




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Investigating real-life emotions in romantic couples: a mobile EEG study

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The neural basis of emotional processing has been largely investigated in constrained spatial environments such as stationary EEGs or fMRI scanners using highly artificial stimuli like standardized pictures depicting emotional scenes. Typically, such standardized experiments have low ecological validity and it remains unclear whether their results reflect neuronal processing in real-life affective situations at all. Critically, emotional situations do not only encompass the perception of emotions, but also behavioral components associated with them. In this study, we aimed to investigate real-life emotions by recording couples in their homes using mobile EEG technology during embracing, kissing and emotional speech. We focused on asymmetries in affective processing as emotions have been demonstrated to be strongly lateralized in the brain. We found higher alpha and beta power asymmetry during kissing and embracing on frontal electrodes during emotional kisses and speech compared to a neutral control condition indicative of stronger left-hemispheric activation. In contrast, we found lower alpha power asymmetry at parieto-occipital electrode sites in the emotional compared to the neutral condition indicative of stronger right-hemispheric activation. Our findings for alpha power asymmetries are in line with models of emotional lateralization that postulate a valence-specific processing over frontal cortices and right-hemispheric dominance in emotional processing in parieto-occipital regions. In contrast, beta power asymmetries pointed more towards valence-specific processing indicating that, while alpha and beta frequencies seem to be functionally associated, they are not reflecting identical cognitive processing.

One of the most intriguing questions in neuroscience revolves around how and where emotions are processed in the brain. More than 100 years ago, studies in patients with unilateral right-hemispheric lesions demonstrated that emotional processing seems to be lateralized in the brain as these patients were impaired in their ability to express their emotions¹. These results were complemented by a large number of behavioral results both from healthy and patient cohorts supporting the notion that emotions are asymmetrically processed in the brain²⁻⁵. With the emergence of brain recording and neuroimaging techniques such as the EEG or fMRI⁶⁻⁸, more specific statements about where affective states are processed within cortical and subcortical regions could be made. For cortical emotional processing, especially frontal alpha power has been strongly associated with changes in affective state and emotional regulation^{9,10}. For example, Hannesdóttir et al.¹¹ investigated relative left frontal asymmetry (rLFA) and found that reduced rLFA in children was predictive of impaired emotional regulation and stronger physiological responses to emotional stimuli. Furthermore, rLFA serves as a suitable predictor for individual differences in emotional expression as well as regulation^{12,13}.

Regarding the nature of emotional lateralization, two theories have been dominant in research on asymmetries of emotion processing. These theories are known as the right hemisphere hypothesis (RHH) and the valence model (VM) of emotional processing. The RHH postulates that all emotions regardless of valence are processed in the right hemisphere¹⁴. In contrast, the VM claims that positive emotions are dominantly processed in the left hemisphere whereas negative emotions are processed in the right hemisphere¹⁵. Both theories have received much support from behavioral, electrophysiological as well as neuroimaging studies¹⁶. The nature of emotional lateralization in the brain therefore remains rather inconclusive to this day. Despite the richness of the neuroscientific literature on emotions, the vast majority of published papers in this field share a common issue: It is largely unclear to what extent the used paradigms elicit neuronal processes that actually resemble the processes

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during real-life emotional encounters. A potential reason for this heterogeneity in the literature might be the lack of ecological validity. Recent systematic review articles have pointed out the necessity for ecologically valid research in neuroscience^{17,18}. This holds especially true for emotion research as the most prevalent method of positive or negative emotional induction is via movies, pictures or music^{19–22}. Thus, emotions are largely only perceived during experimental paradigms. However, merely perceiving emotions might not be sufficient for a valid measurement of the underlying neural substrates. Real-life emotions comprise both the feeling itself as well as a preparation for and performance of an adequate action associated with the felt emotion²³. This for example involves a behavioral expression such as avoidance behavior if someone experiences fear, or approach behavior if someone experiences happiness²⁴. The lack of a behavioral component in laboratory settings challenges the external validity of experimental results and makes it difficult to transfer findings to, for example, mood disorders for which the associated behavior is of paramount importance.

In conventional settings, this behavioral component is unfortunately difficult to realize either due to the experimental design or the environment in which it takes place, for example in an fMRI scanner or during EEG recordings. The past decade however brought forth novel techniques such as mobile EEGs^{25,26}, mobile fNIRS^{27,28} and less constraining MEGs^{29–31}. These technological advancements have been developed and optimized to allow for the investigation of neural correlates in settings of high ecological validity as the participants can move freely and be tested outside the lab. While the number of publications using these techniques are still sparse, a growing body of research is being generated converging neuroscientific research with real-life activities such as cycling^{32,33}, walking³⁴, navigating over obstacles³⁵, real world driving³⁶, viewing real-life faces in natural settings³⁷ or skateboarding³⁸. Recently, Packheiser and colleagues³⁹ investigated the neural basis of hand and foot use while the participants were wearing a mobile EEG. They found that both alpha and beta frequency asymmetries were predictive of the participants' handedness and footedness and that the neural signals could distinguish between limb preferences of individuals. Importantly, they found that the neural signals were unaffected by movement parameters during activities such as jumping or throwing and kicking balls. Thus, mobile EEGs provide a valuable tool to investigate the neural basis of human emotions and their associated behaviors in more natural settings.

