Cross-frequency dynamics of neuromagnetic oscillatory activity: Two mechanisms of emotion regulation

TZVETAN POPOV,^a ASTRID STEFFEN,^a NATHAN WEISZ,^b GREGORY A. MILLER,^{c,d,e} AND BRIGITTE ROCKSTROH^a

^aDepartment of Psychology, University of Konstanz, Konstanz, Germany

^bCenter for Mind/Brain Sciences, University of Trento, Trento, Italy

^cDepartment of Psychology, University of Delaware, Newark, Delaware, USA

^dDepartment of Psychology, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

^eZukunftskolleg, University of Konstanz, Konstanz, Germany

Abstract

Hemodynamic and electromagnetic neuroimaging suggests a sequence of intraregional and interregional activity during emotion processing. Oscillatory activity within trials may offer insight into neural mechanisms involved in this process. MEG was measured in 24 subjects during passive viewing of neutral and unpleasant pictures and emotion regulation by cognitive reappraisal. Regulation prompted more gamma increase and alpha decrease to picture onset than did passive viewing. Source analysis confirmed differential modulation of these power changes in occipitoparietal regions during passive viewing and larger power changes in prefrontal regions during regulation. Local coupling of alpha phase to gamma amplitude within a medial prefrontal region and long-range synchrony of medial prefrontal, occipital, and temporoparietal regions index mechanisms of prefrontal top-down contribution to emotion processing.

Descriptors: Magnetoencephalography, Emotion regulation, Phase synchrony, Brain oscillations

Models of aspects of emotion processing (e.g., Gross, 1998; Gross & Thompson, 2007; Lang, 1979) often distinguish perceptual input-oriented processes of monitoring, appraisal, or evaluation of an emotional stimulus and response- or output-oriented processes that may include cognitive reappraisal, distraction, or response suppression as strategies of emotion regulation. Much recent research effort has been devoted to the mechanism of action of the latter; that is, the way in which controlled processes influence the automatic, facilitated processing of emotionally salient stimuli, and the automatic direction of attention by emotional salience (Bradley et al., 2003; Lang & Bradley, 2010).

Models of emotion regulation distinguish aspects or components according to the stage of influence between “antecedent-focused” strategies, which affect the translation of emotional stimulus processing into responses, and “response-focused” strategies, which affect the response expression (Gross, 1998; Gross & Thompson, 2007; see also Goldin, McRae, Ramel, & Gross, 2008; Hajcak, MacNamara, & Olvet, 2010; Thiruchselvam, Blechert, Sheppes, Rydstrom, & Gross, 2011). In support of this model,

many studies have demonstrated the impact of instruction-guided strategies such as cognitive reappraisal, distraction (antecedent-focused) or response suppression (response-focused) on emotion experience, autonomic, and neurophysiological measures (e.g., Goldin et al., 2008; Hajcak et al., 2010; Thiruchselvam et al., 2011).

Mechanisms of emotion-regulation strategies have been concluded from hemodynamic evidence, for instance, from increased prefrontal and anterior cingulate activity and reduced amygdala and insular activity when implementing cognitive reappraisal (Goldin et al., 2008; Ochsner & Gross, 2007; Urry et al., 2006; van Reekum et al., 2007; Vrticka, Sander, & Vuilleumier, 2011; Winecoff, Labar, Madden, Cabeza, & Huettel, 2011). Cognitive reappraisal relative to passive viewing of visual emotional stimuli also modified activity in parietal association cortices’ intraparietal lobule (IPL) and temporoparietal junction (TPJ; Kanske, Heissler, Schonfelder, Bongers, & Wessa, 2011; Winecoff et al., 2011). As shown by Winecoff and colleagues, amygdala activation is observed during automatic but not during voluntary emotion regulation (see also Phillips, Ladouceur, & Drevets, 2008). This is in line with the hypothesis that voluntary top-down control involves cortical networks including medial and dorsolateral prefrontal and parietal cortices. Cortical processes related to cognitive reappraisal have been inferred from electro- and magnetoencephalographic (EEG, MEG) studies. A reliable finding has been an amplitude reduction of the event-related late positive potential (LPP) 400–700 ms after emotional stimulus onset when subjects were asked to implement cognitive reappraisal strategies for

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Address correspondence to: Prof. Dr. Brigitte Rockstroh, Department of Psychology, P.O. Box D23, University of Konstanz, D-78457 Konstanz, Germany. E-mail: Brigitte.rockstroh@uni-konstanz.de

regulation of emotional responses to emotional pictures relative to passive viewing (Hajcak et al., 2010; Krompinger, Moser, & Simons, 2008; Parvaz, MacNamara, Goldstein, & Hajcak, 2012; Pietrek, Popov, Steffen, Miller, & Rockstroh, 2012). Krompinger and colleagues replicated the amplitude reduction under instruction to decrease the response to pleasant pictures, while no effect of the instruction to increase the response on LPP-amplitude increase could be found. EEG and MEG can further elucidate the temporal dynamics of emotion regulation: Within the time period of emotional picture processing, LPP peaked earlier under instruction of picture viewing than under instruction of cognitive reappraisal (Moser, Krompinger, Dietz, & Simons, 2009; Pietrek et al., 2012). Moreover, earlier modulation of the LPP upon distraction compared to reappraisal strategies indicates when regulation strategies act on the emotion-generation process (Thiruchselvam et al., 2011). These hemodynamic and electrophysiological results encourage the conclusion that prefrontal, top-down control of visual appraisal and emotion-generation processes constitutes a mechanism of cognitive reappraisal in emotion regulation. The neural mechanism of this prefrontal influence remains to be specified.

Hemodynamic responses and event-related potentials (ERP) or neuromagnetic fields (ERF), as typically analyzed, reflect activity averaged over time and stimulus repetitions, limiting what they can show about neural mechanisms that contribute to prefrontal control of attention and stimulus salience appraisal during cognitive reappraisal. Analysis of oscillatory activity on a single-trial basis may provide additional information and thereby offer access to the mechanism of (prefrontal) top-down regulation or modulation. With this aim, the present neuromagnetic study analyzed oscillatory activity, their cross-frequency coupling, and cross-regional connectivity during an emotion-regulation task.

In general, the pattern of synchronized and desynchronized firing involved in the coordination of neural activity within and across neural networks is believed to enable information processing relevant for psychological phenomena (Fries, 2005; Jensen & Mazaheri, 2010; Siegel, Donner, & Engel, 2012). Neuronal oscillations are distinguished as evoked, that is, locked in time and phase to the stimulus onset, and induced, the latter also typically occurring after the stimulus onset but varying in time across trials (Uhlhaas & Singer, 2010). Whereas conventional ERP/ERF analyses adequately describe evoked activity, analysis of oscillatory dynamics on a single-trial basis clarifies both and is particularly suitable for the description of induced activity. Coherent oscillatory activity provides the basis for communication between brain areas (Canolty & Knight, 2010), thereby constituting a mechanism for control in such networks. Coherent oscillations within cortical areas are usually found at higher frequencies (30–80 Hz, gamma band), across cortical areas at lower (beta or alpha) frequencies. High-frequency oscillations are thought to reflect coordination within cell assemblies, and low-frequency oscillations foster communication over longer distances (Canolty & Knight, 2010; Kopell, Ermentrout, Whittington, & Traub, 2000; von Stein & Sarnthein, 2000). The relationship (coupling) between the instantaneous phase of lower frequencies and the amplitude changes of high frequencies, in particular, has been characterized as a basis of local computation and communication (Canolty & Knight, 2010; Siegel et al., 2012). Phase-amplitude coupling describes the statistical dependence between the phase of a low-frequency rhythm and the energy of a high-frequency component. Neurons will be more likely to fire during particular phases or phase network ensembles of low-frequency oscillations (Voytek et al., 2010). Through this

statistical biasing, multiple overlapping long-range networks can communicate, in that “for a given phase difference between two areas, spikes leaving one area will arrive when the other area is maximally excitable, whereas a shift in the relative phase implies that spikes will arrive when the receiving area is less excitable, making communication less effective” (Canolty & Knight, 2010, p. 506).

