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 regulation9,10. 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 regulation12,13.

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. This holds especially true for emotion research as the most prevalent method of positive or negative emotional induction is via movies, pictures or music. 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 emotion. This for example involves a behavioral expression such as avoidance behavior if someone experiences fear, or approach behavior if someone experiences happiness. 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, mobile fNIRS and less constraining MEGs. 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, walking, navigating over obstacles, real world driving, viewing real-life faces in natural settings or skateboarding. Recently, Packheiser and colleagues 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 limbs preferred by individuals. Importantly, they found several 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. Touch is the earliest sensory modality to fully develop during the lifespan and is experienced from birth onwards by being cradled in the mother’s arms. For that reason, social touch has been strongly associated with human development, shaping attachment, emotional regulation and cognitive maturation. 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. Studies on the neural basis of social touch have indicated that somatosensory cortices but also limbic or orbitofrontal brain regions are activated when an experimenter or the romantic partner applies non-sexual pleasant tactile stimulation. 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 relationship. 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 preferences and resting state oscillations, 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 $d = 1.04^{36}$; $\eta_p^2 = 0.36^{36}$). 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
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, T7/T8, FCz, FC1/FC2, FC5/FC6, FT9/FT10, T7/T8, C1/C2, CP5/CP6, TP9/TP10, Pz, P3/P4, P7/P8, 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)65 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, C1/C2, 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:

\[ AI = \ln (power \ right) - \ln (power \ left) \]

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, C1/C2, 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
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. For the embracing condition, we found neither a significant main effect of condition (F(1,30) = 2.39, p = 0.133, η² = 0.07), nor a significant interaction between condition and electrode pairs (F(1,1390) = 0.61, p > 0.250, ηᵖ² = 0.02, Fig. 3A). The interaction between condition, electrode pairs and sex did not reach significance (F(1,377) = 0.73, p > 0.250, ηᵖ² = 0.03). For the kissing condition, we found no significant main effect of condition (F(1,30) = 0.38, p > 0.250, ηᵖ² = 0.01), but a significant interaction between condition and electrode pairs (F(1,1390) = 1.76, p = 0.048, ηᵖ² = 0.06). Bonferroni-corrected post-hoc tests revealed a significantly higher asymmetry index on the FP1/FP2 electrode pair 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) × 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, η² = 0.07), nor a significant interaction between condition and electrode pairs (F(1,1390) = 0.61, p > 0.250, ηᵖ² = 0.02, Fig. 3A). The interaction between condition, electrode pairs and sex did not reach significance (F(1,377) = 1.55, p = 0.096, ηᵖ² = 0.05). For the speech condition, we found no significant main effect of condition (F(1,30) = 0.94, p > 0.250, ηᵖ² = 0.03), but a significant interaction between condition and electrode pairs (F(1,1390) = 2.28, p = 0.007, ηᵖ² = 0.07). Bonferroni-corrected post hoc testing revealed a significantly lower asymmetry index on the P7/P8 electrode pair in the emotional (mean µV²/Hz = −0.24, SEM = 0.10) compared to the neutral condition (mean µV²/Hz = 0.05, SEM = 0.06, p = 0.022, Fig. 3C). The interaction between condition, electrode pairs and sex did not reach significance (F(1,377) = 1.57, p = 0.091, ηᵖ² = 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, η² = 0.11), nor a significant interaction between condition and electrode pairs (F(1,1390) = 1.49, p = 0.118, ηᵖ² = 0.05, Fig. 4A). The interaction between condition, electrode pairs and sex reached significance (F(1,377) = 1.98, p = 0.021, ηᵖ² = 0.06). Here, males showed a higher asymmetry index on the F7/F8 and the FT9/FT10 electrode pairs in the emotional (mean µV²/Hz = 0.21, SEM = 0.18) compared to the neutral condition (mean µV²/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 µV²/Hz = 0.17, SEM = 0.13) compared to the neutral con-
dition (mean μV^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, ƞp^2 = 0.06), but a significant interaction between condition and electrode pairs (F(13,390) = 2.57, p = 0.002, ƞp^2 = 0.08). Bonferroni corrected post hoc testing revealed a significantly higher asymmetry index on the FP1/FP2 electrode pair in the emotional (mean μV^2/Hz = 0.25, SEM = 0.09) compared to the neutral condition (mean μV^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 μV^2/Hz = −0.04, SEM = 0.10) compared to the neutral condition (mean μV^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 μV^2/Hz = 0.11, SEM = 0.12) compared to the neutral condition (mean μV^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, ƞp^2 = 0.05). For the speech condition, we found no significant main effect of condition (F(1,30) = 0.92, p > 0.250, ƞp^2 = 0.03), but a significant interaction between condition and electrode pair (F(13,390) = 2.41, p = 0.004, ƞp^2 = 0.07). Bonferroni corrected post hoc testing revealed a significantly higher asymmetry index on the FP1/FP2 electrode pair in the emotional (mean μV^2/Hz = 0.22, SEM = 0.10) compared to the neutral condition (mean μV^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 μV^2/Hz = −0.06, SEM = 0.13) compared to