A very prominent human behavior that is usually executed in emotional settings is social touch. To convey our social intentions or emotional states to other humans, we strongly rely on the use of a variety of tactile interactions, especially in very intimate social relationships^{40,41}. Touch is the earliest sensory modality to fully develop during the lifespan⁴² and is experienced from birth onwards by being cradled in the mother's arms⁴³. For that reason, social touch has been strongly associated with human development, shaping attachment, emotional regulation and cognitive maturation⁴⁴. Affective social touch has been demonstrated to be highly beneficial for the well-being and physical as well as mental health in humans as it reduces stress, blood pressure and can even protect from viral infections and allergic responses^{45–48}. Studies on the neural basis of social touch have indicated that somatosensory cortices⁴⁹ but also limbic or orbitofrontal brain regions are activated when an experimenter or the romantic partner applies non-sexual pleasant tactile stimulation^{50–52}. Thus, there seems to be a strong overlap in cerebral processing of social touch and emotions indicating that social touch carries a strong affective component. However, as for studies investigating emotions, the experimental designs investigating the neural basis of social touch lack ecological validity as the application of gentle touch to for example the legs while lying perfectly still rarely occurs in real-life settings.

The aim of the present study was to investigate emotional lateralization in a setting with high ecological validity. To this end, we tested romantic partners in their home during both embracing and kissing while the participants were recorded using a mobile EEG system. We also investigated the neural correlates of emotional speech as this type of social interaction is fundamental to maintain a healthy and long-lasting relationship⁵³. We focused on differences in asymmetrical processing in the alpha frequency band due to the pronounced role of frontal alpha asymmetries in emotional processing. Since beta power asymmetries have been demonstrated to be highly comparable in function to alpha power asymmetries in studies investigating motor preferences³⁹ and resting state oscillations⁵⁴, we also included beta power asymmetries as a dependent variable in our study. For each behavioral task (embracing, kissing and speech), we employed a positive and a neutral condition. We hypothesize that emotional lateralization differs between the emotional and neutral condition. If the right-hemisphere hypothesis holds true, we expect stronger right-hemispheric activity in the emotional compared to the neutral condition. If the valence hypothesis holds true, we expect stronger left-hemispheric activity in the emotional compared to the neutral condition.

Methods

Participants. A total of 32 individuals (16 females) took part in this study. The sample size was determined based on prior studies investigating frontal alpha asymmetries using within-subject designs producing reliable and large effects (Cohen's $d = 1.04^{55}$; $\eta_p^2 = 0.36^{56}$). There was no restriction regarding the sexuality of the participants, but all couples were heterosexual in the present study. Age of the participants ranged between 19 and 63 years (mean age = 29 years, SD = 14 years). Participants with neurological or psychiatric disorders were excluded from the study. The study was conducted in accordance with the declaration of Helsinki and was approved by a local ethics committee of the psychological faculty at Ruhr University Bochum. All participants gave written informed consent. Five participants were excluded from the PANAS analysis of the emotional induction and one participant was excluded from the EEG analysis of the behavioral tasks due to technical issues. In total, this left 27 data sets for the PANAS and 31 data sets eligible for EEG data analysis in the final analysis sample. There was no overlap between excluded participants from the PANAS and the EEG data.

Experimental task. The experimental paradigm consisted of conducting three behavioral tasks, i.e. embracing, kissing and listening to speech in both an emotional and neutral condition. The neutral condition

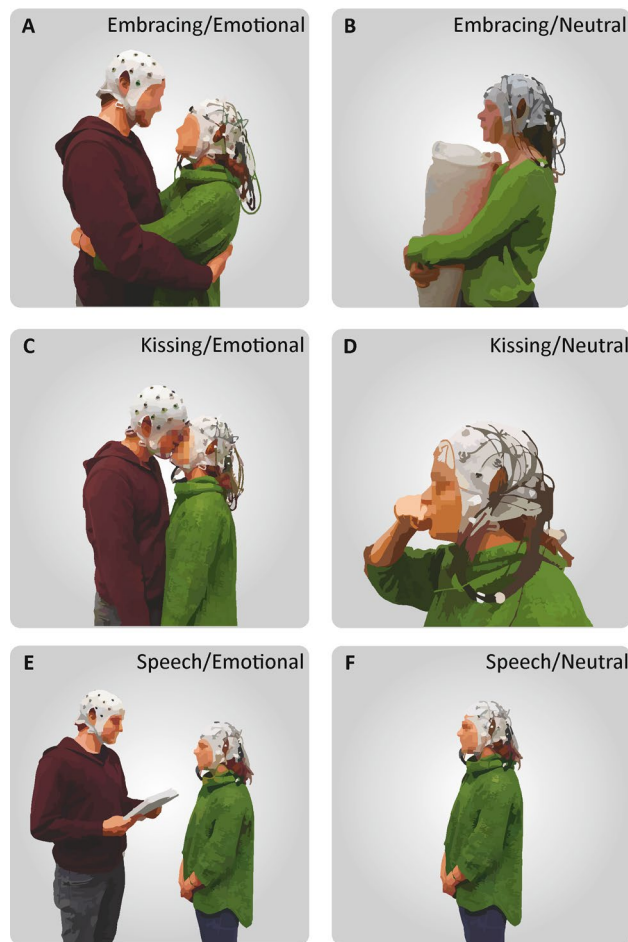


Figure 1. Depiction of the behavioral tasks. **(A)** During the emotional condition, the participant wearing the mobile EEG system embraced his/her partner in a frontal embrace. **(B)** During the neutral condition, the participant embraced a pillow with the partner absent. **(C)** In the emotional kissing condition, the partners kissed each other without using their tongue. **(D)** During the neutral condition, the recorded participant performed a kiss with his or her own hand. **(E)** In the emotional speech condition, the recorded participant listened to an emotional text written by their partner prior to the session about shared life experiences. **(F)** In the neutral speech condition, the recorded participant listened to a pre-recorded weather report without the partner.