The role of cross-frequency, phase-amplitude coupling in visual processing has been demonstrated, for instance, by Voytek and colleagues (2010). The comparison of phase-amplitude coupling in two patients with implanted subdural electroencephalographic grids performing different (visual and auditory) tasks showed higher coupling over visual cortical areas specifically during visual tasks. For a more complex task of emotion regulation, this suggests the hypothesis that prefrontal attentional control of visual input appraisal should be reflected in phase-amplitude coupling in prefrontal and parietal (secondary visual) regions.

In addition to their role in phase-amplitude coupling, alpha oscillations are thought to shape the state of sensory brain regions to direct the flow of information and optimize performance (Hanslmayr, Gross, Klimesch, & Shapiro, 2011; Jensen & Mazaheri, 2010). Phase synchrony across regions is seen as a measure of functional connectivity or functional network states (Buzsaki & Draguhn, 2004; Fries, 2005; Lachaux, Rodriguez, Martinerie, & Varela, 1999). It has also been demonstrated as a mechanism of multisensory integration in humans (Keil, Mueller, Ihssen, & Weisz, 2012). As alpha activity is associated with communication over longer distances (see above), alpha phase synchrony between regions may constitute connected hubs (Bullmore & Sporns, 2009) reflecting the long-range communication serving the hypothesized prefrontal top-down control of visual processing—hence, a mechanism of cognitive reappraisal.

Emotion processing may involve subcortical regions: Fast, early evaluation of or responses to emotionally salient stimuli, in particular, threatening or dangerous stimuli motivating avoidance and emotional experience, are related to amygdala activity (Lang & Bradley, 2010; Winecoff et al., 2011). Emotion-regulation strategies such as response suppression versus cognitive reappraisal modulate cortical and amygdala activity in different directions and with different latency (Goldin et al., 2008). Present analyses explicitly targeted the mechanism of prefrontal control of emotional picture processing upon instructed implementation of cognitive reappraisal. Given that amygdala activity is related to automatic response generation or to response suppression at longer latency, modulation of amygdala activity was not the primary target in the present analyses.

Four hypotheses were tested: (1) An interplay of input- and output-related processing should be reflected in instruction-modulated changes in gamma synchronization (indexing local communication within brain regions) and alpha power decrease (indexing long-range communication between brain regions). (2) Both oscillatory effects would occur in regions involved in emotion regulation, including prefrontal regions in particular. As emotional picture processing varies with activity in secondary visual cortex (e.g., Schupp, Flaisch, Stockburger, & Junghoefer, 2006), modulation of oscillatory activities was also expected in secondary visual regions. (3) Regionally specific relationship between the alpha phase and gamma amplitude were expected in regions related to voluntary emotion regulation such as prefrontal cortex. (4) Top-down influence was expected to be evident in cross-regional communication between sensory and prefrontal areas examined in connectivity analyses.

Of secondary interest, oscillatory activity was also evaluated during processing of the instruction cue that preceded the emotional picture, as enhanced activity has been reported during instruction processing (Gross, 1998; Moser et al., 2009). As alpha oscillations have been related specifically to stimulus-oriented attention (Hanslmayr et al., 2011), a change in alpha power during the anticipatory interval might be expected.

Methods

Participants

Twenty-four volunteers (14 female, mean age $\pm$ SD 32.3 ± 13.0 years, mean years of school education 11.5 ± 1.6) were recruited for the present MEG study. Pietrek et al. (2012) reported conventional analyses of averaged event-related magnetic fields in this sample and task. Subjects were included if they did not meet criteria for a psychological disorder (screened by the M.I.N.I. interview; Ackenheil, Stotz-Ingenlath, Dietz-Bauer, & Vossen, 1999), were not taking any psychoactive medication, and had never suffered from any neurological condition including head injury with loss of consciousness. Participants received 30 € for completing the 3-h protocol, which was approved by the Ethics Committee of the University of Konstanz. Participants were informed in detail about the procedures and provided written informed consent prior to the study.

Materials and Procedure

The experimental design consisted of three within-subjects factors: task (passive viewing [watch], regulate), picture (neutral, unpleasant), and trial period (postcue onset, postpicture onset). Experimental conditions were three of four possible combinations of task and picture: watch neutral, watch unpleasant, and regulate unpleasant. Prior to MEG recording, participants were instructed about strategies of emotion regulation via cognitive reappraisal.¹ During practice trials, sample pictures (not shown during MEG recording) were presented with the instruction to verbalize the selected strategy to reduce the response to unpleasant pictures by cognitive reappraisal. If necessary, subjects were coached on strategy. As a manipulation check, at the end of the session participants were asked to report what strategies they had used.

1. These instructions about the experiment were given to the participants (in German): In the following you will see neutral and unpleasant pictures for about 2 s. Before every picture, you will see a black screen with a cross in the middle for about 2 s. This cross could be white or blue. The white cross tells you to just watch the picture that follows, whether it is neutral or unpleasant. The blue cross tells you that an unpleasant picture will follow and that you should try to diminish feeling stressed or uneasy during the picture. To diminish these feelings, you should try one of the following strategies: You can prepare yourself by thinking that the scene in the unpleasant picture is not real or is from a movie. Or you can try to think that the scene in the unpleasant picture will have a positive ending. For example, when you see an injured person in the picture, you can think that the person will get some help and will be fine. What you should not do is to think some unrelated thoughts that will lighten up your emotions, such as "Today is a nice day," because you should work with the contents of the pictures. Which of the strategies do you think will work best for you? The blue cross signals you to perform the strategy that works best for you to down-regulate your emotions. To make it easier for you, we'll tell you what types of pictures you will see. The neutral pictures show neutral faces and household subjects. The unpleasant pictures show danger from animals or humans and scenes of mutilation.

Thirty unpleasant, high-arousing and 30 neutral, low-arousing color images were used from the International Affective Picture System² (IAPS; Lang, Bradley, & Cuthbert, 2008). Unpleasant and neutral pictures differed in IAPS normatively rated valence ($M \pm$ SD: unpleasant 2.85 ± 0.66 , neutral 4.93 ± 0.27) and arousal (unpleasant 6.29 ± 0.62 , neutral: 2.83 ± 0.57). Picture complexity was estimated by compressed jpeg file size. Neutral and unpleasant picture categories did not differ in physical picture parameters such as brightness, contrast, RGB (red/green/blue) balance of color, or complexity. Pictures (31 cm width $\times$ 24 cm height) were presented via a projection system on a screen about 70 cm from the subject's eyes, a visual angle of 24° (horizontal) $\times$ 19° (vertical). Conditions did not include up-regulation or pleasant pictures in order to limit duration of the MEG session.

Each of two 90-trial blocks lasted about 10 min and was separated by a 1-min break (black screen) that allowed participants to close or move their eyes, in order to facilitate subsequent fixation. Within each block, the 30 neutral pictures were presented once each with watch instructions, and the 30 unpleasant pictures were presented twice each, once with watch instructions and once with down-regulate instructions. Unpleasant and neutral pictures were pseudorandomly intermixed. The cues signaling the passive viewing and active regulation tasks and neutral and unpleasant pictures within each condition appeared in pseudorandom order. MatLab-generated scripts provided random sequences of stimuli across trials per trial block. This served to prevent a confound of task sequence or a repetition effect. Although repetition of unpleasant pictures does not seem to substantially affect modulation by picture arousal or valence (Olofsson, Nordin, Sequeira, & Polich, 2008), potential amplitude reduction by stimulus repetition (Codisopot, Ferrari, & Bradley, 2006) would have been compensated for by the random sequence of stimuli.

