

# Affective picture processing: Alpha- and lower beta-band desynchronization reflects emotional arousal

David Schubring  | Harald T. Schupp

Department of Psychology, University of  
Konstanz, Konstanz, Germany

## Correspondence

David Schubring, General & Biological  
Psychology, University of Konstanz, P.O.  
Box 36, 78457 Konstanz, Germany.  
Email: David.Schubring@uni-konstanz.de

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## Abstract

EEG power analysis is firmly established in the cognitive domain. This contrasts with emotional stimulus processing, which thus far has yielded a complex and ambiguous pattern of findings. To further advance understanding, the present study examined emotional stimulus processing in the context of task variations and baseline activity, which included several manipulation checks as well as internal replication of findings across conditions. Participants ( $N = 16$ ) viewed erotic and romantic pictures, differing in stimulus arousal. Pictures were presented briefly (120 ms), and intertrial interval was systematically varied (~1 vs. ~8 s). In one condition, participants passively viewed the pictures, in the other, they performed an active picture categorization task. The processing of erotic compared to romantic images was associated with a decrease in power in the alpha and lower beta band in posterior and anterior sensor clusters between 600–1,000 ms poststimulus. The finding was robust and confirmed across conditions, different quantifications, and independent from baseline activity. Furthermore, key findings regarding explicit task effects as well as ERPs sensitive to emotional arousal were replicated. Results are discussed with respect to the hypothesis that alpha- and lower beta-band activity may reflect cortical activation associated with emotional stimulus significance.

## KEYWORDS

affect, alpha ERD, attention, emotion, LPP, power

## 1 | INTRODUCTION

Neural oscillations are thought to represent a fundamental brain mechanism. Changes in oscillatory brain activity can be related to states of inhibition and excitation in neural networks (Buzsáki & Watson, 2012). Much progress has been made in delineating brain oscillations to cognitive processes, including attention and memory functions (Foxy & Snyder, 2011; Hanslmayr, Staudigl, & Fellner, 2012; Klimesch, 2012). Changes in brain oscillations induced by emotional stimulus processing are comparatively less well understood, and results are ambiguous. With emphasis on the alpha and lower beta band, the present study aimed to characterize the

oscillatory brain response to emotional stimuli in conjunction with different task sets and systematic differences in prestimulus baseline activity.

So far, perceptual and evaluative processes associated with emotional stimulus processing have been assessed mostly with regard to distinct components of the ERP, which are thought to reflect the attention capture of emotional stimuli. Specifically, the processing of high-arousing emotional (pleasant and unpleasant) compared with low-arousing control images is associated with an early posterior negativity (EPN; i.e., a negative-going potential over temporo-occipital sensor regions, around 150–300 ms poststimulus) and an enlarged late positive potential (LPP) between 300 and

700 ms poststimulus over centro-parietal regions (Lang & Bradley, 2010; Schupp, Flaisch, Stockburger, & Junghöfer, 2006). However, assessing event-related brain perturbations in terms of its frequency characteristics can provide unique insights into emotional stimulus processing. Specifically, event-related oscillations not only assess stimulus-evoked oscillations akin to the traditional ERP analysis but also induced oscillations, which are not phase-locked to the stimulus event. Thus, characterizing event-related oscillations with respect to evoked and induced components provide insights into dynamic shifts of inhibition and excitation in neural networks associated with emotional stimulus processing and the presumed relationship to attention and memory processes.

A number of studies assessed event-related oscillations associated with emotional stimulus processing. However, findings are difficult to integrate because studies focus on different frequencies, time windows, and topographies, and variations in task instructions. For instance, the processing of emotionally arousing (pleasant and unpleasant) compared to neutral stimuli (i.e., words; Otten & Jonas, 2014), facial expression (Balconi & Mazza, 2009; Furl, Lohse, & Pizzorni-Ferrarese, 2017; Knyazev, Bocharov, Levin, Savostyanov, & Slobodskoj-Plusnin, 2008; Popov, Miller, Rockstroh, & Weisz, 2013; Popov, Steffen, Weisz, Miller, & Rockstroh, 2012; Schneider et al., 2018), and images from the International Affective Picture System (IAPS) library (Cui et al., 2013; de Cesarei & Codispoti, 2011; Meng et al., 2016; Mennella et al., 2017) were often associated with a decrease in alpha power caused by an event-related desynchronization (ERD). However, these findings contrast with results from studies that reported an increase rather than decrease in alpha power for emotionally significant stimuli (Aftanas, Reva, Varlamov, Pavlov, & Makhnev, 2004; Aftanas, Varlamov, Pavlov, Makhnev, & Reva, 2002; Güntekin & Başar, 2007; Uusberg, Uibo, Kreegipuu, & Allik, 2013). In addition to the direction of the emotional alpha-power modulation, findings vary considerably in terms of onset latency (e.g., ~200 vs. 800 ms) and topography (anterior vs. centro-parietal vs. occipital). Overall, to reveal oscillatory responses to emotional stimuli as concise as has been achieved for ERP, somatic, and autonomic measures (Bradley, 2000; Schupp et al., 2006), more research is needed characterizing brain oscillatory responses to emotional stimuli by a data-driven approach taking methodological factors into account.

Manipulating the task focus of picture processing has been useful in relating ERP components sensitive to emotional stimulus significance to effects associated with explicit task relevance (Ferrari, Codispoti, Cardinale, & Bradley, 2008; Schupp et al., 2007; Weymar, Löw, Öhman, & Hamm, 2011). Adopting a similar strategy seems helpful for several reasons. Beyond detailing the interaction of implicit emotion and explicit attention effects, differences in task set (passive viewing vs. evaluative task) have been proposed to account for

opposite alpha-power effects in previous research (Uusberg et al., 2013). Furthermore, incorporating explicit task manipulations relates the findings in the emotion domain to a large array of studies examining alpha-band oscillations in the cognitive domain. Alpha-ERD responses are observed in a variety of attention paradigms. For instance, in classical oddball tasks, target as compared to nontarget stimulus processing is associated with an alpha-ERD response over centro-parietal leads between 300–700 ms poststimulus (Bernat, Malone, Williams, Patrick, & Iacono, 2007; Yordanova, Kolev, & Polich, 2001). Furthermore, within the context of visual (dorsal vs. ventral stream), spatial (left vs. right hemifield), cross-modal (auditory vs. visual), and performance (perceived vs. nonperceived or reaction time) attention tasks, anticipatory alpha-ERD responses triggered by cue stimuli have been observed facilitating processing in task-relevant brain systems (Caposto, Babiloni, Romani, & Corbetta, 2009; Foxe, Simpson, & Ahlfors, 1998; Foxe & Snyder, 2011; Hanslmayr et al., 2007; Thut, Nietzel, Brandt, & Pascual-Leone, 2006). Overall, complementing emotional stimulus processing with explicit task demands allows us to more concisely determine increases and decreases in alpha power, presumed to reflect a bias in processing significant stimuli at the expense of irrelevant stimuli.