served as a control condition and was conducted using identical movements to control for motor effects in the experiment. Testing took place in the participants' homes to provide as much natural setting and ecological validity as possible. One participant was set up with the mobile EEG system while the other participant filled out demographic questionnaires, the relationship assessment scale (RAS) and prepared an emotional text about fond memories and experiences with their partner. Importantly, the partner, that was not recorded, was also equipped with an electrode cap to reduce the awkwardness of only one partner wearing the cap. Next, the participants were instructed about the behavioral tasks and how to perform them appropriately by the experimenter and an illustrating photograph. After instructing the participants, the experimenter left the room to allow for privacy for the entire experimental procedure. The behavioral tasks looked as follows:

1. During the embracing condition, the participants were either asked to embrace each other from the front in the emotional condition (Fig. 1A), or embrace a body pillow in the neutral condition with the partner being absent (Fig. 1B). The participants were further instructed to avoid touching the electrode cap and move as little as possible during the embrace.
2. During the kissing condition, the participants were either asked to kiss each other on the lips in the emotional condition (Fig. 1C), or kiss their own hand during the neutral condition by forming a lip-like structure with the thumb and index finger with the partner being absent (Fig. 1D). Importantly, the participants were instructed not to use their tongue during the kiss in either condition to avoid strong motor artifacts.
3. During the speech condition, the participant wearing the mobile EEG system was either listening to the partner reading the previously prepared emotional text in the emotional condition (Fig. 1E), or was listen-

ing to a weather report that was recorded prior to the experimental session in the neutral condition with the partner being absent (Fig. 1F).

The experimental design was counterbalanced so that the experiment could start with the neutral or emotional condition and with the male or female partner being recorded initially. Furthermore, during the emotional and neutral condition, the order of behavioral tasks was fully randomized. Each behavioral task was performed for 1 min in total and the tasks were separated by an intertrial interval (ITI) of 30 s in accordance with the procedures used in Packheiser et al.³⁹. During the ITI, the participant(s) received an additional pre-recorded auditory and visual instruction about the upcoming behavioral task. This was necessary as it was unknown to the participant(s) if the procedure started with embracing, kissing or speech due to the randomization procedure. The instructions were presented using the Presentation software (Neurobehavioral Systems Inc., CA, USA). There was a 5 min break between the emotional and neutral condition to fill out the Positive and Negative Affect Schedule (PANAS), a questionnaire evaluating their positive and negative affective states by indicating the current emotional state on 10 positive and 10 negative items on a scale from 1 (Very slightly or not at all) to 5 (Extremely)⁵⁷. The break was also used to allow for the partner to leave or to join (depending whether the recorded partner was in the emotional or neutral condition, respectively). We deliberately chose to let the partner leave the room in the neutral conditions to account for potential confound variables such as social support and non-verbal communication between the partners.

After one participant had completed the experimental procedure (three emotional and three neutral tasks), the recorded partner again filled out the PANAS so that the affective state was measured after both the emotional and neutral condition. Afterward, the roles of the partners switched, and the non-recorded partner went through the identical experimental protocol.

EEG recording, preprocessing and analysis. EEG signals were obtained with a mobile EEG recording system (LiveAmp 32, Brain Products GmbH, Gilching, Germany). The LiveAmp 32 comprises 32 Ag–AgCl electrodes arranged in the international 10–20 system (C3/C4, FP1/FP2, Fz, F3/F4, F7/F8, FCz, FC1/FC2, FC5/FC6, FT9/FT10, T7/T8, CP1/CP2, CP5/CP6, TP9/TP10, Pz, P3/P4, P7/P8, Oz and O1/O2). The FCz electrode served as reference signal during data recording. All signals were amplified using a wireless amplifier (analog-to-digital conversion: 24-bit) and recorded using the Brain Vision Analyzer software at a sampling rate of 1 kHz. Impedances were lowered to under 10 kΩ prior to the recording session to ensure good signal quality. The EEG system furthermore comprised three acceleration sensors in the X (mediolateral axis), Y (anteroposterior axis) and Z (dorsoventral axis) direction located at the rear of the skull that recorded movements of the participants' head.

Following data acquisition, the EEG signals were preprocessed offline in Brain Vision Analyzer (Brain Products GmbH, Gilching, Germany). The raw data files were band-pass filtered from 0.1 Hz (high pass) to 30 Hz (low pass) at 24 dB (octave). All signals were manually inspected for technical artifacts and channels of poor recording quality. Systematic artifacts, i.e. horizontal or vertical eye movements as well as pulse-associated signals, were removed via the application of an infomax independent component analysis (ICA). The reference channel (FCz) and channels of insufficient signal quality were recalculated via topographic interpolation.

After preprocessing, the individual tasks were first segmented across the entire trial duration (60 s) and then baseline corrected. The 500 ms prior to task onset were used as baseline signal. The large trial segment was then further divided into 58 non-overlapping segments of 1024 ms duration each. Individual segments were excluded via an automatic artifact rejection if any of the following criteria were met: (1) voltage steps of 50 μV / ms, (2) amplitude differences of more than 200 μV within a 200 ms interval and (3) signal strength below 0.5 μV within a 100 ms interval. In a next step, we applied a current source density (CSD)⁵⁸ transformation to remove the reference potential from the filtered and segmented data. Finally, we used a Fast-Fourier transformation to decompose the oscillatory data into its different frequency bands (Hammond window of 10%). Alpha oscillations were defined in the 8–13 Hz range. Beta frequencies were defined in the 13–30 Hz range. We then calculated the average power density (power per unit bandwidth) per electrode with a bilateral arrangement (C3/C4, FP1/FP2, F3/F4, F7/F8, FC1/FC2, FC5/FC6, FT9/FT10, T7/T8, CP1/CP2, CP5/CP6, TP9/TP10, P3/P4, P7/P8 and O1/O2) and extracted it for the three tasks across both conditions individually. In a final step, asymmetry indices (AIs) were computed between the electrode pairs using the following formula in accordance with Ocklenburg et al.⁵⁴:

$$AI = \ln(\text{power right}) - \ln(\text{power left})$$

Statistical analysis. Statistical analyses were conducted using SPSS (version 21, Chicago, Illinois, USA). The PANAS scores were evaluated using a two-factorial repeated measures ANOVA with the factor valence (two levels: average score for all positive and all negative items) and the factor condition (two factors: emotional and neutral). Post hoc testing was performed using a Bonferroni correction. Neural data was analyzed separately for the three behavioral tasks. We investigated differences in AIs in the alpha and beta frequency band on all electrode-pairs for which they could be computed, i.e. for all non-central electrodes. We computed a two-factorial repeated measures ANOVA with each individual electrode pair as the first factor (14 levels: C3/C4, FP1/FP2, F3/F4, F7/F8, FC1/FC2, FC5/FC6, FT9/FT10, T7/T8, CP1/CP2, CP5/CP6, TP9/TP10, P3/P4, P7/P8 and O1/O2) and the experimental condition as second factor (two levels: emotional and neutral). Again, post hoc comparisons were conducted using a Bonferroni correction. For all analyses, we also used sex as a between-subject variable to identify sex-related interactions. Since partners were tested consecutively rather than in parallel, we also used the sequence of testing as a between-subject variable to exclude any effects of testing order. If a significant

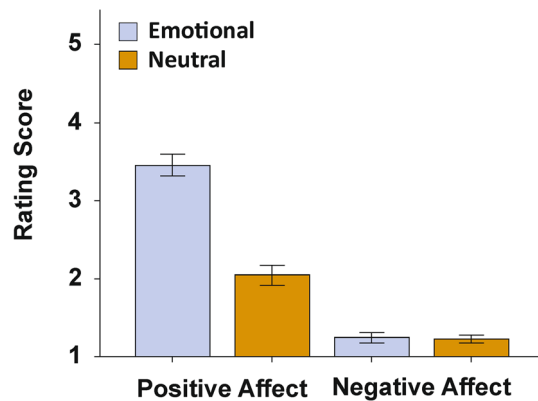


Figure 2. PANAS ratings indicating the momentary emotional state following the emotional or the neutral experimental condition. Error bars represent SEM.

difference between the emotional and neutral condition could be detected on a specific electrode pair, we furthermore correlated this difference with the affectivity score from the RAS questionnaire. To identify movement-related differences between the conditions, we extracted the acceleration sensor signals on the X-, Y- and Z-axis during the emotional and neutral condition. A two-factorial repeated measures ANOVA was performed with the factor orientation (three levels, X, Y and Z) and condition (two levels: emotional and neutral).

Results

Emotional induction. First, we investigated whether our emotional condition elicited more positive affective states compared to the neutral conditions using the PANAS scores. The results of the PANAS questionnaire were evaluated by comparing the average value of all positive and all negative items between the emotional and neutral condition in a 2×2 ANOVA. We found significant main effects of valence ($F_{(1,26)} = 329.72$, $p < 0.001$, $\eta_p^2 = 0.93$) and condition ($F_{(1,26)} = 72.42$, $p < 0.001$, $\eta_p^2 = 0.74$) with the positive items being rated higher (mean score = 2.75) than the negative items (mean score = 1.24) and the emotional condition receiving higher ratings (mean score = 2.35) compared to the neutral condition (mean score = 1.64). We found a significant interaction between item valence and the experimental conditions ($F_{(1,26)} = 54.07$, $p < 0.001$, $\eta_p^2 = 0.68$, see Fig. 2). Bonferroni-corrected post-hoc tests revealed significantly higher positive affect in the emotional (mean score = 3.46, SEM = 0.14) compared to the neutral condition (mean score = 2.05, SEM = 0.13, $p < 0.001$). Negative affect did not differ between the conditions ($p > 0.250$) and was basically absent in both the emotional (mean score = 1.23, SEM = 0.05) and the neutral condition (mean score = 1.25, SEM = 0.07).

Alpha power asymmetries. To investigate differences in neural processing between the emotional and neutral condition, we investigated changes in AIs between the conditions for all three behavioral tasks individually in a 2 (factor condition) \times 14 (factor electrode pair) ANOVA. For the embracing condition, we found neither a significant main effect of condition ($F_{(1,30)} = 2.39$, $p = 0.133$, $\eta_p^2 = 0.07$), nor a significant interaction between condition and electrode pairs ($F_{(13,390)} = 0.61$, $p > 0.250$, $\eta_p^2 = 0.02$, Fig. 3A). The interaction between condition, electrode pairs and sex did not reach significance ($F_{(13,377)} = 0.73$, $p > 0.250$, $\eta_p^2 = 0.03$). For the kissing condition, we found no significant main effect of condition ($F_{(1,30)} = 0.38$, $p > 0.250$, $\eta_p^2 = 0.01$), but a significant interaction between condition and electrode pairs ($F_{(13,390)} = 1.76$, $p = 0.048$, $\eta_p^2 = 0.06$). Bonferroni corrected post hoc testing revealed a significantly higher asymmetry index on the FP1/FP2 electrode pair in the emotional (mean $\mu V^2/Hz = 0.24$, SEM = 0.10) compared to the neutral condition (mean $\mu V^2/Hz = -0.05$, SEM = 0.10, $p = 0.043$, Fig. 3B). The interaction between condition, electrode pairs and sex did not reach significance ($F_{(13,377)} = 1.55$, $p = 0.096$, $\eta_p^2 = 0.05$). For the speech condition, we found no significant main effect of condition ($F_{(1,30)} = 0.94$, $p > 0.250$, $\eta_p^2 = 0.03$), but a significant interaction between condition and electrode pair ($F_{(13,390)} = 2.28$, $p = 0.007$, $\eta_p^2 = 0.07$). Bonferroni corrected post hoc testing revealed a significantly lower asymmetry index on the P7/P8 electrode pair in the emotional (mean $\mu V^2/Hz = -0.06$, SEM = 0.08) compared to the neutral condition (mean $\mu V^2/Hz = 0.18$, SEM = 0.06, $p = 0.022$, Fig. 3C). The interaction between condition, electrode pairs and sex did not reach significance ($F_{(13,377)} = 1.57$, $p = 0.091$, $\eta_p^2 = 0.05$). There were no significant results for sequence. Correlations with RAS scores did not reach significance for any behavioral task.