Each trial started with the presentation of either a white or a blue cross, which appeared in the center of the screen for 2,000 ms. A picture was presented immediately after each cross cue, also for 2,000 ms. Participants were told that the white cross signaled that they should simply view the picture and that it would be either a neutral or an unpleasant picture. They were told that the blue cross would signal that they should implement the previously practiced strategy to control their emotional response to the picture by cognitive reappraisal and that it would be an unpleasant picture. Trials were separated by picture-offset-to-cue-onset intervals varying between 2,000 and 2,500 ms. Those intertrial intervals (ITIs) served for estimation of baseline activity. Participants were asked to fix their gaze on the middle of the screen and to avoid eye and head movements. The white cross cue (passive viewing instruction) preceded a low-arousal picture on 30 trials per block (watch neutral condition) and a high-arousal unpleasant picture on another 30 trials per block (watch unpleasant condition). The blue cross cue (regulate instruction) preceded an unpleasant picture on 30 trials per block.

2. The IAPS pictures used were the following: unpleasant (1050, 1090, 1110, 1113, 1120, 1201, 1220, 1300, 1301, 1930, 3019, 3061, 3150, 3160, 3181, 3213, 3400, 6230, 6243, 6260, 6313, 6350, 6360, 6540, 6560, 6570, 6821, 7361, 8230, 9321) and neutral (2190, 2200, 2210, 2230, 2570, 2840, 5500, 7000, 7002, 7009, 7010, 7020, 7025, 7035, 7050, 7080, 7100, 7150, 7160, 7170, 7175, 7190, 7217, 7224, 7233, 7235, 7550, 7700, 7950, 9070). Unpleasant pictures included danger from animals or humans (similar to Moser et al., 2009) and scenes of mutilation (selection approved by collaborating psychiatrists at the Center of Psychiatry). Neutral pictures were similar to those of Moser et al. (2009), with neutral faces and household objects.

MEG Data Acquisition and Analyses

Data acquisition. MEG was recorded with a 148-sensor magnetometer (Magnes 2500 WH, 4D Neuroimaging, San Diego, CA) in a magnetically shielded room while participants were in a supine position. Prior to each measurement, the participant's nasion,inion, left and right ear canal, and head shape were digitized with a Polhemus 3Space FASTTRACK. This information about the head position relative to MEG sensor locations was used for later transformation of functional (MEG) and structural (MRI template brain) data into the same coordinate system. Neuromagnetic data were continuously sampled at 678.17 Hz in DC mode. DC offset was removed offline with a 0.1 Hz second-order high-pass filter performed on continuous data. First, epochs containing MEG superconducting quantum interference device jumps and muscle artifacts were rejected based on visual inspection. Independent component analysis (ICA; Jung et al., 2001) was used for further artifact control: components with topographies representing saccades, eye blink, or cardiac artifacts were removed. The number of artifact-free trials (on average 165 of the total 180) entering analysis did not differ by condition (60 trials each; watch neutral 55.1 ± 4.2 , watch unpleasant 55.2 ± 4 , down-regulate 55.1 ± 3.7). An estimate of the planar gradient was calculated for each MEG sensor using a nearest-neighbor method (Bastiaansen & Knosche, 2000) to facilitate the interpretation of sensor-level results, as sensors that show maximal activity are typically located above the underlying sources.

Spectral analysis. Epochs starting 4,000 ms before cue onset and ending 4,000 ms after picture onset were extracted from the continuous recording; large epochs were chosen to avoid edge artifacts that may be associated with power spectra calculation. Spectral analysis was performed according to the procedures as described in Tallon-Baudry, Bertrand, Delpuech, and Pernier (1997). Following artifact rejection, convolution with a complex Morlet wavelet was applied to single trials. The tradeoff between frequency and time resolution was determined by the constant $m = 7$ (determining the width of the wavelet in number of cycles). Time-frequency representation of power (TFR) was calculated by averaging the squared absolute values of the convolutions over trials. The inter-trial phase-locking value (PLV, normalized between zero and one) was estimated to determine whether the measured neuronal responses were phase locked (evoked) or nonphase locked (induced) to stimulus onset. PLV was computed as the absolute value of the mean of complex phase Φ across N trials similar to the procedures described in Gross, Schnitzler, Timmermann, and Ploner (2007). The statistical analysis of the time-frequency representations of power was confined to epochs from 500 ms before cue onset to 2,000 ms after picture onset. Two time windows of interest were (1) responses to the cue, in particular, preceding picture onset, and (2) responses to picture onset. The first window referred to the stimulus-preceding negativity (SPN), which has been shown to vary with emotion-regulation instructions (e.g., Moser et al., 2009). For picture and cue stimuli, the TFR of stimulus-evoked activity (post) was expressed as scaled change from cue-preceding activity (pre): (post-pre)/pre. Relevant time-frequency windows were defined using a cluster-based, dependent-sample t test with Monte Carlo randomization (Maris & Oostenveld, 2007). This procedure controls for type I error rate in the context of multiple comparisons and allows the identification of sensor clusters with reliable condition differences at a sensor level (time, frequency, and sensors) and a brain source level (volume). At

least four neighboring sensors per cluster were required from 1,000 random permutations for the time-frequency data, and 500 randomizations were done for the comparisons of voxel clusters at the source level. Sensor or voxel clusters were identified as differentially active when differences between pairs of conditions exceeded a 5% significance threshold; the test statistic was defined as the sum of the t statistics of the sensors or voxels within the respective cluster.

Source analysis. A frequency-domain adaptive spatial filtering algorithm (Gross et al., 2001) served to estimate the sources of activity that contributed to effects at the sensor level. This algorithm uses the cross-spectral density matrix obtained from the data to construct a spatial filter optimized for the specific location (voxel). The time windows and frequency bands of interest were based on the results obtained at the sensor level. A standardized realistic single-shell brain model (Nolte, 2003) was constructed for each subject based on an affine transformation of an MNI (Montreal Neurological Institute) template brain (<http://www.bic.mni.mcgill.ca/brainweb>). Individual magnetic resonance images were not available for the present sample. However, reliable source localization results in contexts like the present can be obtained using a standardized head model (Fuchs, Kastner, Wagner, Hawes, & Ebersole, 2002); the individual head shape information was transformed into the appropriate coordinate system.

Cross-frequency analysis. Cross-frequency between alpha phase and gamma amplitude was computed using procedures described in Voytek et al. (2010). Phase-amplitude coupling (PAC) is captured with a PLV (Lachaux et al., 1999) relating the phase of one frequency band (10–15 Hz) to the amplitude of another (typically higher) frequency band (60–80 Hz). First, the amplitude time course of the 60–80 Hz signal was band-pass filtered with the lower, presumably phase-modulating frequency (10–15 Hz). Subsequently, the phase of this signal was extracted by a Hilbert transform. The PAC index refers to the consistency across trials in phase difference between ongoing alpha phase and alpha-modulated gamma amplitude, with a range normalized between 0 and 1 (no relationship or perfect relationship, respectively; Foster & Parvizi, 2012). The PAC index was applied to a region of interest (ROI) derived from an automated synthesis of human hemodynamic neuroimaging data (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011).

Functional connectivity of neural activity between regions was analyzed in terms of phase synchrony, following procedures described by Lachaux et al. (1999) and Keil et al. (2012): Alpha phase synchrony was computed for the time window of picture presentation and compared as a function of task (passive viewing vs. down-regulate). Based on Fourier transformation of sensor data for time and frequency windows identified in the time-frequency analysis, complex values were extracted containing phase information. These complex values were then projected into source space by multiplying them with beamformer spatial filters (Huang et al., 2004). Complex values were first transformed into angles (radians), and the difference was calculated between the reference voxel (the medial prefrontal voxel that was used in the PAC analyses; see Results) and all other voxels for each trial. Consistency in phase differences between two oscillators was considered an indication that these oscillators were interacting with each other or sharing a common driving input.

