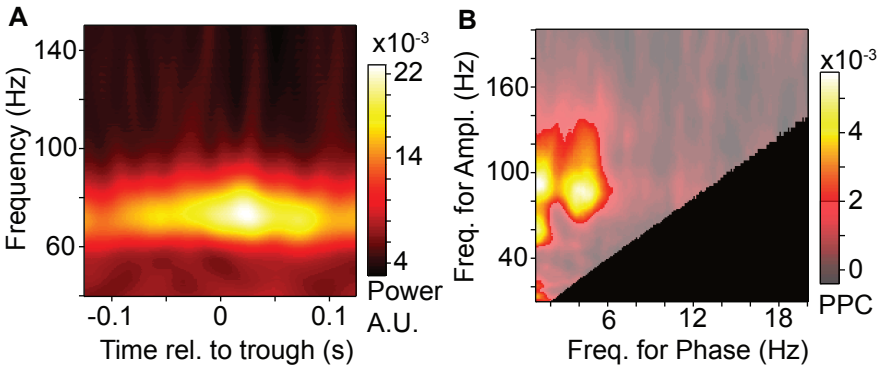

Figure 6
Spyropoulos et al.

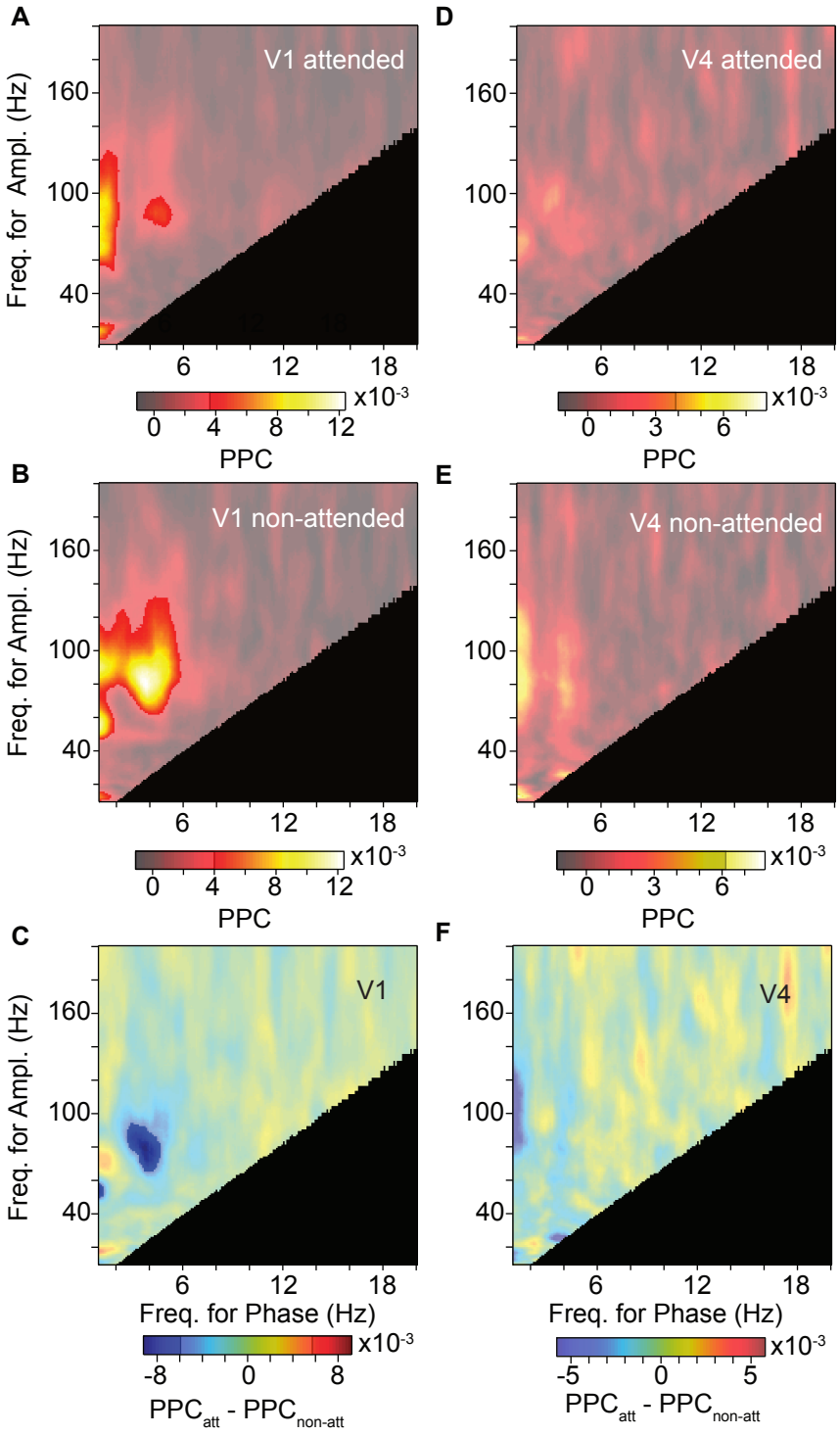

Figure 7
Spyropoulos et al.