Beta power asymmetries. We repeated the analysis conducted for the alpha frequency band in the beta frequency band. For the embracing condition, we found neither a significant main effect of condition ($F_{(1,30)} = 3.58$, $p = 0.068$, $\eta_p^2 = 0.11$), nor a significant interaction between condition and electrode pairs ($F_{(13,390)} = 1.49$, $p = 0.118$, $\eta_p^2 = 0.05$, Fig. 4A). The interaction between condition, electrode pairs and sex reached significance ($F_{(13,377)} = 1.98$, $p = 0.021$, $\eta_p^2 = 0.06$). Here, males showed a higher asymmetry index on the F7/F8 and the FT9/FT10 electrode pairs in the emotional (mean $\mu V^2/Hz = 0.21$, SEM = 0.18) compared to the neutral condition (mean $\mu V^2/Hz = -0.40$, SEM = 0.17, $p = 0.005$). Similarly, males showed a higher asymmetry index on the FT9/FT10 electrode pair on the emotional (mean $\mu V^2/Hz = 0.17$, SEM = 0.13) compared to the neutral con-

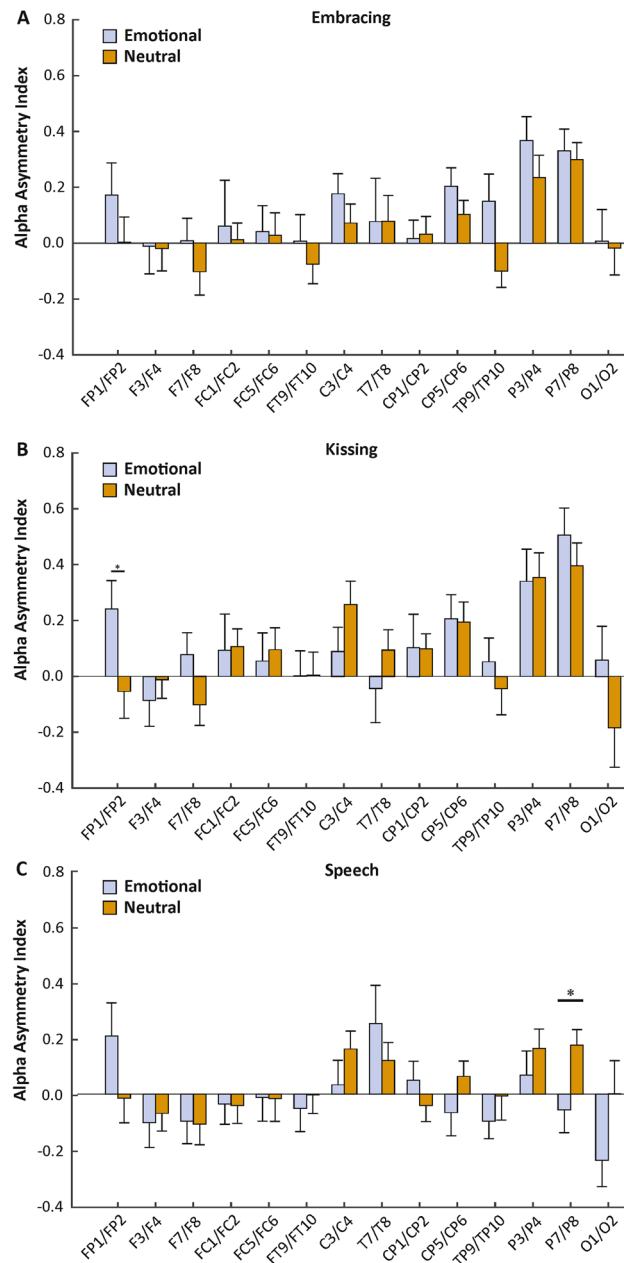


Figure 3. Electrode-specific analysis of alpha power asymmetries during the three behavioral tasks (A: Embracing, B: Kissing, C: Speech) in the emotional and neutral conditions. Error bars represent SEM.