All aspects of offline treatment of the MEG signals were accomplished with the MATLAB-based open source signal

Figure 1. Grand-average (across subjects and MEG sensors) time-frequency representation of power for oscillatory activity < 50 Hz (top row) and 50–120 Hz (bottom row) from cue onset (–2,000 ms), and picture onset (0 ms). Color coding indicates power change in the respective frequency range relative to pretrial baseline (–2,500 to –2,000 ms).

processing toolbox FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011).

Results

Averaged time-frequency of power scores (Figure 1) confirmed that stimulus-related changes were prominent in the 10–15 Hz (alpha) and 60–80 Hz (gamma) frequency bands and extended across time windows of 50 to 2,000 ms after picture onset, whereas a stimulus-related change during the cue interval was evident only in the alpha frequency range.

Figure 2A illustrates the grand-average time course of activity in the alpha band, including modulation by the cue indicating the subsequent task (watch or regulate). A change in both alpha and gamma from precue baseline is evident in response to the stimulus, but only alpha power decrease (event-related desynchronization, ERD) during the anticipatory interval varied by condition, decreasing more when the cue signaled regulation. As expected, there was no difference between the two passive viewing conditions, which used identical cues. Modulation by condition (watch vs. regulate) was evident in the 500-ms window preceding picture onset, with alpha power decrease over bilateral frontocentral regions being larger prior to regulation than prior to the passive viewing of neutral (Figure 2B, cluster spanning both hemispheres, $p_{\text{cluster}} < .001$) and unpleasant pictures (Figure 2C, left cluster $p_{\text{cluster}} < .02$ and right cluster $p_{\text{cluster}} < .03$). It should be noted that the time window of interest was determined based on previous literature (Moser et al., 2009) and that the cluster randomization procedure was applied to the data in the time window 500 ms prior to picture onset. Source reconstruction confirmed an origin in bilateral frontal to precentral gyri (Figure 2B and C).

Figures 3 and 4 illustrate the time course of activity in the alpha (10–15 Hz, Figure 3A) and gamma (60–80 Hz, Figure 4) bands across the cue- and the picture-processing interval, averaged across subjects separately for the three conditions. (Figures 2A and 3A show the same data but illustrate different analysis windows.) In accord with the first hypothesis, picture onset prompted a change in oscillatory activity from precue baseline in both frequency bands, starting 50 ms after picture onset and extending across the remaining analysis interval. Alpha power decreased most during instruction to regulate by cognitive reappraisal during unpleasant pictures and least when viewing neutral pictures (Figure 3A). Statistical comparison of the two passive-viewing conditions in sensor space (Figure 3B) confirmed this arousal effect, larger alpha ERD in response to unpleasant than in response to neutral pictures for bilateral posterior sensor clusters ($p_{\text{cluster}} < .003$). For the same time interval, the effect of regulation on alpha power decrease was confirmed relative to passive viewing of neutral (Figure 3C, $p_{\text{cluster}} < .001$) and unpleasant (Figure 3D, left cluster $p_{\text{cluster}} < .01$ and right cluster $p_{\text{cluster}} < .02$) pictures for right temporal and bilateral anterior sensor clusters. Source analyses (DICS, dynamic imaging of coherent sources; see Figure 3B–D) verified sources of differential activity related to picture salience during both passive viewing conditions and regulation relative to passive viewing of neutral pictures in parietal, posterior cingulate, and subcortical regions (Figure 3B and C), and sources related to regulation in anterior cingulate and medial prefrontal regions (Figure 3D).

Picture onset also prompted a power increase in the gamma bands (event-related synchronization), which was more pronounced during instructed regulation and passive viewing of unpleasant pictures than passive viewing of neutral pictures (Figure 4A). The difference between the two passive viewing

Figure 2. A: Grand-average time course of power in the 10–15 Hz (alpha) frequency band across the pretrial interval (–3,000 to –2,000 ms), the cue (–2,000 to 0 ms), and the picture (0 to 2,000 ms) expressed as power change in percent relative to pretrial baseline (–2,500 to –2,000 ms). Time course of power changes is averaged across subjects separately for the three conditions: passive viewing of neutral pictures (WN, watch neutral), passive viewing of unpleasant pictures (WU, watch unpleasant), and down-regulation to unpleasant pictures (RU, regulate unpleasant). The gray shaded area marks the interval of power modulation by condition during the cue interval. The 500-ms interval before picture onset corresponds to the time window of the stimulus preceding negativity (SPN) as determined in ERP analyses. B & C: Left panels: Topographical distribution of sensor clusters that reflect significant differences between down-regulation of unpleasant pictures and passive viewing of neutral pictures (RU > WN), and between down-regulation to unpleasant pictures (RU, regulate unpleasant) and passive viewing of unpleasant pictures (RU > WU) during the 500-ms interval before picture onset. Color indicates statistical effects, with negative t values representing decrease in alpha power from precue baseline. T -value threshold for sensor clusters or regions of significant difference between conditions was set to $p < .05$ in all cases. Black circles indicate individual sensors in a significant cluster. Right panels: Source reconstruction of regions of statistical differences ($p < .05$) between the conditions as described above, based on DICS.

conditions (the arousal effect) was confirmed for a bilateral occipitoparietal sensor cluster (Figure 4B, $p_{\text{cluster}} < .001$). Source reconstruction indicated a primary source of this differential activity in occipitoparietal brain regions and an additional source in left superior frontal gyrus (Figure 4B). Cognitive reappraisal of unpleasant

pictures relative to passive viewing of neutral pictures intensified gamma at frontocentral sensor clusters (Figure 4C, $p_{\text{cluster}} < .001$), verified by source reconstruction of differential activity in frontal, posterior cingulate, and right posterior regions. The contrast of regulation versus passive viewing of unpleasant pictures produced differential effects in left frontal and anterior and medial cingulate cortex indexed at sensor (Figure 4D, $p_{\text{cluster}} < .04$) and source levels. No differential gamma response was evident in primary and secondary sensory areas for these comparisons. Thus, in support of the second hypothesis, source reconstruction indicated oscillatory modulation by instructed regulation in those frontal and cingulate regions that have been related to an emotion-regulation network based on hemodynamic neuroimaging evidence. By definition, ERD reflects induced, that is, nonphase-locked activity, which is not obligatory for synchronization in the gamma frequency range. Evoked and induced activity for both frequency bands in Figure 5 illustrates an initial increase in phase locking of alpha oscillations around 100 ms after cue and after picture onset. This reflects the transient evoked responses typically seen in ERP/ERF and in single-trial analyses. Thereafter, however, a rapid drop in intertrial phase locking confirms the induced, nonphase-locked properties of ERD. No such increase in intertrial phase locking was evident for the gamma-band response. This indicates that gamma oscillations were not phase locked to stimulus onset and, hence, reflects induced not evoked oscillatory activity.

The third hypothesis proposed a systematic coupling of the two spectral measures and their condition-related changes in brain regions relevant for the top-down direction of information flow in regions related to the emotion-regulation network. This correlation of alpha phase and gamma amplitude was evaluated for a ROI that (a) was defined on the basis of the literature discussed above, and (b) for which DICS demonstrated an overlap of condition effects (larger change in the respective measure during regulation than during passive viewing of unpleasant pictures).

Figure 6A illustrates the result of an automated synthesis of human hemodynamic neuroimaging studies, using the search term “emotion regulation,” available at <http://www.neurosynth.org> (Yarkoni et al., 2011). Increase in signal change expressed in z scores is projected on a schematic sagittal view of the MNI template brain, based on the probability of a given voxel being active in hemodynamic neuroimaging studies that used the term “emotion regulation” compared to studies that did not use the term. Using this ROI defined in the hemodynamic literature, Figure 6B shows the source reconstruction of alpha-gamma power change overlap resulting from the present data analysis. For the medial prefrontal ROI, coupling was stronger during regulation than during passive viewing, $t(23) = 2.43$, $p < .03$; Figure 6C (left panel). As illustrated in Figure 6C (right panel), gamma increase during regulation was largest at alpha phase peaks, indicating a systematic relationship between the amplitude of high-frequency oscillation and the phase of an ongoing slow oscillation. Thus, instructed, top-down control of processing of emotional pictures was accompanied by a specific pattern of local coherent alpha-gamma interaction. This coherent activity was evident in medial prefrontal cortex.