The main aim of the present study was to determine induced brain oscillatory responses to emotional stimuli varying explicit task demands. Stimulus materials included pictures depicting erotic couples, which were contrasted with images showing couples in romantic contexts. Pictures were selected to elicit robust modulations of the EPN and LPP component, serving as an experimental manipulation check within this study. Furthermore, in two separate blocks, explicit task focus was manipulated. In one block, participants performed an explicit categorization in which participants were asked to press a button whenever a picture from the target category (erotic or romantic) was seen. In the other block, pictures were viewed passively (i.e., without an explicit task). Emotion and task effects and their interactions on induced brain oscillations were assessed in two separate streams of analysis (1–40 Hz and 40–100 Hz) relying on conservative thresholds at sensor and cluster level to correct for multiple testing. Based on previous research (de Cesarei & Codispoti, 2011), alpha-power decreases were predicted for erotic compared to romantic pictures during passive viewing conditions. Based on previous research analyzing ERP components (Codispoti, Ferrari, & Bradley, 2006; Ferrari et al., 2008; Schupp et al., 2007), one may assume a similar emotional modulation effect for the explicit task condition. Alternatively, if task set is critical for observing increases in alpha power (Uusberg et al., 2013), alpha power may be increased when processing erotic images. Furthermore, taking into account baseline power is critical for the assessment of alpha-power decreases (Başar & Güntekin, 2012). To systematically vary baseline power,

pictures were presented in both blocks with short (~1 s) and long (~8 s) intertrial intervals (ITI), and the dependency of the emotional modulation of brain oscillations from baseline activity was determined as a function of ITI, task, and block (first vs. second block). Finally, we aimed to replicate emotional modulation of the EPN and LPP components and analyzed evoked responses to reveal their representation in the time-frequency domain.

## 2 | METHODS

### 2.1 | Participants

Sixteen healthy volunteers (8 male/8 female) with a mean age of 21.1 years ( $SD = 1.5$ ) were recruited on the campus of the University of Konstanz. All participants had normal or corrected-to-normal vision. Sample size was determined based on previous research reporting strong and consistent effects on the modulation of ERPs with samples of 16 participants (e.g., Schupp et al., 2007, 2008). Participants received monetary compensation or course credit for participation. The ethical committee of the University of Konstanz approved the experimental procedure in accordance with the regulations of the Declaration of Helsinki, and all methods were carried out in full compliance with the approved guidelines. All participants provided informed consent.

### 2.2 | Stimulus materials

Picture selection comprised 20 images of nude couples in erotic poses (erotic) and 20 images of dressed couples in romantic situations (romantic) that have been used in previous research (Flaisch et al., 2015). Functional imaging studies provided strong evidence that the activation of visual-associative as well as subcortical limbic structures is driven by the emotional arousal dimension and accentuated for erotic stimuli (Junghöfer, Schupp, Stark, & Vaitl, 2005; Sabatinelli, Bradley, Fitzsimmons, & Lang, 2005). Similarly, erotic pictures elicit robust and consistent modulations in specific ERP components (i.e., EPN and LPP; Schupp, Junghöfer, Weike, & Hamm, 2004, 2007), alpha ERD (de Cesarei & Codispoti, 2011), as well as peripheral physiological response (Bradley, Codispoti, Cuthbert, & Lang, 2001). The romantic control category was selected to promote the comparability of the two picture categories in terms of picture composition and categorical homogeneity. Specifically, all pictures were black and white and showed heterosexual dyads of socially interacting couples. Each picture was presented equally often both normally or as a mirror image with flipped left-right axis to prevent a bias in lateralization.

Given the emphasis of the arousal dimension in previous research on ERPs (e.g., Schupp et al., 2006) and brain oscillations (e.g., de Cesarei & Codispoti, 2011), self-report data

were obtained at the end of the experiment using the Self-Assessment Manikin (Bradley & Lang, 1994). Findings were as predicted. Specifically, erotic ( $M = 6.27$ ,  $SD = 0.99$ ) images were evaluated as more arousing than romantic images ( $M = 2.66$ ,  $SD = 1.09$ ,  $t(15) = 12.6$ ,  $p < 0.001$ ). In addition, there were no significant differences in valence for the two categories (erotic:  $M = 5.83$ ,  $SD = 1.13$ ; romantic:  $M = 6.34$ ,  $SD = 1.16$ ,  $t(15) = 1.3$ ,  $p = 0.21$ ; corresponding to a Bayes factor of 1.92).

### 2.3 | Task

The experiment consisted of two conditions: passive and active picture viewing. Order of active and passive viewing conditions was balanced across participants.

#### 2.3.1 | Passive viewing condition

In the passive viewing condition, participants passively viewed the pictures in random order without explicit task instruction. Each picture was shown 10 times for 120 ms, which resulted in a total of 400 trials. Half of the trials were separated with a short ITI of 800–1,200 ms and the other half with a long ITI of 7,200–8,800 ms. Order of short and long ITIs was randomized.

#### 2.3.2 | Active task condition

In the active task condition, participants were asked to react to one of the two picture categories via button press. The block was divided into four blocks with 100 trials each. After each block, the target category changed, with half of the participants starting with erotic as target category and the other half with romantic. Presentation times and ITIs were identical to the passive condition. Half the participants responded with the left index finger, the other half with the right index finger. Due to a programming error, only the reaction times for participants responding with the right finger were recorded. A significant main effect of picture category,  $t(7) = 3.63$ ,  $p = 0.008$ , indicated that participants responded faster to erotic target stimuli ( $M = 429$  ms,  $SD = 37$  ms) than to romantic targets ( $M = 457$  ms,  $SD = 31$  ms).