dition (mean $\mu V^2/Hz = -0.07$, SEM = 0.09, $p = 0.017$). No difference could be detected for female participants. For the kissing condition, we found no significant main effect of condition ($F_{(1,30)} = 1.89$, $p = 0.189$, $\eta_p^2 = 0.06$), but a significant interaction between condition and electrode pairs ($F_{(13,390)} = 2.57$, $p = 0.002$, $\eta_p^2 = 0.08$). Bonferroni corrected post hoc testing revealed a significantly higher asymmetry index on the FP1/FP2 electrode pair in the emotional (mean $\mu V^2/Hz = 0.25$, SEM = 0.09) compared to the neutral condition (mean $\mu V^2/Hz = -0.10$, SEM = 0.09, $p = 0.007$). Furthermore, there was a significantly higher asymmetry index on the F7/F8 electrode pair in the emotional (mean $\mu V^2/Hz = -0.04$, SEM = 0.10) compared to the neutral condition (mean $\mu V^2/Hz = -0.49$, SEM = 0.14, $p = 0.011$, Fig. 4B). Finally, we found a significantly higher asymmetry index on the O1/O2 electrode pair in the emotional (mean $\mu V^2/Hz = 0.11$, SEM = 0.12) compared to the neutral condition (mean $\mu V^2/Hz = -0.25$, SEM = 0.15, $p = 0.024$). The interaction between condition, electrode pairs and sex did not reach significance ($F_{(13,377)} = 1.57$, $p = 0.092$, $\eta_p^2 = 0.05$). For the speech condition, we found no significant main effect of condition ($F_{(1,30)} = 0.92$, $p > 0.250$, $\eta_p^2 = 0.03$), but a significant interaction between condition and electrode pair ($F_{(13,390)} = 2.41$, $p = 0.004$, $\eta_p^2 = 0.07$). Bonferroni corrected post hoc testing revealed a significantly higher asymmetry index on the FP1/FP2 electrode pair in the emotional (mean $\mu V^2/Hz = 0.22$, SEM = 0.10) compared to the neutral condition (mean $\mu V^2/Hz = -0.08$, SEM = 0.11, $p = 0.016$). Furthermore, there was a significantly higher asymmetry index on the F7/F8 electrode pair in the emotional (mean $\mu V^2/Hz = -0.06$, SEM = 0.13) compared to

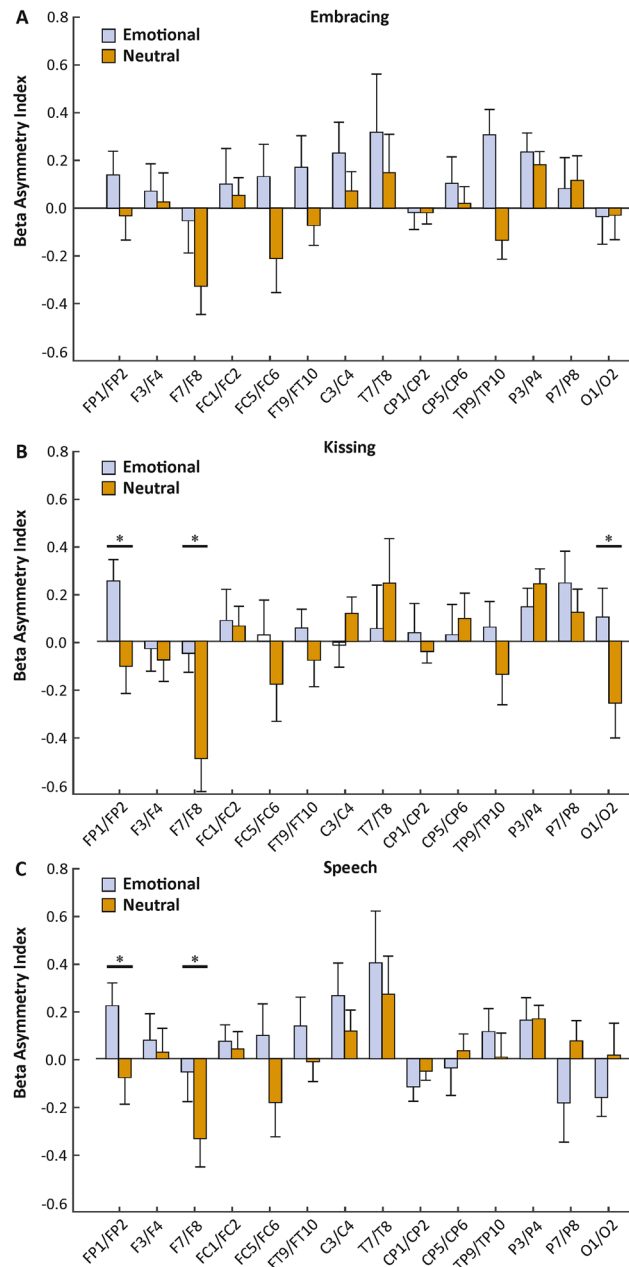


Figure 4. Electrode-specific analysis of beta power asymmetries during the three behavioral tasks (A: Embracing, B: Kissing, C: Speech) in the emotional and neutral conditions. Error bars represent SEM.

the neutral condition (mean $\mu V^2/Hz = -0.34$, SEM = 0.12, $p = 0.047$, Fig. 4C). The interaction between condition, electrode pairs and sex did not reach significance ($F_{(13,377)} = 1.09$, $p > 0.250$, $\eta_p^2 = 0.04$). There were no significant results for sequence. Correlations with RAS scores did not reach significance for any behavioral task.

Acceleration sensors. To identify whether the emotional condition was associated with stronger movement, we compared the acceleration sensor signals between the emotional and neutral condition for each behavioral task. To this end, we computed 2×3 ANOVA with the factors condition (two levels: emotional and neutral) and orientation (three levels: X, Y, and Z-axis). For embracing, we found no main effect of condition ($F_{(1,30)} = 4.15$, $p = 0.051$, $\eta_p^2 = 0.12$), nor an interaction with the movement orientation ($F_{(2,60)} = 1.93$, $p = 0.154$, $\eta_p^2 = 0.06$, see Fig. 5A). For kissing, the results were comparable as we also did not detect a main effect of condition ($F_{(1,30)} = 1.01$, $p > 0.250$, $\eta_p^2 = 0.03$), nor an interaction with the movement orientation ($F_{(2,60)} = 0.08$, $p > 0.250$, $\eta_p^2 = 0.003$, see Fig. 5B). Finally, the speech condition also did not yield any significant main effect of condition ($F_{(1,30)} = 0.57$, $p > 0.250$, $\eta_p^2 = 0.02$), nor an interaction with the movement orientation ($F_{(2,60)} = 1.20$, $p > 0.250$, $\eta_p^2 = 0.04$, see Fig. 5C). Grand averages of the movement signals split by frequency band (alpha, beta, gamma, delta) for the three behavioral tasks are depicted in SI Fig. 1.

