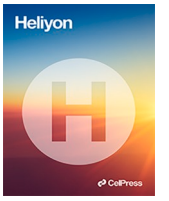
Heliyon 10 (2024) e34581

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon



Research article

Theta oscillations underlie the interplay between emotional processing and empathy

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ARTICLE INFO

Keywords:
Emotional processing
Valence
Arousal
Empathy
EEG source analysis
Theta oscillations

ABSTRACT

Emotional reactions to salient stimuli are well documented in psychophysiological research. However, some individual variables that can influence how people process emotions (i.e., empathy traits) have received little consideration. The present study investigated the relationship between emotions and empathy. Forty participants completed the Interpersonal Reactivity Index, a questionnaire that measure general and specific empathy dimensions. Then, emotional (erotic and mutilation) and non-emotional pictures were presented, during electroencephalographic recording. Valence and arousal were evaluated for each stimulus. Behavioral results revealed a positive correlation between the arousal induced by mutilation pictures and personal distress (i.e., feeling discomfort in emergency situations). At the electrophysiological level, theta activity elicited by positive and negative emotion processing in the superior frontal gyrus was associated with personal distress. Moreover, erotic-related theta in the middle frontal gyrus was associated with subjective judgement of erotic stimulus valence. Overall, theta activity modulated the interplay between emotions and empathy.

1. Introduction

Electroencephalography (EEG) is a widely used technique in cognitive and emotional research that allow to investigate the frequency characteristics and the temporal dynamics associated to the processing of a variety of information, ranging from sensory to cognitive domains, to emotions [1–6]. In particular, a series of EEG studies showed that slow frequency bands (i.e., delta and theta) play an important role in emotional processing [7–10]. For example, although delta waves are classically measured during inactive states or sleep [11], there is evidence of their involvement in emotional and motivational processes [9,12]. Compared to neutral material, high arousing emotional pictures increase the delta power in central-parietal regions, regardless of the valence of the stimuli (positive or negative) [9,13–15]. Greater delta power is also observed for high arousing *vs.* low arousing stimuli [7,8]. With respect to theta waves, they are observed during REM sleep [16], but also during motor (e.g., preparation, orienting) and mnemonic processes [17,18]. Similarly to delta, greater theta power is found in response to emotional compared to neutral contents and to arousing stimuli [2,7,9,19]. In addition, thanks to its connections with subcortical regions, theta band participates to the cognitive integration of emotional information [10]. Results on alpha activity are rather heterogeneous: some research observed alpha decreasing during emotional processing, whereas other found the opposite pattern [7,13,20–24]. Notably, some studies did not confirm any relation

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https://doi.org/10.1016/j.heliyon.2024.e34581
Received 2 May 2024; Received in revised form 16 June 2024; Accepted 11 July 2024
Available online 19 July 2024

between emotions and alpha oscillations [2,25]. Fast EEG frequencies (i.e., beta and gamma bands) appeared particularly sensitive to unpleasant emotional contents [26]. In particular, negative pictures elicited higher beta [27] and gamma activity compared to neutral ones [25,28].

Measures extracted from the EEG signal (i.e., spectral proprieties or event-related potentials) are very informative. However, by combining electrophysiological indices with behavioral ones (such as the evaluation of dimensions like valence and arousal elicited by different emotional stimuli), we can have a more comprehensive picture of the affective experience. Another aspect to consider in emotional research is the level of empathy of the participants. Despite there being no single definition, empathy is characterized by a cognitive and an emotional part: the first one refers to the ability to understand the internal states of other people, while the second one to the sharing of someone else's feelings [29,30].

Surprisingly, the effect of empathy on emotional reactions has been poorly investigated. Indeed, most studies do not collect information on participants' empathic dimensions, with the risk of mixing data coming from individuals with high and low empathy levels. Whether there is a relation between empathy and emotional processing, controlling for the empathic variable becomes fundamental, as empathy level might represent a confounding variable that should be controlled in all experiment focusing on emotion.

Actually, only a few studies compared psychophysiological responses to emotional stimuli in participants with different levels of empathy. In particular, more empathic individuals showed increased heart rate responses and skin conductance, regardless of stimulus valence (positive/negative emotion) [31]. Furthermore, participants with high empathy traits showed a greater mimicking reaction in response to pictures of facial expressions [32]. In a recent EEG study by Maffei and colleagues, video clips with different contents (i.e., erotic, compassion, fear and neutral) were presented to young women with low and high empathy traits and subjective evaluations were collected after each clip presentation [33]. Results showed that arousal evaluations for all emotional clips were higher for the group with high empathic levels. Moreover, compared with participants with low empathy traits, a higher gamma activity was observed for those individuals with high empathy traits during the presentation of emotional *vs.* neutral stimuli [33]. This suggests that empathy could influence both behavioral and psychophysiological responses to emotional information.