### 2.4 | EEG data acquisition and main analysis

Brain and ocular scalp potential fields were measured with a 257-lead geodesic sensor net, online band-pass filtered from 0.01 to 100 Hz, and sampled at 250 Hz using Net Station acquisition software and Electrical Geodesics (EGI, Eugene, OR) amplifiers. Data were recorded continuously with the vertex sensor as the reference electrode. Stimulus-synchronized epochs lasting from 2,000 ms before until 2,000 ms

after picture onset were extracted. Heart and eyeblink artifacts were corrected by independent component analysis. Trials containing movement artifacts and noisy channels were rejected based on visual inspection of variance. For each participant, trials and channels with extreme variance were removed. On average, 16 channels ( $SD = 5.0$ ) were removed per participant. Removed EEG channels were interpolated by the mean of their neighboring sensors. The mean waveforms were calculated using on average 92.4% ( $SD = 5.2\%$ ) of the trials, which did not differ significantly across experimental conditions,  $F(1, 11) = 1.67$ ,  $p = 0.08$ . After artifact correction, data were converted to an average reference. EEG data analysis was conducted using the open-source signal processing toolbox FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011) and in-house functions using MATLAB 9.3.0 R2017b (MathWorks Inc., Natick, MA).

## 2.4.1 | Frequency analysis

### 1–40 Hz

EEG frequency analysis focused on induced brain activity. Accordingly, in a first step, the ERP average of each condition was computed and subtracted from the single trials comprising this condition. In a second step, a fast Fourier transform was calculated for single-trial data in the frequency range from 1–40 Hz. Specifically, a sliding window of 200 ms was multiplied by a Hanning taper resulting in a spectral resolution of 5 Hz and a time resolution of  $\pm 100$  ms. The sliding window advanced in 16 ms and 1 Hz increments to estimate changes in power over time and frequency. For each condition, single-trial power estimates were then averaged across trials and expressed as a decibel change from prestimulus baseline. To avoid poststimulus activity in the baseline, baseline activity was calculated in a time window from  $-400$  ms to  $-100$  ms.

### 40–100 Hz

In higher frequency ranges (i.e., gamma), the frequency power diminishes, and effects are often seen in broader frequency bands. Accordingly, a separate analysis was conducted to determine emotion and task effects in the 40–100 Hz in 2 Hz steps with a  $\pm 6$  Hz frequency smoothing via multitapering. All other parameters were identical to the main analyses.

## 2.4.2 | Statistics

To determine main effects of emotion (erotic vs. romantic) and task (target vs. nontarget), data from each time point (0–1,000 ms), sensor, and frequency bin (1–40 Hz) were submitted separately to a dependent samples  $t$  test. Furthermore, the interaction of Task  $\times$  Emotion was examined with the contrast (erotic<sub>target</sub> – romantic<sub>target</sub>) versus (erotic<sub>nontarget</sub> – romantic<sub>nontarget</sub>). To account for the multiple comparisons problem, a

cluster-based permutation test (Maris & Oostenveld, 2007) was performed. In short, this procedure clusters adjacent  $t$  values (in time, frequency, and sensor space) to a single summed cluster test statistic. Clusters were formed when they had at least two neighbors that reached a cluster-forming threshold of  $p < 0.001$ . These clusters were then tested against a Monte Carlo approximation of the test statistic, which was formed by randomly shuffling the data for 1,000 permutations and reporting the proportion of random shuffles that were bigger than the actual observed cluster test statistic as a cluster  $p$  value. Following recommendations to increase reproducibility (Benjamin et al., 2018), cluster-level  $p$  values were considered meaningful if they reached  $p < 0.005$ . To enable comparability with previous research, findings obtained with conventional significance criteria ( $p < 0.05$ ) are reported in the online supporting information, Appendix S1.

Furthermore, exploratory follow-up tests were conducted to reproduce the effect separately in each condition and to test for interactions between conditions using the main effects of emotion and task as a region of interest. To this end, all sensors, time points, and frequencies forming a significant cluster effect were summed per condition and submitted to a Wilcoxon signed-rank test.

## 2.4.3 | Evoked oscillations and ERPs

As the main analyses excluded evoked activity, evoked activity phase-locked to stimulus onset was analyzed separately in two ways: For one, the main analyses were repeated using evoked instead of induced activity. For the second, ERPs were computed by averaging the raw data per condition and referring them to a  $-100$  ms to 0 ms prestimulus baseline. Data were filtered with a high-pass ( $-6$  dB cutoff 1 Hz, transition width 2 Hz, order 414) and a low-pass filter ( $-6$  dB cutoff 40 Hz, transition width 10 Hz, order 84). Both filters were zero-phase Kaiser-windowed sinc FIR filters with a maximum passband deviation of 0.22% and a stopband attenuation of  $-53$  dB (reporting as suggested by Widmann, Schröger, & Maess, 2015). Afterward, ERPs were subject to the same cluster analyses as the main analyses, albeit with one fewer dimension (no frequency dimension).