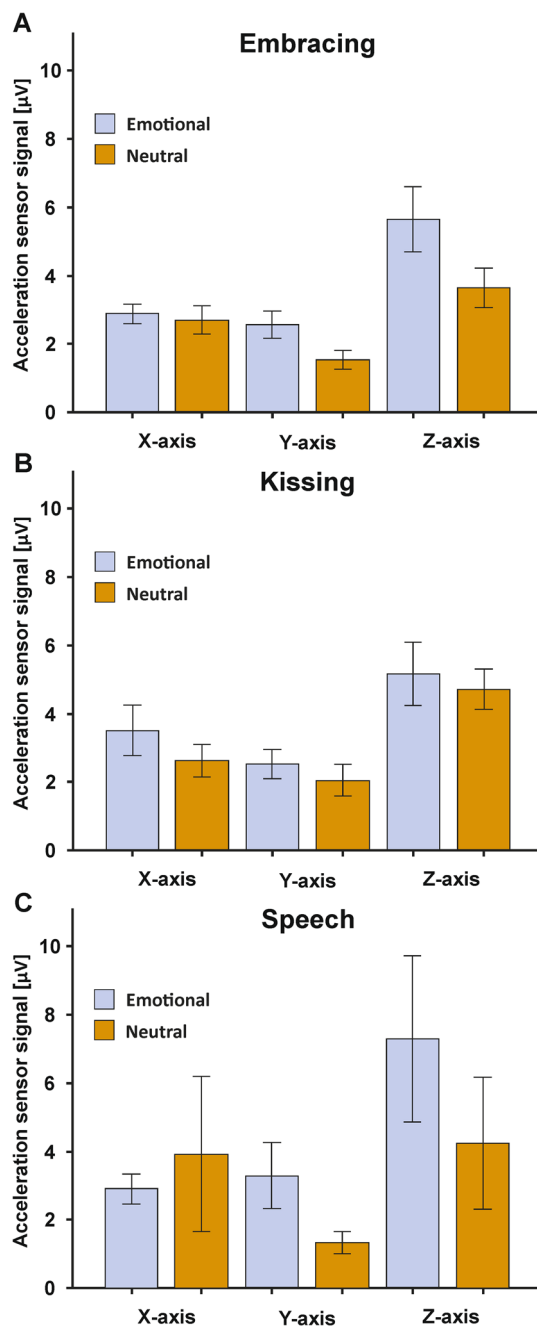


Figure 5. Acceleration sensor signals in the embracing (A), kissing (B) and speech condition (C) for the X-, Y- and Z-axis orientation. Error bars represent SEM.

Artifact rejection. To assess whether there was a difference in rejected segments between the emotional and neutral condition, we conducted a 2×3 ANOVA with the factors condition (two levels: emotional and neutral) and behavioral task (three levels: embracing, kissing and speech). We found a significant main effect of condition ($F_{(1,30)} = 31.57, p < 0.001, \eta_p^2 = 0.51$) with the emotional condition having less segments left for analysis following the automatic artifact rejection (mean segments = 45.24, SEM = 1.69) compared to the neutral condition (mean segments = 54.53, SEM = 0.88). Furthermore, we found an interaction between the factors condition and behavioral task ($F_{(2,60)} = 4.03, p = 0.023, \eta_p^2 = 0.12$). There were less segments left to analyze for the emotional speech (mean segments = 41.07, SEM = 2.98) compared to emotional embrace condition (mean segments = 48.00, SEM = 1.61, $p = 0.028$).

Discussion

In the present study, we used a mobile EEG to record brain activity of romantic partners during affective social touch and emotional speech in their everyday environment to provide high ecological validity. We specifically focused on asymmetries in our analysis due to the pronounced lateralization of emotional processing in the brain. We found that the participants were in a more positive mood after they executed the behavioral tasks with their respective partner. On the neural level, we found a higher alpha AIs on the FP1/FP2 electrode pair in the emotional compared to the neutral condition during kissing. For speech, we found a lower alpha AI in the emotional compared to the neutral condition on the P7/P8 electrode pair. In the beta frequency band, we found higher AIs in the emotional compared to the neutral condition on the F7/F8 and FT9/FT10 electrodes only for males in the embracing condition. Across both sexes, we found higher AIs in the emotional compared to the neutral condition on the FP1/FP2 and F7/F8 electrode pair during both kissing and emotional speech. Furthermore, there was an increased AI on the O1/O2 electrode pair during the emotional compared to the neutral condition during emotional kisses. Movement signals did not differ between the emotional and neutral condition.