To the best of our knowledge, no studies have investigated the role of slow EEG bands in the relationship between empathy and emotions. As reported above, slow EEG oscillations are modulated by high arousing emotional stimuli [7–10] and, in our view, it could be interesting to explore their association with the empathic domain. Thus, the present study aimed to explore the relation between empathy and subjective reactions to positive and negative emotional pictures, together with the investigation of neural correlates of emotional processing in relation to empathic disposition. We conducted a correlational study in which behavioral and electrophysiological data were collected from a group of young healthy participants. A series of questionnaires were administered to assess the presence of specific phobias and the levels of anxiety and empathy. In particular, we measured the total empathy level by means of the Interpersonal Reactivity Index (IRI), as well as the scores obtained from its subscales (Perspective Taking, Fantasy scale, Empathic Concern and Personal Distress) [29]. Each subscale measures a different facet of empathy. During the experimental session, pictures from the International Affective Pictures System (IAPs), ranging from positive (erotic stimuli) to negative (mutilation stimuli) emotions, were presented [34]. Neutral pictures were also presented as a control condition. Subjective levels of valence and arousal were evaluated for each stimulus. Electrophysiological data were acquired during the passive viewing of emotional and neutral pictures. At the behavioral level, correlations between empathy traits and subjective emotional reactions were computed. Then, an EEG source analysis was carried out to investigate whether delta and theta bands were modulated by emotional stimuli depending on different empathy dimensions.

We expect to find an association between emotions and empathy both at the behavioral and electrophysiological level. In

Table 1
Individual characteristics and behavioral measures of participants (n = 40).

	Mean ± SD	Standardized data or Range (min-max)	One sample *t*-test
STAI – Y1	33.73 ± 5.41	37.94[a]	t = 4.9, p < 0.001, Cohen's D = 0.8
STAI – Y2	40.88 ± 7.72	39.62[a]	t = 1.0, n.s., Cohen's D = 0.2
IRI – total score	95.90 ± 11.44	Range = 28-140	
IRI – FS	24.70 ± 4.96	7–35	
IRI – EC	26.10 ± 4.38	7–35	
IRI – PT	27.55 ± 3.80	7–35	
IRI – PD	17.55 ± 4.32	7–35	
SAM – Valence		**Standardized data**	
Erotic	6.70 ± 1.13	6.72	t = 0.1, n.s., Cohen's D = 0.02
Neutral	4.47 ± 1.24	4.91	t = 2.2, p = 0.031, Cohen's D = 0.4
Mutilation	1.64 ± 0.74	1.91	t = 2.3, p = 0.026, Cohen's D = 0.4
SAM – Arousal		**Standardized data**	
Erotic	5.14 ± 1.74	6.39	t = 4.5, p < 0.001, Cohen's D = 0.7
Neutral	1.48 ± 0.75	2.64	t = 9.8, p < 0.001, Cohen's D = 1.5
Mutilation	5.76 ± 1.74	6.29	t = 1.9, p = 0.061, Cohen's D = 0.3

SD = standard deviation.
FS = fantasy scale; EC = empathic concern; PT = perspective taking; PD = personal distress.
[a] Note that we obtained the mean and DS by averaging the data of the female (Y1 = 39.62 ± 10.64; Y2 = 42.06 ± 9.67) and the male Italian sample (Y1 = 36.27 ± 9.54; Y2 = 37.19 ± 9.58) (Santinello and Pedrabissi, 1989).

particular, we assume that greater valence and arousal ratings characterize individuals with marked empathy traits, according to previous psychophysiological studies [31,32]. Furthermore, we expect to find a positive correlation between delta/theta activity and empathy level during the processing of high-arousing contents. Indeed, although all EEG frequencies have been associated to emotions [33], slow EEG oscillations (i.e., delta and theta) play a key role in the processing of arousing stimuli and, in particular, of salient affective information [8,13,35].

2. Results

2.1. Behavioral measures

The questionnaires administered before the experimental session confirmed the absence of specific phobias in all selected participants. As can be seen in Table 1, the state anxiety (STAI-Y1) scores were significantly lower than the average results found for Italian participants (young adult sample), whereas the trait anxiety (STAI-Y2) scores were similar to the typical anxiety levels for the Italian sample [36].

The levels of empathy were normally distributed (Kolmogorov-Smirnov test performed on the total score as well as the four subscales; all D values < 0.14, $p > 0.36$), and participants revealed a moderate to high level of empathy in the total score as well as the subscales, apart from the Personal Distress scale, were participants revealed lower scores (Table 1).

Finally, the self-evaluations of valence and arousal for all stimuli showed the typical pattern, neutral stimuli showing the average valence/pleasantness (erotic maximum, mutilation minimum values) and lower arousal than both emotional stimuli (regardless of their valence) (Table 1). As can be seen in Table 1, the valence scores of our participants were similar to the standardized values for erotic pictures only, whereas both neutral and mutilation stimuli were rated as less pleasant compared with the standardized values. On the contrary, considering arousal scores, our participants provided significantly lower subjective evaluations compared with standardized values [34], with mutilation images that approached normative sample data (Table 1).