In service of hypothesis 4, the final analysis explored whether the proposed prefrontal top-down regulation was evident in connectivity measured by alpha phase synchrony between this medial prefrontal region and other brain regions. The medial prefrontal region that had shown high PAC (shown in Figure 6) was chosen as a seed region for correlations of alpha phase synchrony with other brain regions (voxels). Color patches in Figure 7 index the two regions with significant phase relationship, representing more

Figure 3. A: Grand-average time course of power in the 10–15 Hz (alpha) frequency band across all intervals (same as Figure 2A), with the time window of modulation by condition during picture presentation marked in gray. B–D: Left panels: Topographical distribution of sensor clusters that reflect significant differences between the two passive viewing conditions (watch unpleasant, WU > watch neutral, WN), between down-regulation and passive viewing of neutral (RU > WN), and between down-regulation and passive viewing of unpleasant pictures (RU > WU) 50–2,000 ms after picture onset. Color indicates statistical effects, with negative t values representing decrease in alpha power from precue baseline. Black circles indicate individual sensors in a significant cluster. Middle panels: DICS-based source reconstruction of regions of statistical differences ($p < .05$) between the conditions projected onto a schematic cortical sheet, top view. Right panels: Source reconstruction projected on right and left hemisphere sagittal view.

alpha phase synchrony between the medial prefrontal ROI and visual areas and temporoparietal junction during regulation than during passive viewing of unpleasant pictures. This suggests condition-specific connectivity by means of long-range phase synchrony (in contrast to the local phase-to-amplitude coupling in the medial prefrontal cortex) as a potential mechanism of the prefrontal interaction with regions involved in picture appraisal. The interaction means that processing of physically identical pictures is varied

by instruction. No comparable alpha phase synchrony was found between the medial prefrontal ROI and areas that might be associated with subcortical, potentially amygdala activity.

Discussion

In Pietrek et al. (2012), ERF averaged across trials showed an emotional arousal effect 300–600 ms after picture onset; passive

Figure 4. Same as Figure 3 except for power change in the 60–80 Hz (gamma) band.

viewing of unpleasant pictures evoked larger responses than passive viewing of neutral pictures. The down-regulation effect occurred later, 600–1,000 ms into picture presentation. Present analyses of single-trial oscillatory activity investigated neural mechanisms of emotion regulation involving cognitive reappraisal, in particular the neural mechanisms of prefrontal top-down control of attention to, appraisal of, and reappraisal of visual emotional stimuli, which has been proposed in models on emotion regulation. Results suggest two neural mechanisms driving those averaged ERF results that explain top-down control: *local* coupling of alpha oscillatory phase with gamma amplitude fluctuations within medial prefrontal cortex and cross-regional *long-range* communication by means of phase synchrony between the medial prefrontal cortex

and the primary visual areas as well as the right temporoparietal junction. The former has been reported to be involved in response inhibition (Nakata, Inui, Wasaka, Akatsuka, & Kakigi, 2005), the latter in emotion regulation (Cheng et al., 2007).

Hypotheses were tested for down-regulation of emotional responses to unpleasant pictures by cognitive reappraisal as strategy. Whether the proposed neural mechanisms enabling prefrontal control are specifically related to the instructed cognitive reappraisal, reflect voluntary control that could be related to any other active task, or are even more specific to down-regulation of emotional responses to unpleasant stimuli has to be determined in future studies that compare different tasks and strategies, different directions of regulation, or different stimulus salience. Studies

Figure 5. Top row: Time course of power in the 10–15 Hz (alpha) frequency band across the entire time interval 1-s precue, 2-s cue interval, and 2-s picture interval, averaged across subjects and a group of occipital sensors (see schematic map at right) expressed as power change in percent relative to precue baseline (left y axis). The three graphs represent the three conditions: watch neutral (black line), watch unpleasant (blue line), and regulate unpleasant (red line). For all conditions, gray lines (right y axis) represent the corresponding intertrial phase-locking values as a function of time. A transient phase-locking (PLV) increase around 100 ms after cue and picture onset, respectively, is followed by PLV decrease, which characterizes nontime-locked, induced responses. Bottom row: Same time course for power and intertrial PLV changes in the 60–80 Hz (gamma) band. The lack of intertrial PLV increase in all conditions confirms that gamma power changes were induced and not evoked by stimulus onset.

demonstrating task-specific phase-amplitude coupling or cross-regional phase synchrony (Keil et al., 2012; Voytek et al., 2010) suggest that cross-frequency, cross-regional phase coupling reflects a mechanism of communication within and across task-specific networks, which may vary with task between networks. A similar mechanism of communication may be assumed for all conditions, including prefrontal regulation of visual processing. For emotion regulation, this regulation process could be the appraisal of the motivational salience of the visual stimulus to stir an emotional response. It is conceivable, though, that the network involved in the prefrontal top-down control varies with the task or strategy. Thus, cross-regional connectivity may involve prefrontal regions and amygdala or insular regions under specific regulation instructions such as suppression of the emotional response (Goldin et al., 2008).

Four results suggest that the regionally specific interplay of gamma power increase, alpha power decrease, and cross-regional alpha phase synchrony assist prefrontal cortex influence on visual emotional stimulus processing. In accord with hypothesis 1, a combination of stimulus-induced gamma power increase and alpha power decrease varied systematically, especially during regulation by instructed cognitive reappraisal. Supporting hypothesis 2, condition effects appeared in regions similar to those associated with a regulation network proposed based on hemodynamic studies. Per hypothesis 3, regionally specific, cross-frequency, phase-to-amplitude coupling varied with condition, more pronounced for down-regulation than for passive viewing of unpleasant stimuli. In line with hypothesis 4, cross-regional alpha phase synchrony between regions involved in a proposed emotion-regulation network suggests an additional element of a top-down emotion-

regulation mechanism. These results substantiate the role of prefrontal regions in emotion regulation and suggest modulation of visual processing as a mechanism that, in psychological terms, would reflect modulation of perception (appraisal) mediated by cognitive reappraisal.

Alpha and gamma activity are particularly well suited for the roles identified here. Stimulus-induced gamma synchrony has been related to various sensory and cognitive functions, including perceptual encoding, salience processing, and working memory (Pulvermüller, Keil, & Elbert, 1999; Tallon-Baudry & Bertrand, 1999; for an overview, see Gandal, Edgar, Klook, & Siegel, 2012). Gamma synchrony with dominance over frontocortical regions has been found in response to high-arousing emotional stimuli (e.g., Balconi, Brambilla, & Falbo, 2009), in response to awareness of emotional stimulus content (Luo et al., 2009), and when monitoring of one's own affective state (Dan Glausser & Scherer, 2008). Decreased alpha synchrony (typically quantified at 8–12 or 10–15 Hz) is believed to facilitate processing in a given region, whereas increased alpha serves to actively suppress irrelevant or interfering processing (Haegens, Nacher, Luna, Romo, & Jensen, 2011; Jensen, Bonnefond, & VanRullen, 2012), thus shaping the functional architecture of the brain (Jensen & Mazaheri, 2010). A relation between alpha power decrease and better performance has been demonstrated for diverse tasks including recognition and retrieval of stimulus material (Haegens et al., 2011) and also recently in the context of cognitive reappraisal (Parvaz et al., 2012). Both frequencies are related to communication and coordination, with high-frequency oscillations thought to reflect coordination within cell assemblies and low-frequency oscillations