Increases in oscillatory alpha power have been strongly associated with functional inhibition, for example during visuospatial attention^{59,60}, face recognition⁶¹ and working memory tasks⁶². Alpha oscillations are hypothesized to be generated by rhythmic burst of local inhibitory GABAergic interneurons⁶². Increases in AIs are therefore indicative of stronger right-hemispheric inhibition or increased left frontal activity whereas decreases in AIs reflect stronger left hemispheric inhibition or right-hemispheric activation. Thus, the frontal increase in alpha power asymmetries during emotional compared to neutral kisses indicates that frontal regions of the left hemisphere were more strongly activated in the presence of strong positive affect. These results are in line with the VM of emotional lateralization which postulates that positive emotions are processed in the left hemisphere and oppose predictions made by the RHH claiming that all emotions are processed in the right hemisphere irrespective of valence. Interestingly, previous behavioral research on the effects of emotional context on the lateralization of social behavior has indicated that the RHH provides the overall best prediction to explain changes in laterality in emotional compared to neutral situations^{63–65}. Prete and colleagues⁶⁶ similarly found that behavioral and neural findings regarding hemispheric asymmetries were incongruent and do not necessarily correspond. It should be noted however that the VM and RHH are not necessarily mutually exclusive⁶⁷. Killgore and Yurgelun-Todd⁶⁸ have proposed an integrative model postulating that the VM provides accurate predictions for anterior or frontal asymmetries whereas posterior or parietal asymmetries are more in line with predictions of the RHH. Since we could find lower asymmetry scores during emotional compared to neutral speech on the P7/P8 electrode pair indicating stronger right-hemispheric activation in the emotional condition, our results corroborate that emotional lateralization does not seem to be uniform across cortical brain regions but is rather region-specific.

For asymmetries in the beta frequency band, we found mostly comparable and sometimes even larger effects compared to the alpha band. Opposed to oscillatory alpha power, the functional role of the beta frequency band has been rather inconclusive. While some studies have suggested that beta activity is indicative of cognitive activation^{69,70}, beta power has also been suggested to be associated with the function of inhibitory interneuron networks indicating that alpha and beta activity share similar characteristics⁷¹. In a previous mobile EEG study investigating alpha and beta asymmetries during motor execution, we also found that alpha and beta asymmetries were functionally similar and associated with inhibition³⁹. Ocklenburg et al.⁵⁴ even found that alpha, beta, delta and theta oscillations were all significantly correlated indicating that there might be some common function underlying rhythmic brain activity in general. In contrast to alpha power however, beta asymmetries did not reveal decreased AIs on occipital electrodes during the emotional kiss, but rather increased AIs comparable to frontal electrodes. Thus, while there are evidently similarities between alpha and beta power, they are not simply functionally identical. These findings suggest that beta power asymmetries should be investigated more thoroughly in the future to clearly identify the functional role of beta asymmetries in the brain.

Opposed to the kissing and speech condition, we could not find any overall effects in the alpha or beta frequency band for the embracing condition. One potential explanation for this lack of a finding relates to the fact that in contrast to long lasting kisses or emotional speech, embraces take place frequently between platonic friends and even unfamiliar individuals⁴³. Thus, the emotional condition might have lacked a strong affective component as embraces are not a partner-specific interaction eliciting strong emotional responses. Furthermore, embraces are usually shorter than the 1-min interval employed in our experiment⁷², which was necessary for reliable data acquisition. The unusually long duration could have negatively influenced our results in this experiment. Interestingly, we however found a sex-specific effect in the beta frequency band with only males displaying higher asymmetry indices over frontal electrode sites. It could be speculated that males experienced the embrace more emotionally because they engage in embraces less often in everyday life as compared to females, especially in close male-male relationships⁷³.

An important issue that needs to be addressed are potential effects of eye movements that might have affected our present results since eye movements were not captured by the acceleration sensors. While ICA algorithms can reduce eye movement artefacts, results over FP1/FP2 electrodes still raise suspicions. We however firmly believe that eye movements did not influence the present findings for two major reasons: first, the calculation of asymmetry indices likely cancels out all ocular artefacts due to eye movements and occurring for both eyes simultaneously during blinks. Since signals from the left hemisphere are subtracted from right hemisphere signals, all residual artefacts should have been eliminated by this computation. Second, our individual segments were not time-locked to a trial start since we investigated 1 min of oscillatory data for each behavioral task in each condition. We then segmented this data and averaged it. This procedure likely averages out any remaining ocular signals as they occur randomly across the trial length.

Given the relative novelty of the approach and the experimental paradigm, there are several limitations associated with the present study. First, the sample size of the study was rather low even for a within-subject design.

Thus, it might have prevented the detection of smaller effects due to insufficient power. Second, the present paradigm employed no negative emotional condition due to both practical reasons (difficulty to artificially induce negative emotions during embraces and kisses) and ethical reasons (possible tension arising in the relationship). Unfortunately, the lack of a negative emotional condition does not allow to conclusively embed our results into theories of emotional lateralization as the valence hypothesis distinguishes between positive and negative rather than positive and neutral affective states. Finally, we could not investigate brain-to-brain synchrony between both partners as there was only one mobile EEG system available.

In conclusion, we found differences in alpha power asymmetries during emotional compared to neutral conditions in highly ecological situations that are congruent with models of emotional lateralization integrating frontal valence and posterior right-hemispheric processing. To provide conclusive evidence in this regard, future studies should however conceive a similar experiment and include a negative emotional condition (e.g. listing annoying habits of the partner) that was not present in this study. Additionally, future studies should investigate beta frequencies in more detail as the functional role does not seem to be identical compared to alpha frequencies. Furthermore, the ecological validity of the present study is rather limited to couples from Western societies. For kissing, there are notable differences in both frequency and lateralization based on the context^{74–76}, especially for cultural contexts⁷⁷. Similar results have been found for the frequently observed left cradling bias of children^{78,79}. Thus, it would be interesting to see if cultural differences in social behavior are reflected in altered neurophysiological processing of these types of interactions. Finally, there was little variance in relationship satisfaction in our sample. Future studies could replicate similar experimental designs, but specifically invite participants from both happy and unhappy relationships to identify possible differences due to the difference in affectivity.

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Author contributions

J.P. and G.B. conceived the study, analyzed the data and wrote the manuscript. N.R. consulted on analyses and reviewed the manuscript. L.S. and C.B. collected data and reviewed the manuscript. O.G. provided materials and reviewed the manuscript. S.O. conceived the study, consulted on data analyses and reviewed the manuscript.

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