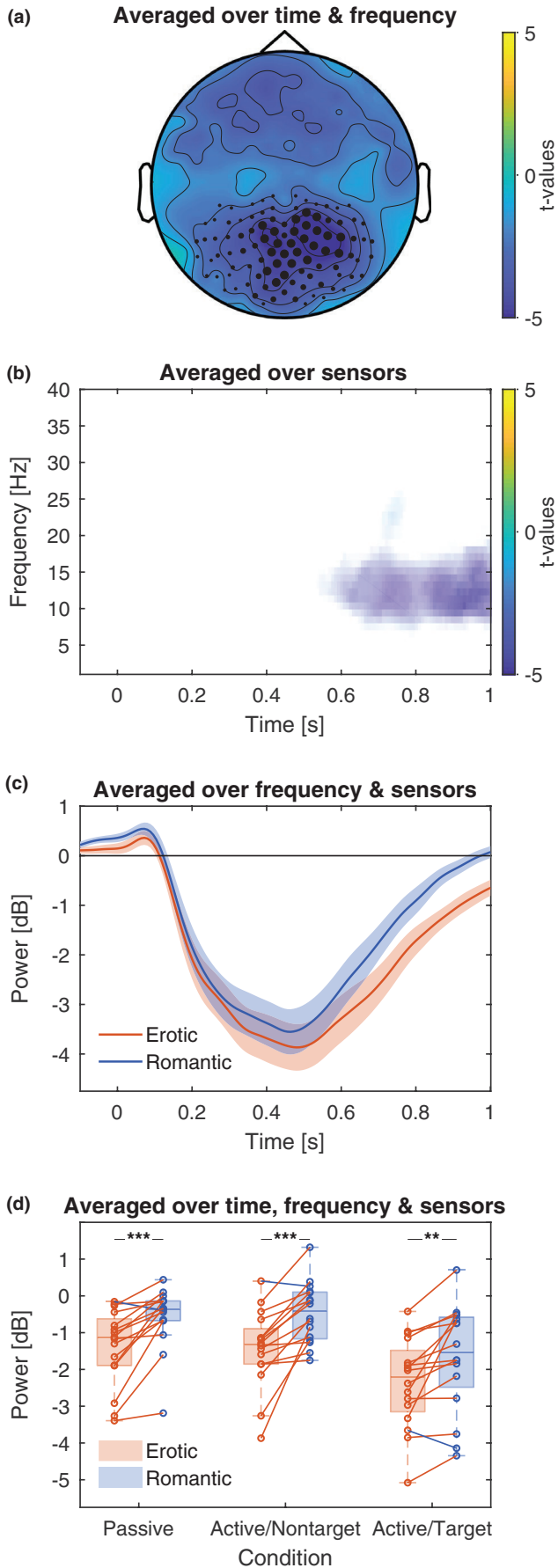
## 3 | RESULTS

### 3.1 | Lower frequency analysis (1–40 Hz)

#### 3.1.1 | Emotion main effect

Combined across active and passive task conditions, erotic as compared to romantic picture processing was associated with a stronger ERD in two clusters (see Figures 1 and 2).

As shown in Figure 1a,b, the first cluster effect appeared over extended posterior regions and was most apparent



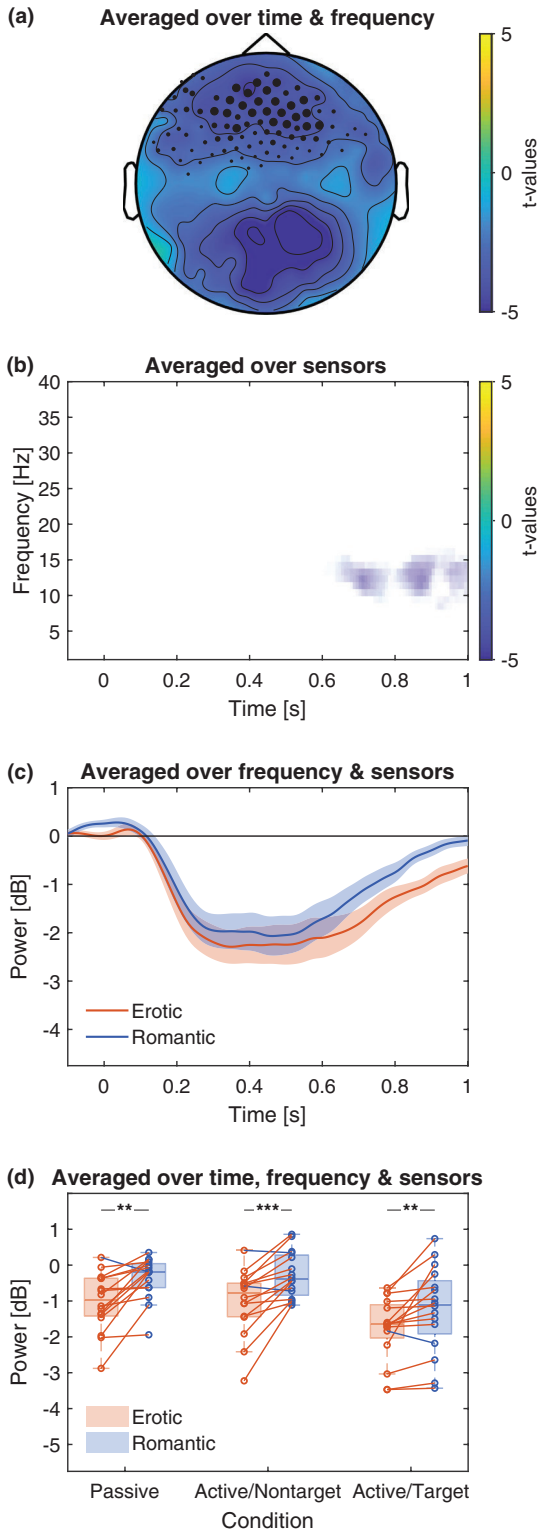
**FIGURE 1** Illustration of the emotion ERD main effect for the posterior cluster: Erotic pictures elicit a stronger ERD than romantic pictures. Each panel represents the same data averaged over different dimensions. (a) Topography of  $t$  values averaged across the significant time points and frequency bins (see view b). The size of the marked sensors over posterior regions are displayed proportional to their contribution to the cluster. (b) Time-frequency plot of  $t$  values, averaged across sensors of the respective emotion ERD cluster (see view a). Only time-frequency bins that are part of the cluster are displayed. Opacity represents the percentage of sensors showing the effect (e.g., nearly opaque time-frequency bins indicate that only few sensors contribute to this effect). (c) Time course of the posterior ERD cluster. Values were averaged over the respective sensors (see a) and frequencies (see b). Colored shaded areas signify standard errors. (d) Box plot and single subject values from the cluster of the posterior emotion ERD main effect averaged across time, sensors, and frequency, separately for passive, active/nontarget, and active/target conditions. Each circle represents one subject, with colored lines connecting the paired samples. Red connecting lines indicate a stronger ERD for erotic pictures for the respective subject, blue connecting lines indicate a stronger ERD for romantic pictures. Asterisks indicate the significance of exploratory post hoc subgroup comparisons: \*\*\* $p < 0.001$ ; \*\* $p < 0.01$ ; \* $p < 0.05$

in the upper alpha band (10–12 Hz) and lower beta band (12–20 Hz). Statistical findings indicated that the effect ( $p < 0.001$ ) reached significance in a window from 536–1,000 ms and a frequency range from 6–25 Hz (see Figure 1b,c). Furthermore, as shown in Figure 1d, emotional modulation appeared similarly across the three task conditions. Exploratory post hoc tests (Wilcoxon signed ranked test) showed stronger ERDs for erotic compared to romantic pictures for passive viewing,  $z = -3.309$ ,  $p < 0.001$ , active nontarget condition,  $z = -3.361$ ,  $p < 0.001$ , and active target condition,  $z = -3.154$ ,  $p = 0.002$  (Figure 1d).