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.
the neutral condition (mean µV^2/Hz = −0.34, SEM = 0.12, \( p = 0.047 \), Fig. 4C). The interaction between condition, electrode pairs and sex did not reach significance (\( F(13,377) = 1.09, p > 0.250, \eta^2_p = 0.04 \)). 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 (\( F(1,30) = 4.15, p = 0.051, \eta^2_p = 0.12 \)), nor an interaction with the movement orientation (\( F(2,60) = 1.93, p = 0.154, \eta^2_p = 0.06 \), see Fig. 5A). For kissing, the results were comparable as we also did not detect a main effect of condition (\( F(1,30) = 1.01, p > 0.250, \eta^2_p = 0.03 \)), nor an interaction with the movement orientation (\( F(2,60) = 0.08, p > 0.250, \eta^2_p = 0.003 \), see Fig. 5B). Finally, the speech condition also did not yield any significant main effect of condition (\( F(1,30) = 0.57, p > 0.250, \eta^2_p = 0.02 \)), nor an interaction with the movement orientation (\( F(2,60) = 1.20, p > 0.250, \eta^2_p = 0.04 \), 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 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.
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 ($F_{(1,30)} = 31.57, p < 0.001, \eta^2_p = 0.51$) 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 ($F_{(2,60)} = 4.03, p = 0.023, \eta^2_p = 0.12$). 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, $p = 0.028$).

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.
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 attention59,60, face recognition61 and working memory tasks62. Alpha oscillations are hypothesized to be generated by a rhythmic burst of local inhibitory GABAergic interneurons63. 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 situations61,65. If the 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 exclusive65. Killgore and Yurgelun-Todd66 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 inhibition 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 activation59,70, beta power has also been suggested to be associated with the function of inhibitory interneuron networks indicating that alpha and beta activity share similar characteristics51. 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 inhibition55. Ocklenburg et al.44 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\cite{74–76}, especially for cultural contexts\cite{77}. Similar results have been found for the frequently observed left cradling bias of children\cite{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 from both happy and unhappy relationships to identify possible differences due to the difference in affectivity.