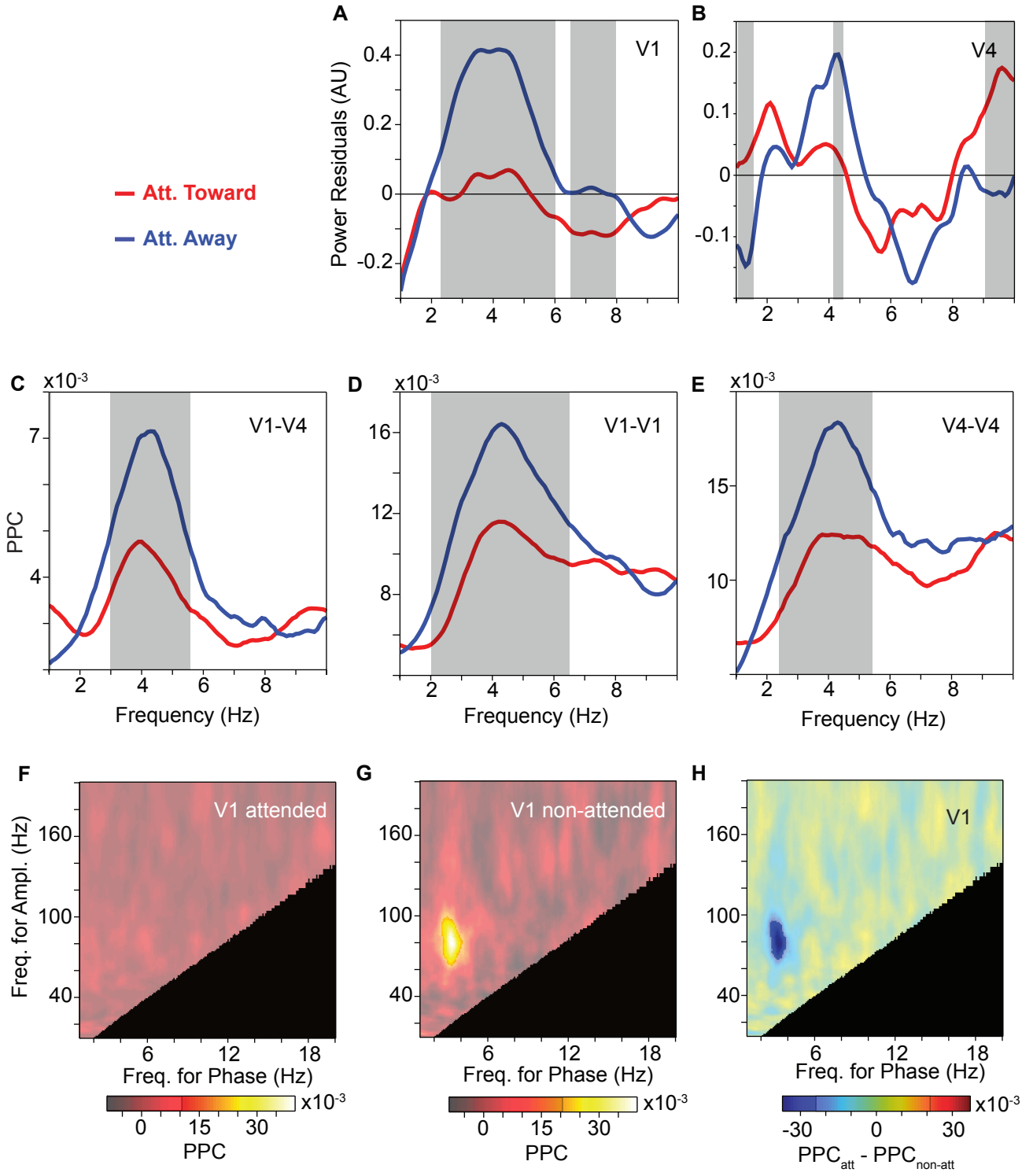

Figure 8

Spyropoulos et al.