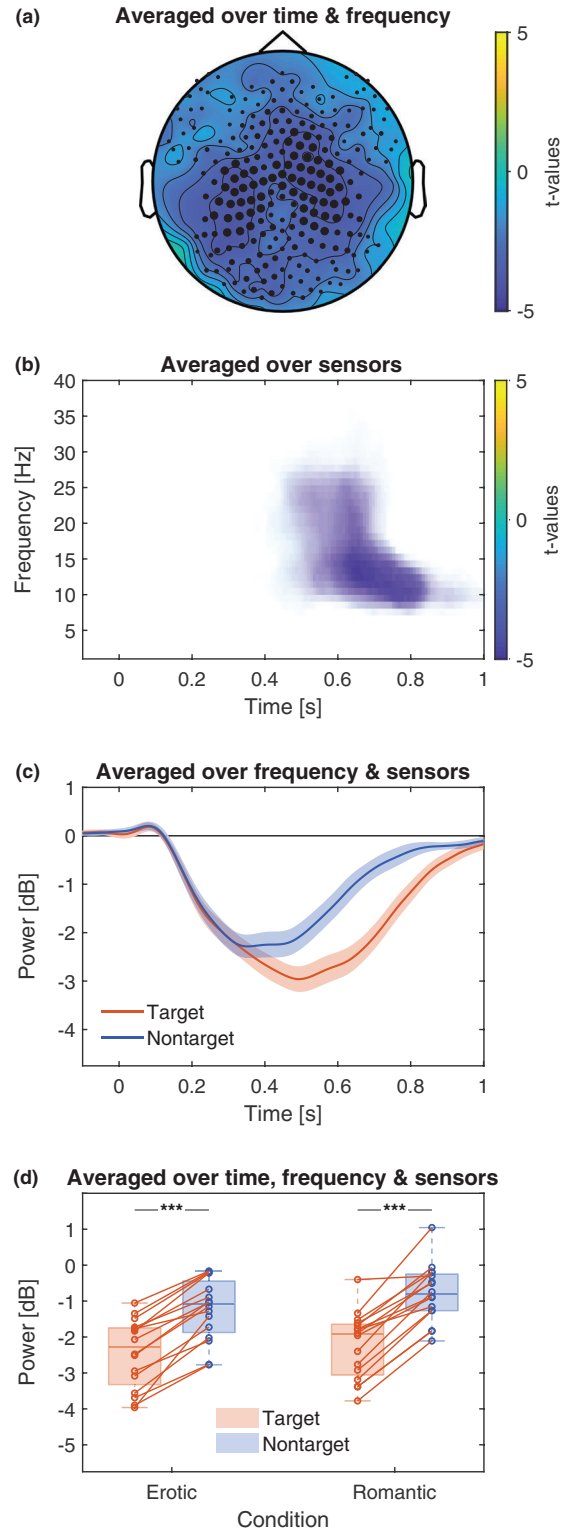
A second cluster effect for emotion was found over anterior regions ( $p = 0.003$ ). The effect was most apparent in the upper alpha band (see Figure 2b) and reached significance in a time window of 608–1,000 ms and a frequency range of 8–16 Hz (see Figure 2c). Exploratory post hoc tests showed stronger ERD for erotic compared to romantic pictures for passive viewing,  $z = -3.103$ ,  $p = 0.002$ ; active nontarget condition,  $z = -3.309$ ,  $p < 0.001$ ; and active target condition,  $z = -3.051$ ,  $p = 0.002$  (Figure 2d).

### 3.1.2 | Categorization task: Target main effect

Assessing task effects combined across erotic and romantic conditions, target compared to nontarget stimuli elicited an overall stronger ERD response, which was most pronounced in the alpha and beta band in an earlier time window (i.e., between ~400–650 ms) and confined to the alpha band afterward (see Figure 3b,c). Statistical findings revealed a highly



**FIGURE 2** Illustration of the emotion ERD main effects for the anterior cluster: Erotic pictures elicit a stronger ERD than romantic pictures. (a) Topography of  $t$  values averaged across the significant time points and frequency bins. (b) Time-frequency plot of  $t$  values, averaged across sensors of the respective emotion ERD cluster. (c) Time course of the anterior ERD cluster. (d) Box plot and single subject values from the cluster of the anterior emotion ERD main effect averaged across time, sensors, and frequency, separately for passive, active/nontarget, and active/target conditions



**FIGURE 3** Illustration of the target ERD main effect: Target pictures elicit a stronger ERD than nontarget pictures. (a) Topography of  $t$  values averaged across the significant time points and frequency bins. (b) Time-frequency plot of  $t$  values, averaged across sensors of the target ERD cluster. (c) Time course of the target ERD effect. (d) Bar plot and single subject values from the cluster of the target ERD main effect

significant cluster ( $p < 0.001$ ) over extended sensor regions with a central maximum in a frequency range of 7–35 Hz and a time window from 368–1,000 ms (see Figure 3a). Exploratory tests revealed stronger ERD responses to target as compared to nontarget stimuli for erotic and romantic picture categories,  $z = 3.051$ ,  $p = 0.002$ , and  $z = 3.413$ ,  $p < 0.001$ , respectively (see Figure 3d).

### 3.1.3 | Interaction effects: Task $\times$ Emotion

No significant interaction cluster effects were found when contrasting emotion effects for passive versus active viewing conditions,  $ps > 0.4$ . Similarly, no significant interaction effects emerged for the task effect contrasting erotic versus romantic picture conditions,  $ps > 0.6$ . Furthermore, no interaction effects appeared in these analyses when using a cluster-forming threshold of  $p < 0.05$ ,  $ps > 0.3$ , and when conducting exploratory post hoc testing in clusters showing main effects of emotion and task,  $zs < 1.1$ ,  $ps > 0.25$ .