References

1. Mills, C. K. The cerebral mechanisms of emotional expression. Trans. Coll. Phys. Philadel. 34, 381–390 (1912).
2. Ley, R. G. & Bryden, M. P. Hemispheric differences in processing emotions and faces. Brain Lang. 7, 127–138 (1979).
3. Landis, T., Assal, G. & Perret, E. Opposite cerebral hemispheric superiorities for visual associative processing of emotional facial expressions and objects. Nature 278, 739–740 (1979).
4. Suber, M. & Mckeever, W. F. Differential right hemispheric memory storage of emotional and non-emotional faces. Neuropsychologia 15, 757–768 (1977).
5. Borod, J. C. et al. Right hemisphere emotional perception: Evidence across multiple channels. Neuropsychology 12, 446–458 (1998).
6. Ekmann, P., Davidson, R. J. & Friesen, W. V. The Duchenne smile: Emotional expression and brain physiology. II. J. Pers. Soc. Psychol. 58, 342–353 (1990).
7. Davidson, R. J., Ekmant, P., Baron, C. D., Senulis, J. A. & Friesen, W. V. Approach-withdrawal and cerebral asymmetry: Emotional expression and brain physiology. I. J. Pers. Soc. Psychol. 58, 330–341 (1990).
8. Wager, T. D., Phan, K. L., Libenzon, I. & Taylor, S. F. Valence, gender, and lateralization of functional brain anatomy in emotion: a meta-analysis of findings from neuroimaging. NeuroImage 19, 513–531 (2003).
9. Allen, J. B., Keune, P. M., Schonenberg, M. & Nusslock, R. Frontal EEG alpha asymmetry and emotion: From neural underpinnings and methodological considerations to psychopathology and social cognition. Psychophysiology 55, e13028 (2018).
10. Reznik, S. J. & Allen, J. B. Frontal asymmetry as a mediator and moderator of emotion: An updated review. Psychophysiology 55, e12965 (2018).
11. Hannesdottir, D. K., Duxie, J., Bell, M. A., Ollendick, T. H. & Wolfe, C. D. A longitudinal study of emotion regulation and anxiety in middle childhood: associations with frontal EEG asymmetry in early childhood. Dev. Psychobiol. 52, 197–204 (2010).
12. Papousek, I., Harald Freudenthaler, H. & Schulter, G. Typical performance measures of emotion regulation and emotion perception and frontal EEG asymmetry in an emotional contagion paradigm. Personal. Individ. Differ. 51, 1018–1022 (2011).
13. Minnix, J. A. & Klein, J. P. Neuroticism predicts resting frontal EEG asymmetry variability. Personal. Individ. Differ. 36, 823–832 (2004).
14. Gainotti, G. A historical review of investigations on laterality of emotions in the human brain. J. Hist. Neurosci. 28, 23–41 (2019).
15. Prete, G., Laeng, B. & Tommasi, L. Lateralized hybrid faces: evidence of a valence-specific bias in the processing of implicit emotions. Laterality 19, 439–454 (2014).
16. Demaree, H. A., Everhart, D. E., Youngstrom, E. A. & Harrison, D. W. Brain lateralization of emotional processing: historical roots and a future incorporating “dominance”. Behav. Cogn. Neurosci. Rev. 4, 3–20 (2005).
17. Shamay-Tsoory, S. G. & Mendelsohn, A. Real-life neuroscience: an ecological approach to brain and behavior research. Perspect. Psychol. Sci. 14, 841–859 (2019).
18. Schlabach, L. et al. Toward a second-person neuroscience 1. Behav. Brain Sci. 36, 393–414 (2013).
19. Gross, J. J. & Levenson, R. W. Emotion elicitation using films. Cogn. Emot. 9, 87–108 (1995).
20. Hewig, J. et al. Brief report. Cogn. Emot. 19, 1095–1109 (2005).
21. Hausmann, M., Hodgetts, S. & Eerola, T. Music-induced changes in functional cerebral asymmetries. Brain Cogn. 104, 58–71 (2016).
22. Uhrig, M. K. et al. Emotion elicitation: A comparison of pictures and films. Front. Psychol. 7, 180 (2016).
23. Güntürkün, O. Biologische Psychologie (Hogrefe Verlag, 2019).
24. Ocklenburg, S., Berretz, G., Packheiser, J. & Friedrich, P. Laterality 2020: entering the next decade. Laterality, 1–33 (2020).
25. de Vos, M. & Debener, S. Mobile EEG: towards brain activity monitoring during natural action and cognition. Int. J. Psychophysiol. 91, 1–2 (2014).
26. Gramann, K. et al. Cognition in action: imaging brain/body dynamics in mobile humans. Rev. Neurosci. 22, 593–608 (2011).
27. Holtzer, R. et al. NIRS study of walking and walking while talking in young and old individuals. J. Gerontol. Sci. A Biol. Sci. Med. Sci. 66, 879–887 (2011).
28. Quaresima, V. & Ferrari, M. Functional near-infrared spectroscopy (fNIRS) for assessing cerebral cortex function during human behavior in natural/social situations: A concise review. Organ. Res. Methods 22, 46–68 (2019).
29. Roberts, G. et al. Towards OFM-MEG in a virtual reality environment. NeuroImage 199, 408–417 (2019).