Figure 6. A: Regions of significant activation, resulting from a meta-analysis of 29 hemodynamic neuroimaging studies as enabled by www.neurosynth.org. The definition of regions is based on the probability of a given voxel being active in studies that use the term “emotion regulation” compared to studies that did not use the term. The hemodynamic responses are projected on a standard MNI brain. The right brown box shows the MNI coordinates of the approximate location of the ROI (on standard brain projections) that was then used for analysis of present MEG data. B: Medial prefrontal region determined for present data, in which significant alpha power decrease and gamma power increase during regulation relative to passive viewing of unpleasant pictures overlapped. Schematic sagittal views in A and B represent activity in one slice only. C: Left: Statistical comparison of phase-amplitude coupling (PAC) index for this medial prefrontal ROI between down-regulation (left bar) and passive viewing of unpleasant pictures (right bar), indicating stronger phase-to-amplitude coupling during the former condition. Right: Example coupling of alpha phase (bottom) to gamma amplitude (top): alpha phase peaks coincide with gamma power increase (red).

accomplishing communication over longer distances. Therefore, an interplay of these two frequency bands should be expected for complex processes like emotion regulation, which is believed to involve prefrontal influence on stimulus appraisal, hence, input processing in primary and secondary sensory areas.

Present findings of linked changes in alpha and gamma power across the processing interval support this interplay and suggest two neural mechanisms for portions of the complex process of emotion. Specifically, present results suggest coherent, cross-frequency communication across an extended network as one mechanism of this interplay. Alpha phase-locked gamma amplitude was largest when communication between networks was most important—during down-regulation, perhaps accomplishing pre-

frontal, top-down influence on visual perceptual stimulus appraisal. In support, Jensen and colleagues (2012) reported a role for gamma oscillations phase locked to alpha oscillations in the modulation of perception. Thus, if emotion regulation is accomplished via modulation of stimulus perception in visual sensory areas, this modulation requires the communication realized by cross-frequency interaction. In psychological terms, stimulus salience is constantly evaluated in order to up- or down-regulate response to input.

This cross-frequency, phase-amplitude coupling was pronounced in brain regions that have been associated with automatic and voluntary emotion regulation (Phillips et al., 2008). Linked changes in power were evident in regions associated with top-down control by attention and working memory (Gazzaley & Nobre,

Figure 7. Regions of significant phase synchrony in the alpha frequency range between the medial prefrontal ROI (as in Figure 6) and other brain areas. Left: Clusters of significant phase synchrony thresholded at $p < .05$ between the medial prefrontal ROI chosen as a seed region and all other voxels of the brain volume during regulation relative to passive viewing of unpleasant pictures are projected onto an inflated brain template (back and right hemispheric view). Significant differences in cross-regional phase synchrony between the two conditions are indicated by t values (color bar) with positive t values representing stronger phase synchrony between clusters during down-regulation than during passive viewing of unpleasant pictures. Right: The (alpha) phase-locking value (PLV, mean and standard deviation across subjects) between the medial prefrontal ROI and the occipital ROI marked by red in the left graph (approximating V1) and the right temporal ROI (approximating temporoparietal junction). Circular histograms illustrate the effective phase difference between both conditions expressed as mean phase difference per subject; red arrows mark the mean direction across all subjects.

2012) and motivated response selection (Holroyd & Yeung, 2012). Alpha synchrony between the medial prefrontal region, visual areas (V1), and temporoparietal junction indicates that the region of condition-specific phase-amplitude coupling is related to regions associated with visual input processing and reorienting to salient stimuli (Decety & Lamm, 2007).

As suggested by Gross and Thompson (2007), appraisal and reappraisal of emotional information are linked in emotion regulation. Hemodynamic studies have shown associated activity modulation in subcortical (amygdalae) regions with early appraisal, late response suppression, and activity modulation in prefrontal regions with reappraisal (Goldin et al., 2008; Gross & Thompson, 2007; Ochsner et al., 2004). The ventromedial prefrontal cortex has been described as a “hub” (Roy, Shohamy, & Wager, 2012) connecting cortical and subcortical systems involved in affect processing and coordination of emotional responses. From that, cross-regional alpha synchrony between the prefrontal regions and subcortical regions might have been inferred. On the other hand, subcortical regions are particularly associated with emotion processing: Fast and first evaluation of or responses to emotionally salient (in particular, threatening or dangerous) stimuli motivating avoidance and emotional experience are related to amygdala activity (Lang & Bradley, 2008, 2010; Winecoff et al., 2011). Emotion-regulation strategies such as reappraisal and suppression influence amygdala activity in different directions and with different latency (Goldin et al., 2008). However, these effects that might have prominently activated subcortical regions were not explicitly targeted by the present experimental conditions, so that modulation of amygdala activity may have been small and less obvious.

As posterior regions believed to be part of an emotion-regulation network are also related to visuospatial attention and oculomotor control (van Reekum et al., 2007), it might be that present results reflect gaze shifting during down-regulation. Indeed, van Reekum et al. (2007) reported that variation in gaze fixation accounted for substantial variance in fMRI brain activation

during instructed reappraisal of unpleasant pictures. Accordingly, special care was taken in the present MEG protocol to control for eye movements: participants were asked to keep their eyes focused on the screen throughout the trial series, as MEG measurement is particularly sensitive to eye movements; the break between the two trial series enabled eye movements, in order to facilitate fixation during the subsequent trial series; and eye-movement correction procedures were used prior to data analysis. The number of artifact-free trials entering analyses did not vary by condition, which suggests that systematic, condition-specific eye movements were not a factor. Although the prominent cross-regional alpha synchrony did not involve frontal eye fields, the connectivity between prefrontal cortex and regions associated with visual processing may have been influenced by visual attention shifting (as an emotion down-regulation strategy) even without visible oculomotor activity.

These mechanisms could account for any active task that involves cognitive aspects activating frontal regions and/or visual processing. The direct comparison of cognitive reappraisal and other strategies or another active task has to identify a specific role of the described oscillatory activity measures in cognitive reappraisal as an emotion-regulation strategy. However, the present cross-regional alpha phase synchrony between prefrontal (seed) and visual areas suggests a mechanism of shaping visual processing, as suggested for reappraisal. Studies demonstrating the task-specific nature of phase-amplitude coupling (e.g., Voytek et al., 2010) and cross-regional coupling (Keil et al., 2012) investigated and described specific networks likely to be involved in the respective active task. Similarly, the present study focused on prefrontal cortex because of its proposed role in cognitive modulation of reappraisal.

Alpha power decrease was evident even prior to picture onset, prompted by the cue for down-regulation. As alpha activity has been related to long-range network communication facilitating input processing, anticipatory alpha power decrease might reflect top-down (attention and working memory; see also Gazzaley &

Nobre, 2012) information flow that paves the way for subsequently efficient stimulus processing. In contrast, stimulus encoding, which has been related to gamma power increase, did not differ as a function of instruction cue, implying that encoding was efficient for both task instruction conditions, whereas preparation for implementing the more demanding down-regulation strategy prompted differential alpha activity. These condition-specific effects may point to a mechanism of preparation for efficient emotion processing.

In summary, analyses of oscillatory phenomena at the single-trial level point to specific neural control mechanisms in support of emotion regulation. Determining cross-frequency phase-to-power coupling as the psychophysiological correlate of the prefrontal top-down control inferred from hemodynamic findings advances

understanding of how emotion regulation may be locally realized in the medial prefrontal cortex. Results encourage further modeling of a potential mechanism enabling modulation of processing of emotional stimuli with identical physical properties: Modulation may start in the primary visual cortex, where relevant and irrelevant information might be distinguished, as reflected in the phase of the ongoing signal. Relevant information is then transmitted via the temporoparietal junction to prefrontal regions. Present results do not allow further specification of the order or sequence of regions involved. However, long-range communication with visual processing areas where the relevant information has been initially processed may constitute the mechanism of prefrontal control, with phase synchronization constituting the neural correlate of this mechanism.