### 3.1.4 | Effects of baseline activity on emotion effects

Previous research indicated that ERD effects can be strongly affected by the level of activity in the baseline (cf. Başar & Güntekin, 2012). With the manipulation of ITI (short and long), the current study included systematic manipulations of baseline activity, allowing the assessment of this issue. As expected, long compared to the short ITI condition elicited larger baseline activity ( $p < 0.001$ ) over extended sensor regions (Figure 4a). The effect appeared as a strong and stable alpha difference in the baseline period and a weaker transient effect in the alpha and beta range between 100–400 ms poststimulus containing a transient broad frequency distribution between 100 and 200 ms. Post hoc tests indicated that the effect reached significance when tested separately for erotic and romantic picture categories,  $zs > -3.5$ ,  $ps < 0.001$  (see Figure 4d). Notably, there was only minimal difference between short and long ITI conditions in the time window when emotion and task main effects were observed (Figure 4c).

A second analysis determined whether task and emotion effects varied as a function of ITI differences using baseline-corrected data as in the main analyses. No significant clusters were found, either for Emotion  $\times$  ITI,  $ps > 0.1$ , or for Target  $\times$  ITI,  $ps > 0.5$ . As illustrated in Figure 4e,f, main effects of emotion and task reported in the main analysis were reproduced separately for long and short ITI intervals,  $zs > -3.5$ ,  $ps < 0.001$ .

In a third approach, poststimulus frequencies were estimated with respect to an absolute baseline instead of a decibel conversion. This scoring approach has been used in previous research, and different scoring methods may contribute to an ambiguous pattern of findings in previous

research (e.g., Müller, Keil, Gruber, & Elbert, 1999). In particular, low baseline activity may prevent the detection of alpha ERD (Başar & Güntekin, 2012), and decibel scoring is more susceptible to low baseline activity than a simple difference score of post-prestimulus alpha activity. Notably, the findings reproduced the emotion effects with similar topography and latency to the analysis based on decibel baseline correction (see supporting information, Figures S1, S2).

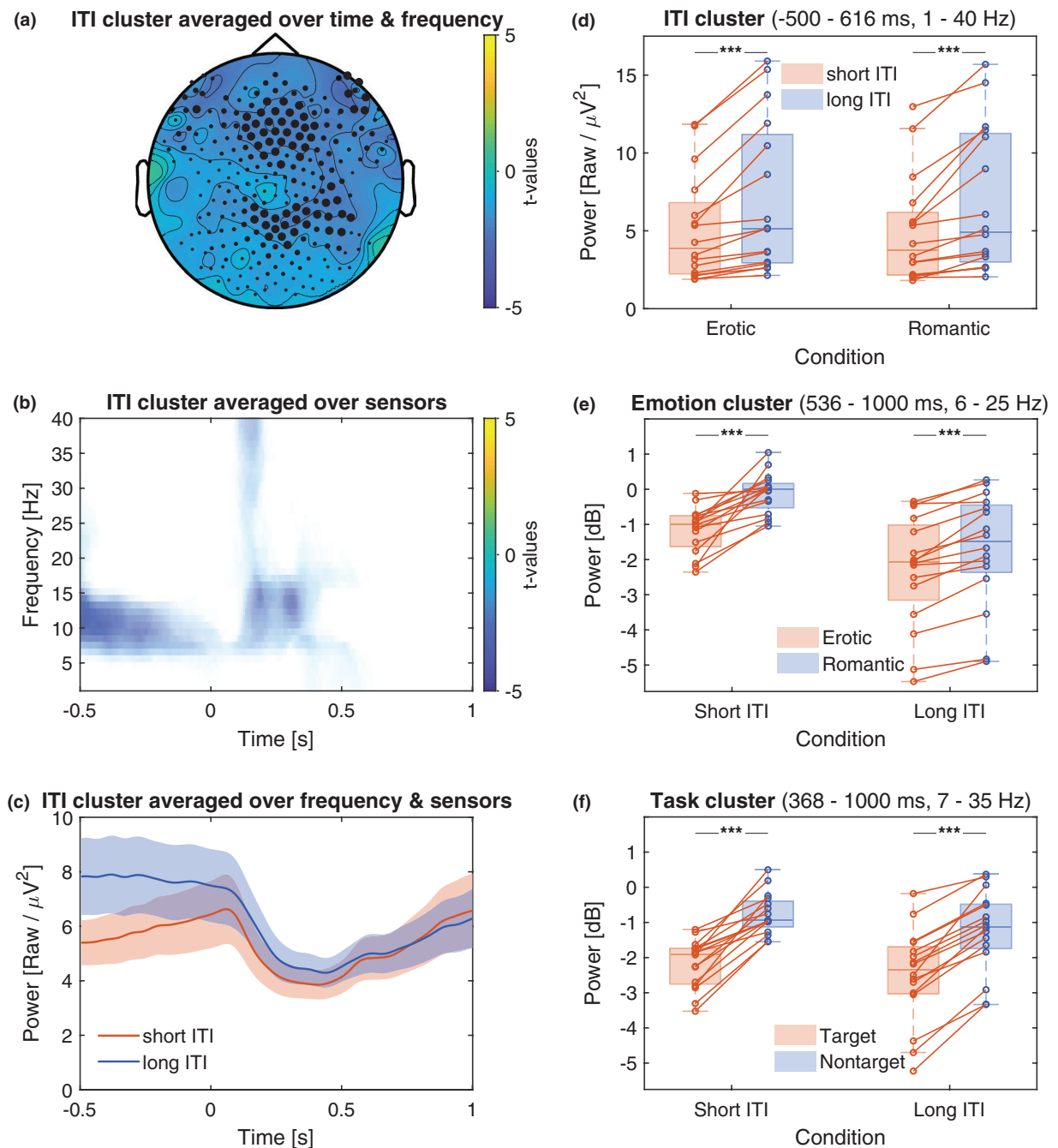
Similar to the manipulation of the baseline via short versus long ITI, effects of active versus passive task conditions and first block versus second block were also tested. Results revealed significant effects for both factors only at conventional thresholds ( $p < 0.05$ ), and, similar to the ITI effects, there were no significant interactions with emotion or task (cf. Figures S3, S4; see Appendix S1, pp 1–6, for a detailed description).

### 3.2 | Higher frequency analysis (40–100 Hz)

No significant cluster effects were found when contrasting emotion (erotic vs. romantic,  $ps > 0.5$ ) and task (target vs. nontarget,  $ps > 0.18$ ) effects and the interaction of both factors ( $ps > 0.6$ ), even when using conventional statistical thresholding ( $p < 0.05$ ).