30. Roto, E. et al. Wearable neuroimaging: Combining and contrasting magnetoencephalography and electroencephalography. NeuroImage 201, 116099 (2019).
31. Roto, E. et al. Moving magnetoencephalography towards real-world applications with a wearable system. Nature 555, 657–661 (2018).
32. Scanlon, J. E. M., Townsend, K. A., Cormier, D. L., Kazieck, J. W. P. & Mathewson, K. E. Taking off the training wheels: Measuring auditory P3 during outdoor cycling using an active wet EEG system. Brain Res. 1716, 50–61 (2019).
33. Zink, R., Hunyadi, B., van Huffel, S. & de Vos, M. Mobile EEG on the bike: disentangling attentional and physical contributions to auditory attention tasks. J. Neural Eng. 13, 46017 (2016).
34. Lin, W. et al. Sitting or walking? Analyzing the neural emotional indicators of urban space behavior with mobile EEG. J. Urban Health 97, 191–203 (2020).
35. Nordin, A. D., Hairston, W. D. & Ferris, D. P. Human electrocortical dynamics while stepping over obstacles. Sci. Rep. 9, 4693 (2019).
36. Protzak, J. & Gramann, K. Investigating established EEG parameter during real-world driving. Front. Psychol. 9, 2289 (2018).
37. Soto, V. et al. Brain responses to emotional faces in natural settings: A wireless mobile EEG recording study. Front. Psychol. 9, 2003 (2018).
38. Robles, D. et al. Attention in Motion: Using an Oddball Task to Record Brain Activity in Skateboarders (2020).
39. Packheiser, J. et al. Using mobile EEG to investigate alpha and beta asymmetries during hand and foot use. Front. Neurosci. 14, 109 (2020).
40. Frith, C. D. & Frith, U. Social cognition in humans. Current Bio. CB 17, R724–R732 (2007).
41. Dunbar, R. I. M. The social role of touch in humans and primates: behavioural function and neurobiological mechanisms. Neurosci. Biobehav. Rev. 34, 260–268 (2010).
42. Maurer, D. & Maurer, C. The World of the Newborn (Basic Books, New York, 1988).
43. Forsell, L. M. & Åström, J. A. Meanings of hugging: From greeting behavior to touching implications. Compr. Psychol. 1, 02–17 (2012).
44. Cascio, C. L., Moore, D. & McGlone, F. Social touch and human development. Dev. Cogn. Neurosci. 35, 5–11 (2019).
45. Light, K. C., Green, K. M. & Amico, J. A. More frequent partner hugs and higher oxytocin levels are linked to lower blood pressure and heart rate in premenopausal women. Biol. Psychol. 69, 5–21 (2005).
46. Cohen, S., Janicki-DeVries, D., Turner, R. B. & Doyle, W. J. Does hugging provide stress-buffering social support? A study of susceptibility to upper respiratory infection and illness. Psychol. Sci. 26, 135–147 (2015).
47. Floyd, K. et al. Kissing in marital and cohabiting relationships: Effects on blood lipids, stress, and relationship satisfaction. West. J. Commun. 73, 113–133 (2009).
48. Kimata, H. Kissing selectively decreases allergen-specific IgE production in atopic patients. J. Psychosom. Res. 60, 545–547 (2006).
49. Gazzola, V. et al. Primary somatosensory cortex discriminates affective significance in social touch. Proc. Natl. Acad. Sci. USA 109, E1657–E1666 (2012).
50. Morrison, I. A. E Meta-analysis reveals dissociable networks for affective and discriminative aspects of touch. Hum. Brain Mapp. 37, 1308–1320 (2016).
51. Li, Q. et al. Foot massage evokes oxytocin release and activation of orbitofrontal cortex and superior temporal sulcus. Psychoneuroendocrinology 101, 193–203 (2019).
52. Nummenmaa, L. et al. Social touch modulates endogenous µ-opioid system activity in humans. NeuroImage 138, 242–247 (2016).
53. Litzinger, S. & Gordon, K. C. Exploring relationships among communication, sexual satisfaction, and marital satisfaction. J. Sex Marital Ther. 31, 409–424 (2005).
54. Ocklenburg, S. et al. Beyond frontal alpha: investigating hemispheric asymmetries over the EEG frequency spectrum as a function of sex and handedness. Laterality 24, 505–524 (2019).
55. Mikutta, C., Altorfer, A., Strik, W. & Koenig, T. Emotions, arousal, and frontal alpha rhythm asymmetry during Beethoven's 5th symphony. Brain Topogr. 25, 423–430 (2012).
56. Flo, E. et al. Transient changes in frontal alpha asymmetry as a measure of emotional and physical distress during sleep. Brain Res. 1367, 234–249 (2011).
57. Crawford, J. R. & Henry, J. D. The positive and negative affect scale (PANAS): construct validity, measurement properties and normative data in a large non-clinical sample. Br. J. Clin. Psychol. 43, 245–265 (2004).