References

- Ackenheil, M., Stotz-Ingenlath, G., Dietz-Bauer, R., & Vossen, A. (1999). *M.I.N.I. Mini International Neuropsychiatric Interview* (German version 5.0.0 DSM IV). München, Germany: Psychiatrische Universitätsklinik München.
- Balconi, M., Brambilla, E., & Falbo, L. (2009). Appetitive vs. defensive responses to emotional cues. Autonomic measures and brain oscillation modulation. *Brain Research*, 1296, 72–84. doi: 10.1016/j.brainres.2009.08.056
- Bastiaansen, M. C., & Knosche, T. R. (2000). Tangential derivative mapping of axial MEG applied to event-related desynchronization research. *Clinical Neurophysiology*, 111, 1300–1305.
- Bradley, M. M., Sabatinelli, D., Lang, P. J., Fitzsimmons, J. R., King, W., & Desai, P. (2003). Activation of the visual cortex in motivated attention. *Behavioral Neuroscience*, 117, 369–380.
- Bullmore, E., & Sporns, O. (2009). Complex brain networks: Graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience*, 10, 186–198. doi: 10.1038/nrn2575
- Buzsaki, G., & Draguhn, A. (2004). Neuronal oscillations in cortical networks. *Science*, 304, 1926–1929. doi: 10.1126/science.1099745
- Canolty, R. T., & Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in Cognitive Sciences*, 14, 506–515. doi: 10.1016/j.tics.2010.09.001
- Cheng, Y., Lin, C. P., Liu, H. L., Hsu, Y. Y., Lim, K. E., Hung, D., & Decety, J. (2007). Expertise modulates the perception of pain in others. *Current Biology*, 17, 1708–1713. doi: 10.1016/j.cub.2007.09.020
- Codispoti, M., Ferrari, V., & Bradley, M. M. (2006). Repetitive picture processing: Autonomic and cortical correlates. *Brain Research*, 1068, 213–220. doi: 10.1016/j.brainres.2005.11.009
- Dan Glausser, E. S., & Scherer, K. R. (2008). Neuronal processes involved in subjective feeling emergence: Oscillatory activity during an emotional monitoring task. *Brain Topography*, 20, 224–231. doi: 10.1007/s10548-008-0048-3
- Decety, J., & Lamm, C. (2007). The role of the right temporoparietal junction in social interaction: How low-level computational processes contribute to meta-cognition. *Neuroscientist*, 13, 580–593. doi: 10.1177/1073858407304654
- Foster, B. L., & Parvizi, J. (2012). Resting oscillations and cross-frequency coupling in the human posteromedial cortex. *Neuroimage*, 60, 384–391. doi: 10.1016/j.neuroimage.2011.12.019
- Fries, P. (2005). A mechanism for cognitive dynamics: Neuronal communication through neuronal coherence. *Trends in Cognitive Sciences*, 9, 474–480. doi: 10.1016/j.tics.2005.08.011
- Fuchs, M., Kastner, J., Wagner, M., Hawes, S., & Ebersole, J. S. (2002). A standardized boundary element method volume conductor model. *Clinical Neurophysiology*, 113, 702–712.
- Gandal, M. J., Edgar, J. C., Klook, K., & Siegel, S. J. (2012). Gamma synchrony: Towards a translational biomarker for the treatment-resistant symptoms of schizophrenia. *Neuropharmacology*, 62, 1504–1518. doi: 10.1016/j.neuropharm.2011.02.007
- Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: Bridging selective attention and working memory. *Trends in Cognitive Sciences*, 16, 129–135. doi: 10.1016/j.tics.2011.11.014
- Goldin, P. R., McRae, K., Ramel, W., & Gross, J. J. (2008). The neural bases of emotion regulation: Reappraisal and suppression of negative emotion. *Biological Psychiatry*, 63, 577–586. doi: 10.1016/j.biopsych.2007.05.031
- Gross, J., Kujala, J., Hamalainen, M., Timmermann, L., Schnitzler, A., & Salmelin, R. (2001). Dynamic imaging of coherent sources: Studying neural interactions in the human brain. *Proceedings of the National Academy of Sciences USA*, 98, 694–699. doi: 10.1073/pnas.98.2.694
- Gross, J., Schnitzler, A., Timmermann, L., & Ploner, M. (2007). Gamma oscillations in human primary somatosensory cortex reflect pain perception. *PLoS Biology*, 5, e133. doi: 10.1371/journal.pbio.0050133
- Gross, J. J. (1998). Antecedent- and response-focused emotion regulation: Divergent consequences for experience, expression, and physiology. *Journal of Personality and Social Psychology*, 74, 224–237.
- Gross, J. J., & Thompson, R. A. (2007). Emotion regulation: Conceptual foundations. In J. J. Gross (Ed.), *Handbook of emotion regulation* (pp. 3–26). New York, NY: Guilford Press.
- Haegens, S., Nacher, V., Luna, R., Romo, R., & Jensen, O. (2011). Alpha-oscillations in the monkey sensorimotor network influence discrimination performance by rhythmic inhibition of neuronal spiking. *Proceedings of the National Academy of Sciences USA*, 108, 19377–19382. doi: 10.1073/pnas.1117190108
- Hajcak, G., MacNamara, A., & Olvet, D. M. (2010). Event-related potentials, emotion, and emotion regulation: An integrative review. *Developmental Neuropsychology*, 35, 129–155. doi: 10.1080/87565640903526504
- Hanslmayr, S., Gross, J., Klimesch, W., & Shapiro, K. L. (2011). The role of alpha oscillations in temporal attention. *Brain Research Reviews*, 67, 331–343. doi: 10.1016/j.brainresrev.2011.04.002
- Holroyd, C. B., & Yeung, N. (2012). Motivation of extended behaviors by anterior cingulate cortex. *Trends in Cognitive Science*, 16, 122–128. doi: 10.1016/j.tics.2011.12.008
- Huang, M. X., Shih, J. J., Lee, R. R., Harrington, D. L., Thoma, R. J., Weisend, M. P., . . . Canive, J. M. (2004). Commonalities and differences among vectorized beamformers in electromagnetic source imaging. *Brain Topography*, 16, 139–158.
- Jensen, O., Bonnefond, M., & VanRullen, R. (2012). An oscillatory mechanism for prioritizing salient unattended stimuli. *Trends in Cognitive Sciences*, 16, 200–206. doi: 10.1016/j.tics.2012.03.002
- Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: Gating by inhibition. *Frontiers in Human Neuroscience*, 4, 186. doi: 10.3389/fnhum.2010.00186
- Jung, T. P., Makeig, S., McKeown, M. J., Bell, A. J., Lee, T. W., & Sejnowski, T. J. (2001). Imaging brain dynamics using independent component analysis. *Proceedings of the IEEE Institute of Electrical and Electronic Engineers*, 89, 1107–1122. doi: 10.1109/5.939827
- Kanske, P., Heissler, J., Schonfelder, S., Bongers, A., & Wessa, M. (2011). How to regulate emotion? Neural networks for reappraisal and distraction. *Cerebral Cortex*, 21, 1379–1388. doi: 10.1093/cercor/bhq216
- Keil, J., Mueller, N., Ihssen, N., & Weisz, N. (2012). On the variability of the McGurk effect: Audiovisual integration depends on prestimulus brain states. *Cerebral Cortex*, 22, 221–231. doi: 10.1093/cercor/bhr125
- Kopell, N., Ermentrout, G. B., Whittington, M. A., & Traub, R. D. (2000). Gamma rhythms and beta rhythms have different synchronization properties. *Proceedings of the National Academy of Sciences USA*, 97, 1867–1872.