### 3.3 | Evoked oscillations and ERPs

Induced frequency measures preclude any contribution of ERP components to the findings by subtracting the grand mean ERP before conducting power analysis. However, a number of previous studies reported event-related spectral perturbations (ERSPs) containing both induced and evoked brain activity. To capture evoked activity phase-locked to stimulus onset, the main analyses were also conducted using evoked frequencies and ERPs. As shown in Figures S5 and S7, significant main effects of emotion were observed in two clusters. In the first cluster, appearing in a frequency range from 1–10 Hz (mean 4.6 Hz) over extended posterior regions between 168 ms and 320 ms (mean 238 ms), evoked frequencies were reduced for erotic compared to romantic pictures ( $p < 0.001$ ). In contrast, in the second cluster ( $p < 0.001$ ), erotic compared to romantic images elicited larger evoked frequencies in a range from 1–7 Hz (mean 3.2 Hz) over centro-parietal regions between 336 ms and 656 ms. The close relationship of the evoked frequency analysis to ERPs is illustrated in Figures S6 and S8, showing the EPN and LPP emotional modulation effect, respectively. Erotic as compared to romantic pictures elicited a larger EPN between 184 ms and 308 ms ( $p < 0.001$ ) and the LPP was larger to erotic than romantic pictures in a centro-parietal cluster between 376 ms and 456 ms ( $p = 0.002$ ). Similar relationships also existed between evoked frequencies for the target effect and the target P3 ERP component (cf. Figures S9, S10).



**FIGURE 4** Illustration of the ITI effect: While the long ITI leads to more baseline alpha and early perturbations, later emotion and target ERD effects were observed for short and long ITIs. (a) Topography of  $t$  values averaged across the significant time points and frequency bins. (b) Time-frequency plot of  $t$  values, averaged across sensors of the target ERD cluster. (c) Time course of ITI baseline effect. (d) Box plot and single subject values from the cluster of the ITI main effect averaged across time, sensors, and frequency, separately for erotic and romantic picture conditions. (e) Box plot and single subject values from the emotion ERD main effect (values from the posterior emotion ERD cluster shown in Figure 1). (f) Box plot and single subject values from the target ERD main effect (values from the ERD cluster shown in Figure 3)

## 4 | DISCUSSION

The main goal of the present study was to examine induced cortical oscillations associated with emotional stimulus significance. The central finding is that the processing of erotic

as compared to romantic images was associated with a decrease in power in the alpha and lower beta band. The effect was strongest between  $\sim 600$ – $1,000$  ms poststimulus and was seen in extended posterior as well as anterior sensor sites. Notably, comparable effects were observed when

participants passively viewed the pictures as well as when they performed an explicit categorization task. Furthermore, the effect was consistently observed both for low and high levels of alpha activity in the baseline and different methods to scale the effect (i.e., absolute vs. logarithmic scale). These findings suggest that increased stimulus arousal is associated with power decreases in the alpha and lower beta band presumed to reflect cortical activation.

In light of conflicting findings regarding alpha-power modulations associated with emotional stimulus processing in previous research, the present study incorporated several experimental manipulations and additional measures to secure the interpretation of findings. EPN and LPP components are consistently and robustly modulated by emotional stimulus significance (Lang & Bradley, 2010; Schupp et al., 2006). Replicating EPN and LPP modulations to erotic stimuli with predicted polarity, topography, and latency served as a within-study check that the experimental manipulation was successful. Similarly, interpretation of effects associated with the explicit categorization task was substantiated by replicating established target effects. Specifically, target as compared to nontarget stimuli elicited a larger P3 component and a widespread decrease in alpha power. Overall, a number of established findings related to emotion and task effects have been revealed in the present study as foundation for the meaningfulness of the main findings associated with induced brain oscillations by emotionally significant stimuli.

The main finding is that erotic stimulus processing is associated with a decrease in alpha power. The effect was robust and revealed in every subanalyses of the various conditions (i.e., passive viewing and active categorization conditions, and target and nontarget stimulus processing). In the present study, picture contents were all related to mating and sexual reproduction, but differed in their explicitness. This difference is reflected in self-report data, which revealed a profound difference in stimulus arousal but not valence. Similar to the ERP findings (Lang & Bradley, 2010; Schupp et al., 2006), the alpha ERD to erotic compared to romantic pictures is presumed to reflect the intensity/arousal rather than valence dimension. This reasoning is consistent with previous findings reporting a negative association of the power in the alpha band with increasing stimulus arousal for both pleasant and unpleasant stimulus categories, with the largest alpha ERD to pictures of erotica and mutilations (de Cesarei & Codispoti, 2011). Research in the cognitive domain (i.e., perception, attention, working memory) revealed a decrease in alpha power in brain regions activated during a cognitive task. Conversely, alpha synchronization occurred over brain regions that are not engaged by or potentially interfere with a given task (Foxe & Snyder, 2011; Klimesch, 2012; Mathewson et al., 2011). Acknowledging the limits of reverse inference (Poldrack, 2006), widespread decreases in

alpha power may reflect cortical activation associated with emotional stimulus significance.

The effect of decreased synchronization to erotic images was not confined to the alpha band (~8–12 Hz) but was also observed in the lower beta band. However, the trade-off in frequency-time resolution selected for the main analyses (i.e., 5 Hz and 200 ms) may have resulted in the smearing of the effect due to low frequency resolution. To increase frequency resolution, a control analysis was conducted based on higher frequency (2 Hz) and lower time (500 ms) resolution. As expected, the emotion effect was seen in frequency bands defined more sharply (i.e., between 5 Hz and 19 Hz posterior and 8 to 13 Hz anterior), most pronounced in the higher alpha- and lower beta-frequency bands (see Figure S11). Interestingly, effects distributed in both alpha and beta frequencies have been observed in research on memory processes (Hanslmayr et al., 2012). Specifically, while early research observed that remembered items in a memory task were associated with alpha-power decreases, later research extended this notion to the adjacent beta-frequency range. Providing an integrative account for power decreases in the frequency range from 8–30 Hz, Hanslmayr and colleagues (2012) suggested that power decreases reflect the degree of information that needs to be encoded. The network model of emotion assumes that emotional and neutral memory representations differ in terms of number of elements and strength of interconnectivity (Lang, 1993). Accordingly, the hypothesis that richer memory representation of emotionally significant stimulus contents leads to power decreases in the alpha- and lower beta-frequency bands needs to be examined in future research.