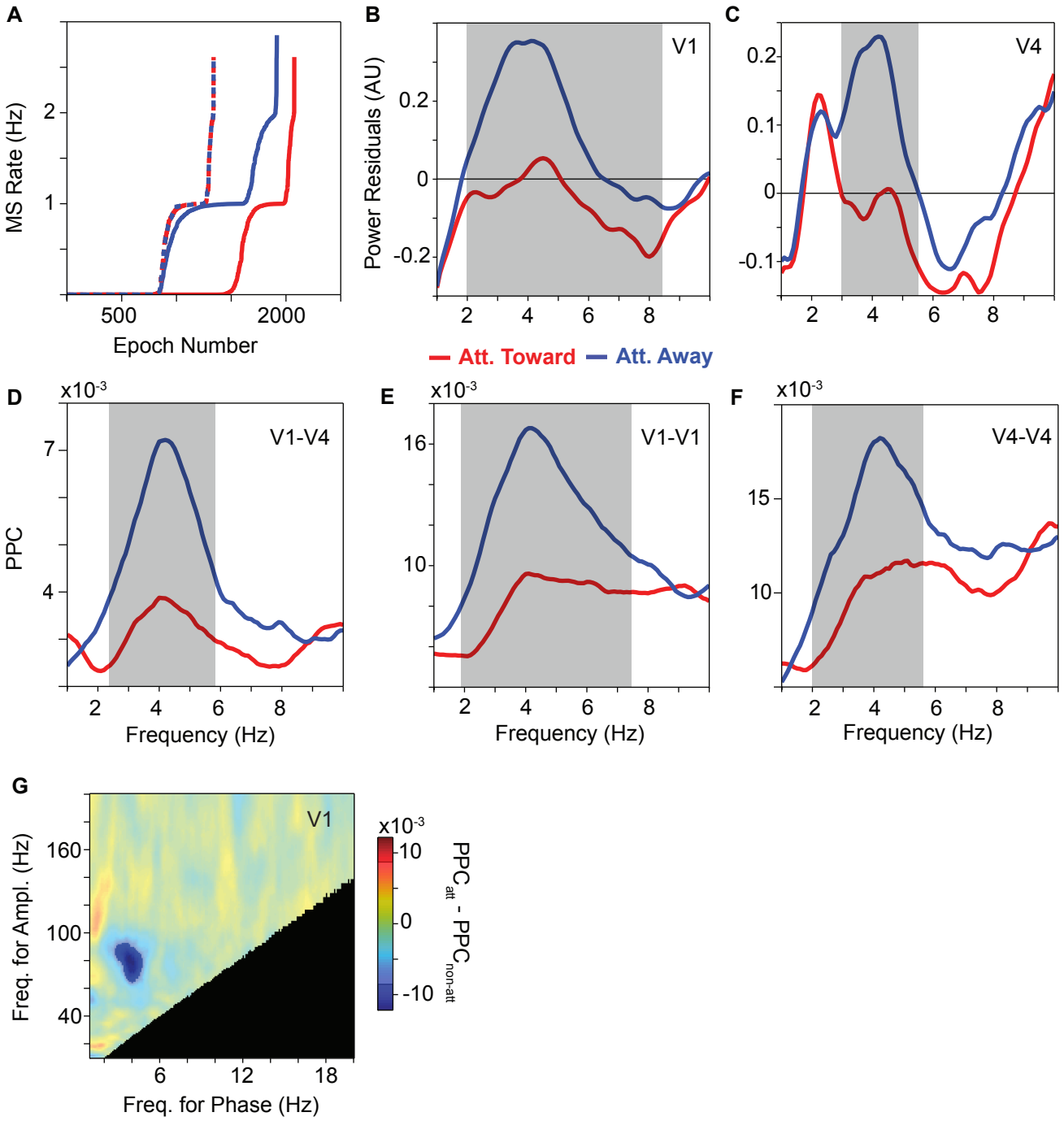

Figure 9
Spyropoulos et al.

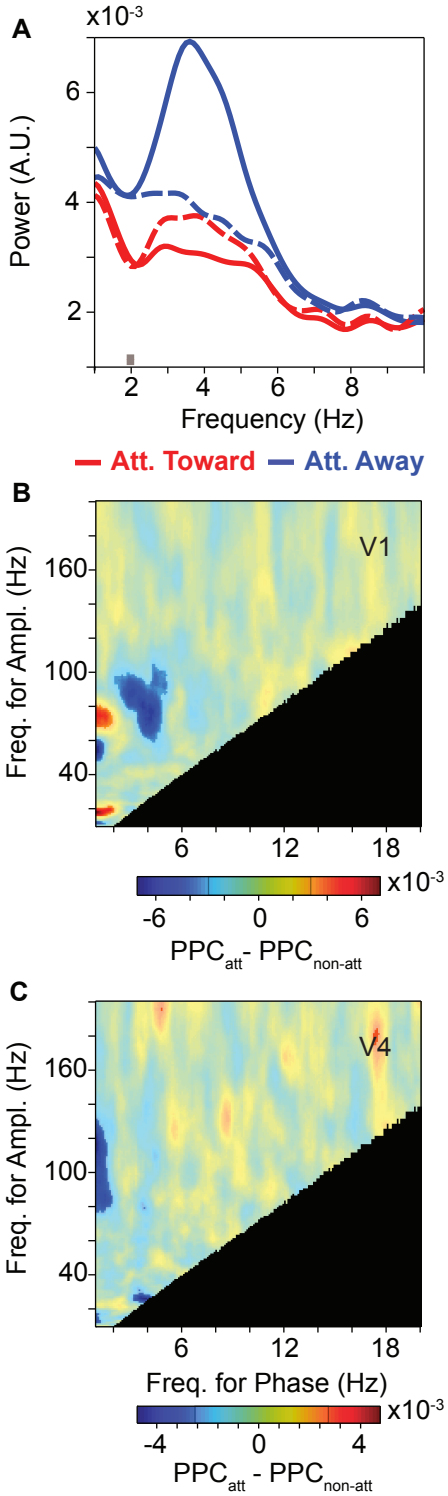

Figure 10
Spyropoulos et al.