- Krompinger, J. W., Moser, J. S., & Simons, R. F. (2008). Modulations of the electrophysiological response to pleasant stimuli by cognitive reappraisal. *Emotion*, 8, 132–137. doi: 10.1037/1528-3542.8.1.132
- Lachaux, J. P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, 8, 194–208.
- Lang, P. J. (1979). Presidential address, 1978. A bio-informational theory of emotional imagery. *Psychophysiology*, 16, 495–512.
- Lang, P. J., & Bradley, M. M. (2008). Appetitive and defensive motivation is the substrate of emotion. In A. Elliot (Ed.), *Handbook of approach and avoidance of emotion*. (pp. 51–66): New York, NY: Taylor & Francis Group.
- Lang, P. J., & Bradley, M. M. (2010). Emotion and the motivational brain. *Biological Psychology*, 84, 437–450. doi: 10.1016/j.biopsycho.2009.10.007
- Lang, P. J., Bradley, M. M., & Cuthbert, B. N. (2008). International affective picture system (IAPS): Affective ratings of pictures and instruction manual. Technical report A-8. Gainesville, FL: University of Florida.
- Luo, Q., Mitchell, D., Cheng, X., Mondillo, K., McCaffrey, D., Holroyd, T., . . . Blair, J. (2009). Visual awareness, emotion, and gamma band synchronization. *Cerebral Cortex*, 19, 1896–1904. doi: 10.1093/cercor/bhn216
- Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods*, 164, 177–190. doi: 10.1016/j.jneumeth.2007.03.024
- Moser, J. S., Krompinger, J. W., Dietz, J., & Simons, R. F. (2009). Electrophysiological correlates of decreasing and increasing emotional responses to unpleasant pictures. *Psychophysiology*, 46, 17–27. doi: 10.1111/j.1469-8986.2008.00721.x
- Nakata, H., Inui, K., Wasaka, T., Akatsuka, K., & Kakigi, R. (2005). Somato-motor inhibitory processing in humans: A study with MEG and ERP. *European Journal of Neuroscience*, 22, 1784–1792. doi: 10.1111/j.1460-9568.2005.04368.x
- Nolte, G. (2003). The magnetic lead field theorem in the quasi-static approximation and its use for magnetoencephalography forward calculation in realistic volume conductors. *Physics in Medicine and Biology*, 48, 3637–3652.
- Ochsner, K. N., & Gross, J. J. (2007). The neural architecture of emotion regulation. In J. J. Gross (Ed.), *Handbook of emotion regulation* (pp. 87–109): New York, NY: Guilford Press.
- Ochsner, K. N., Ray, R. D., Cooper, J. C., Robertson, E. R., Chopra, S., Gabrieli, J. D., & Gross, J. J. (2004). For better or for worse: Neural systems supporting the cognitive down- and up-regulation of negative emotion. *Neuroimage*, 23, 483–499. doi: 10.1016/j.neuroimage.2004.06.030
- Olofsson, J. K., Nordin, S., Sequeira, H., & Polich, J. (2008). Affective picture processing: An integrative review of ERP findings. *Biological Psychology*, 77, 247–265. doi: 10.1016/j.biopsycho.2007.11.006
- 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. doi: 10.1155/2011/156869
- Parvaz, M. A., MacNamara, A., Goldstein, R. Z., & Hajcak, G. (2012). Event-related induced frontal alpha as a marker of lateral prefrontal cortex activation during cognitive reappraisal. *Cognitive Affective Behavioral Neuroscience*. Advance online publication. doi: 10.3758/s13415-012-0107-9
- Phillips, M. L., Ladouceur, C. D., & Drevets, W. C. (2008). A neural model of voluntary and automatic emotion regulation: Implications for understanding the pathophysiology and neurodevelopment of bipolar disorder. *Molecular Psychiatry*, 13, 829–857. doi: 10.1038/mp.2008.65
- Pietrek, C., Popov, T., Steffen, A., Miller, G. A., & Rockstroh, B. (2012). Neuromagnetic indication of dysfunctional emotion regulation in affective disorders. *Depression Research and Treatment*, 2012, 156529. doi: 10.1155/2012/156529
- Pulvermueller, F., Keil, A., & Elbert, T. (1999). High-frequency brain activity: Perception or active memory? *Trends in Cognitive Sciences*, 3, 250–252.
- Roy, M., Shohamy, D., & Wager, T. D. (2012). Ventromedial prefrontal-subcortical systems and the generation of affective meaning. *Trends in Cognitive Sciences*, 16, 147–156. doi: 10.1016/j.tics.2012.01.005
- Schupp, H. T., Flaisch, T., Stockburger, J., & Junghoefer, M. (2006). Emotion and attention: Event-related brain potential studies. *Progress in Brain Research*, 156, 31–51. doi: 10.1016/S0079-6123(06)56002-9
- Siegel, M., Donner, T. H., & Engel, A. K. (2012). Spectral fingerprints of large-scale neuronal interactions. *Nature Reviews Neuroscience*, 13, 121–134. doi: 10.1038/nrn3137
- Tallon-Baudry, C., & Bertrand, O. (1999). Oscillatory gamma activity in humans and its role in object representation. *Trends in Cognitive Sciences*, 3, 151–162.
- Tallon-Baudry, C., Bertrand, O., Delpuech, C., & Pernier, J. (1997). Oscillatory gamma-band (30–70 Hz) activity induced by a visual search task in humans. *Journal of Neuroscience*, 17, 722–734.
- Thiruchselvam, R., Blechert, J., Sheppes, G., Rydstrom, A., & Gross, J. J. (2011). The temporal dynamics of emotion regulation: An EEG study of distraction and reappraisal. *Biological Psychology*, 87, 84–92. doi: 10.1016/j.biopsycho.2011.02.009
- Uhlhaas, P. J., & Singer, W. (2010). Abnormal neural oscillations and synchrony in schizophrenia. *Nature Reviews Neuroscience*, 11, 100–113. doi: 10.1038/nrn2774
- Urry, H. L., van Reekum, C. M., Johnstone, T., Kalin, N. H., Thurow, M. E., Schaefer, H. S., . . . Davidson, R. J. (2006). Amygdala and ventromedial prefrontal cortex are inversely coupled during regulation of negative affect and predict the diurnal pattern of cortisol secretion among older adults. *Journal of Neuroscience*, 26, 4415–4425. doi: 10.1523/JNEUROSCI.3215-05.2006
- van Reekum, C. M., Urry, H. L., Johnstone, T., Thurow, M. E., Frye, C. J., Jackson, C. A., . . . Davidson, R. J. (2007). Individual differences in amygdala and ventromedial prefrontal cortex activity are associated with evaluation speed and psychological well-being. *Journal of Cognitive Neuroscience*, 19, 237–248. doi: 10.1162/jocn.2007.19.2.237
- von Stein, A., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: From local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology*, 38, 301–313.
- Voytek, B., Canolty, R. T., Shestuyuk, A., Crone, N. E., Parvizi, J., & Knight, R. T. (2010). Shifts in gamma phase-amplitude coupling frequency from theta to alpha over posterior cortex during visual tasks. *Frontiers in Human Neuroscience*, 4, 191. doi: 10.3389/fnhum.2010.00191
- Vrticka, P., Sander, D., & Vuilleumier, P. (2011). Effects of emotion regulation strategy on brain responses to the valence and social content of visual scenes. *Neuropsychologia*, 49, 1067–1082. doi: 10.1016/j.neuropsychologia.2011.02.020
- Wincoff, A., Labar, K. S., Madden, D. J., Cabeza, R., & Huettel, S. A. (2011). Cognitive and neural contributors to emotion regulation in aging. *Social and Cognitive Affective Neuroscience*, 6, 165–176. doi: 10.1093/scan/nsq030
- Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C., & Wager, T. D. (2011). Large-scale automated synthesis of human functional neuroimaging data. *Nature Methods*, 8, 665–670. doi: 10.1038/nmeth.1635