This study provided robust evidence that paying explicit attention to the pictures led to similar findings as revealed in passive viewing conditions. Interestingly, while both explicit task-defined and implicit emotional significance resulted in alpha-power decrease, topography and timing of the effect were rather different. The target effect had a centro-parietal focus and was most pronounced between 400–800 ms post-stimulus, while the emotion effect appeared in two separate clusters over posterior and anterior sites and was most pronounced between 700–1,000 ms. Future studies need to substantiate these findings by conclusively determining whether these two avenues of stimulus significance rely on at least partially distinct brain systems and unique temporal dynamics. A further difference was observed regarding the frequency distribution of both effects with the task effects including higher beta frequencies. However, the latter findings presumably reflect contamination by the button press, which shows a corresponding frequency distribution when calculating spectral power locked to the button press. In addition, a few studies observed that paying attention to emotional stimuli had synergistic effects (Ferrari et al., 2008; Schupp

et al., 2007; Weymar et al., 2011). However, in the present study, task and emotion effects had no measurable impact on each other. Systematically manipulating the attention focus toward and away from emotional stimuli may provide a powerful strategy to reveal conditions resulting in synchronized or desynchronized brain oscillations. Specifically, previous ERP research observed attenuated or abolished emotional EPN and LPP effects when emotional stimuli served as distractors (Schupp et al., 2007; Schupp, Schmäzle, & Flaisch, 2014). Thus, competition paradigms may provide the means to experimentally induce event-related synchronization to emotional stimuli including simultaneous assessment of according ERP effects.

Previous findings regarding the direction of the alpha power elicited by emotional stimuli have been inconsistent (Güntekin & Başar, 2014). Specifically, while some studies observed desynchronized brain oscillations (Balconi & Mazza, 2009; Cui et al., 2013; de Cesarei & Codispoti, 2011; Furl et al., 2017; Knyazev et al., 2008; Meng et al., 2016; Mennella et al., 2017; Otten & Jonas, 2014; Popov et al., 2013, 2012; Schneider et al., 2018), others reported null findings (Baumgartner, Esslen, & Jäncke, 2006) or even partly opposite effects (i.e., an increase in alpha power; Aftanas et al., 2002; Aftanas et al., 2004; Güntekin & Başar, 2007; Uusberg et al., 2013). Disentangling conflicting findings is difficult as studies differ in many important aspects. An important methodological issue is regarding the level of baseline activity and the scoring of brain oscillations (cf. Başar & Güntekin, 2012). Duration of picture presentation and ITI systematically affect alpha power, and the detection of event-related alpha desynchronization presupposes alpha power in the prestimulus period. Here, systematic differences in alpha-baseline activity were induced by varying the length of the ITI (i.e., ~1 vs. ~8 s). This manipulation resulted in a roughly 30% decrease in alpha activity for short compared to long ITIs (cf. Figure 4c). Importantly, the effect lasted for approximately 500 ms after stimulus onset, showing a clear difference to the timing of the emotion effect. Furthermore, alpha desynchronization to erotic images was observed for long and short ITIs relying on two different ways to score event-related alpha power (i.e., logarithmic and absolute scoring). Overall, within the present study, the effect of alpha desynchronization to erotic stimuli was observed independent from systematic differences in alpha-power baseline activity.

Desynchronization effects in the alpha- and beta-frequency bands can be accompanied by synchronized responses in higher frequencies (i.e., gamma-band activity). For instance, visual attention and memory studies in humans and animals revealed an inverse relationship between lower alpha and higher gamma frequency responses (e.g., Buffalo, Fries, Landman, Buschman, & Desimone, 2011; Fries, Reynolds, Rorie, & Desimone, 2001; Jensen, Bonnefond, & VanRullen, 2012; Jokisch & Jensen, 2007). However, contrasting findings

were observed in the memory domain, observing that lower and higher frequency effects were uncoupled on a trial-by-trial basis or finding no gamma-band effects in the presence of lower frequency desynchronizations (Hanslmayr et al., 2012). With regard to emotion processing, the pattern of findings is ambiguous. While several studies reported synchronized gamma responses to emotional stimuli, effects considerably vary in topography and timing (e.g., Keil et al., 2001; Keil, Stolarova, Moratti, & Ray, 2007; Luo, Holroyd, Jones, Hendler, & Blair, 2007; Martini et al., 2012; Müller et al., 1999), and findings and reporting regarding the coupling of lower and higher frequencies vary across studies. The present study observed no modulation of the gamma band as a function of emotion or explicit task. This finding may in part be a consequence of the short presentation of the picture. The chosen presentation time (i.e., 120 ms) was selected to prevent scanning movements of the eyes (Christianson, Loftus, Hoffman, & Loftus, 1991). However, the sustained presence of the picture may be needed to observe emotional modulations in the gamma band, a hypothesis that needs to be tested in future research.

The present findings suggest that the LPP component and induced alpha- and lower beta-desynchronization effects may tap into at least partially distinct facets of emotional stimulus processing. This notion is primarily supported by the differences in the topographies of both emotion effects. Specifically, the LPP cluster has its focus over central sensor sites, while alpha and beta clusters have a more posterior focus with a parieto-occipital focus as well as a second cluster over anterior sites. Future research needs to reproduce these topographical differences and determine whether LPP and brain oscillations reflect distinct or similar neuron populations. Resolving the issue has implications for the presumed significance of the LPP and alpha- and beta-power emotion effects and may lead to the examination of the hypothesis that the LPP primarily relates to the initial activation of emotional memories, while alpha and beta power reflect the continued access to stored memory representation (Klimesch, 2012; Schupp, Kirmse, Schmäzle, Flaisch, & Renner, 2016).

## 4.1 | Summary

While emotional modulation effects assessed by ERPs appear robust and consistent, findings in the frequency domain are complex and ambiguous. To further advance understanding, the present study assessed induced frequency modulations by emotional stimuli in the context of an experimental design involving the replication of established brain oscillatory effects of task on alpha and beta power as well as ERP effects of both task and emotion. A consistent pattern of effects was observed, indicating that emotional stimuli decrease alpha and beta power across task contexts (categorization task, passive viewing), frequency scoring (absolute, decibel), and systematic differences in baseline power activity. Overall,

a systematic research program is needed assessing a broad array of pleasant and unpleasant stimulus categories to further detail the reproducibility and functional significance of alpha and beta power as useful measures of emotional stimulus processing.

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## ORCID

David Schubring  <https://orcid.org/0000-0003-2716-5588>

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