58. Peters, M. & Servos, P. Performance of subgroups of left-handers and right-handers. Can. J. Psychol. 43, 341–358 (1989).
59. Worden, M. S., Foxe, J. J., Wang, N. & Simpson, G. V. Anticipatory biasing of visuospatial attention indexed by retinotopically specific α-band electroencephalography increases over occipital cortex. J. Neurosci. 20, RC63 (2000).
60. Kelly, S. P., Gomez-Ramirez, M. & Foxe, J. J. The strength of anticipatory spatial biasing predicts target discrimination at attended locations: a high-density EEG study. Eur. J. Neurosci. 30, 2224–2234 (2009).
61. Haegens, S., Oostenveld, R. & Jensen, O. Somatosensory working memory performance in humans depends on both engagement and disengagement of regions in a distributed network. Hum. Brain Mapp. 31, 26–35 (2010).
62. Jensen, O. & Mazzaheri, A. Shaping functional architecture by oscillatory α activity: gating by inhibition. Front. Hum. Neurosci. 4, 186 (2010).
63. Ocklenburg, S. et al. Hugs and kisses—The role of motor preferences and emotional lateralization for hemispheric asymmetries in human social touch. Neurosci. Biobehav. Rev. 95, 353–360 (2018).
64. Packheiser, J. et al. Embracing your emotions: affective state impacts lateralisation of human embraces. Psychol. Res. 83, 26–36 (2019).
65. Packheiser, J. et al. Asymmetries in social touch-motor and emotional biases on lateral preferences in embracing, cradling and kissing. Laterality 25, 325–348 (2020).
66. Prete, G., Capotosto, P., Zappasodi, F. & Tommasi, L. Contrasting hemispheric asymmetries for emotional processing from event-related potentials and behavioral responses. Neuropsychology 32, 317–328 (2018).
67. Prete, G., Laeng, B., Fabri, M., Fossi, N. & Tommasi, L. Foschini, N. & Tommasi, L. Foschini, N. & Tommasi, L. The processing of hybrid faces in the intact and callosotomized brain. Neuropsychologia 68, 94–106 (2015).
68. Kilgore, W. D. S. & Yurgelun-Todd, D. A. The right-hemisphere and valence hypotheses: could they both be right (and sometimes left)? Soc. Cogn. Affect. Neurosci. 2, 240–250 (2007).
69. Buschman, T. J., Denovanllis, E. L., Diogo, C., Bullock, D. & Miller, E. K. Synchronous oscillatory neural ensembles for rules in the premotor cortex.Neuron 76, 838–846 (2012).
70. Kamiński, J., Brzezińska, A., Gola, M. & Wrobel, A. β band oscillations engagement in human alertness process. Int. J. Psychophysiol. 85, 125–128 (2012).
71. Porjesz, B. et al. Linkage disequilibrium between the beta frequency of the human EEG and a GABAA receptor gene locus. Proc. Natl. Acad. Sci. USA 99, 3729–3733 (2002).
72. Namy, E. Sharing the moment; the duration of embraces in humans. J. Ethol. 29, 389–393 (2011).
73. Robinowit, F. É. The male-to-male embrace: Breaking the touch taboo in a men’s therapy group. J. Counseling Dev. 69, 574–576 (1991).
74. Sedgwick, J. R. & Elias, L. J. Family matters: Directionality of turning bias while kissing is modulated by context. Laterality 21, 662–671 (2016).
75. Sedgwick, J. R., Hultlander, A. & Elias, L. J. Kissing right? Absence of rightward directional turning bias during first kiss encounters among strangers. J. Nonverb. Behav. 43, 271–282 (2019).
76. Jankowiak, W. R., Volsche, S. L. & Garcia, J. R. Is the romantic-sexual kiss a near human universal?. Am. Anthropol. 117, 535–539 (2015).
77. Karim, A. K. M. R. et al. The right way to kiss: Directionality bias in head-turning during kissing. *Sci. Rep.* 7, 5398 (2017).

78. Saling, M. M. & Cooke, W.-L. Cradling and transport of infants by South African mothers: A cross-cultural study. *Curr. Anthropol.* 25, 333–335 (1984).

79. Packheiser, J., Schmitz, J., Berretz, G., Papadatou-Pastou, M. & Ocklenburg, S. Handedness and sex effects on lateral biases in human cradling: Three meta-analyses. *Neurosci. Biobehav. Rev.* 104, 30–42 (2019).

**Acknowledgements**

This work was supported by the Deutsche Forschungsgemeinschaft Grant Number OC127/9-1 and the Research Training Group "Situated Cognition" (GRK 2185/1). We acknowledge support by the Open Access Publications funds of the Ruhr-Universität Bochum.

**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.

**Funding**

Open Access funding enabled and organized by Projekt DEAL.

**Competing interests**

The authors declare no competing interests.

**Additional information**

*Supplementary Information* The online version contains supplementary material available at https://doi.org/10.1038/s41598-020-80590-w.

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