The separate ANOVAs carried out on valence and arousal confirmed the stimulus main effect (Fig. 1), showing the well-known typical linear decrease moving from erotic to neutral to mutilation picture valence rates ($F_{2,78} = 286.59$, GG epsilon $= 0.99$, $p < 0.001$; HSD post-hoc Tukey test = all ps < 0.001), and the "V" shaped pattern with erotic-neutral-mutilation image arousal levels ($F_{2,78} = 135.89$, GG epsilon $= 0.97$, $p < 0.001$; HSD post-hoc Tukey test on neutral vs. both emotional stimuli = all ps < 0.001).

We carried out a series of correlation analyses to explore the relation between the various empathy domains (total empathy score, perspective taking, fantasy scale, empathic concern and personal distress; see Fig. 2), between the valence and the arousal associated with erotic and mutilation pictures, and finally between all measures of empathy and the self-reported valence and arousal. These analyses revealed a series of significant results. As expected, the scores obtained from the four IRI subscales were all positively correlated with the IRI total score (all $p < 0.01$; see Fig. 2).

In addition, valence and arousal of erotic pictures were positively correlated ($r_{(38)} = 0.43$, $p = 0.006$), whereas valence and arousal of mutilation pictures were negatively correlated ($r_{(38)} = -0.44$, $p = 0.004$) (Fig. 3A, left and right panel, respectively).

Finally, a positive correlation was also found between personal distress and arousal induced by mutilation stimuli ($r_{(38)} = 0.43$, $p = 0.05$; Fig. 3B), suggesting that participants that feel increased discomfort when experiencing or thinking about emergency situations

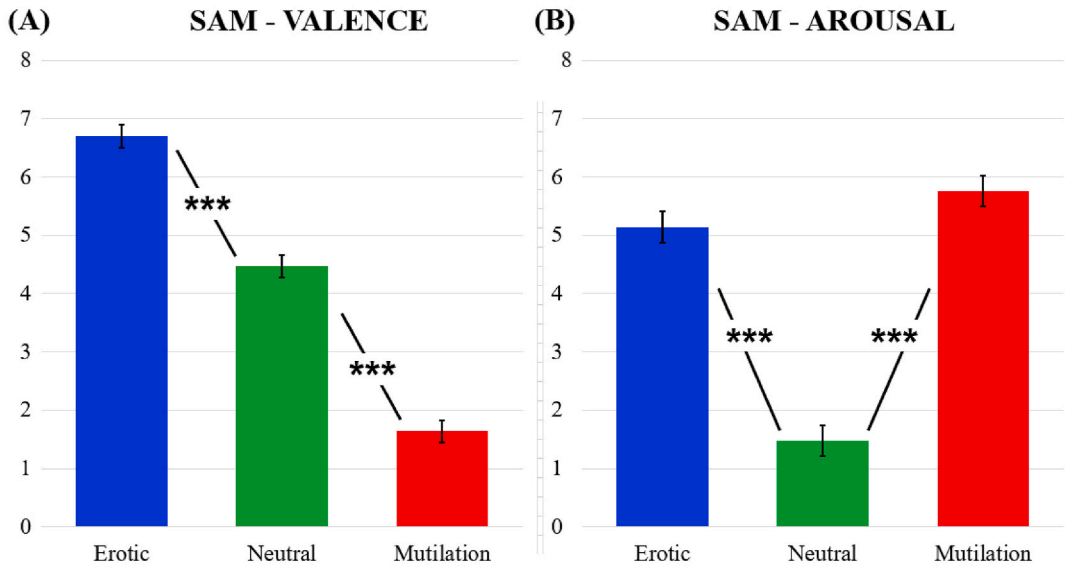

Fig. 1. Subjective evaluations assessed with the Self-Assessment Manikin (SAM), showing (A) the valence and (B) the arousal scores to erotic, neutral and mutilation stimuli. Bars represent standard errors (SE). *** for p values < 0.001 (HDS post-hoc Tukey test).

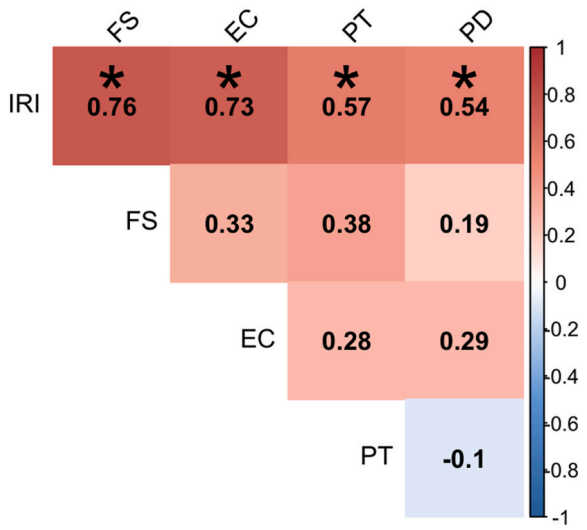

Fig. 2. Correlations between IRI (total score) and the four subscales (FS: fantasy scale, EC: empathic concern, PT: perspective taking and PD: personal distress). Asterisks indicate significant correlations FDR-corrected.

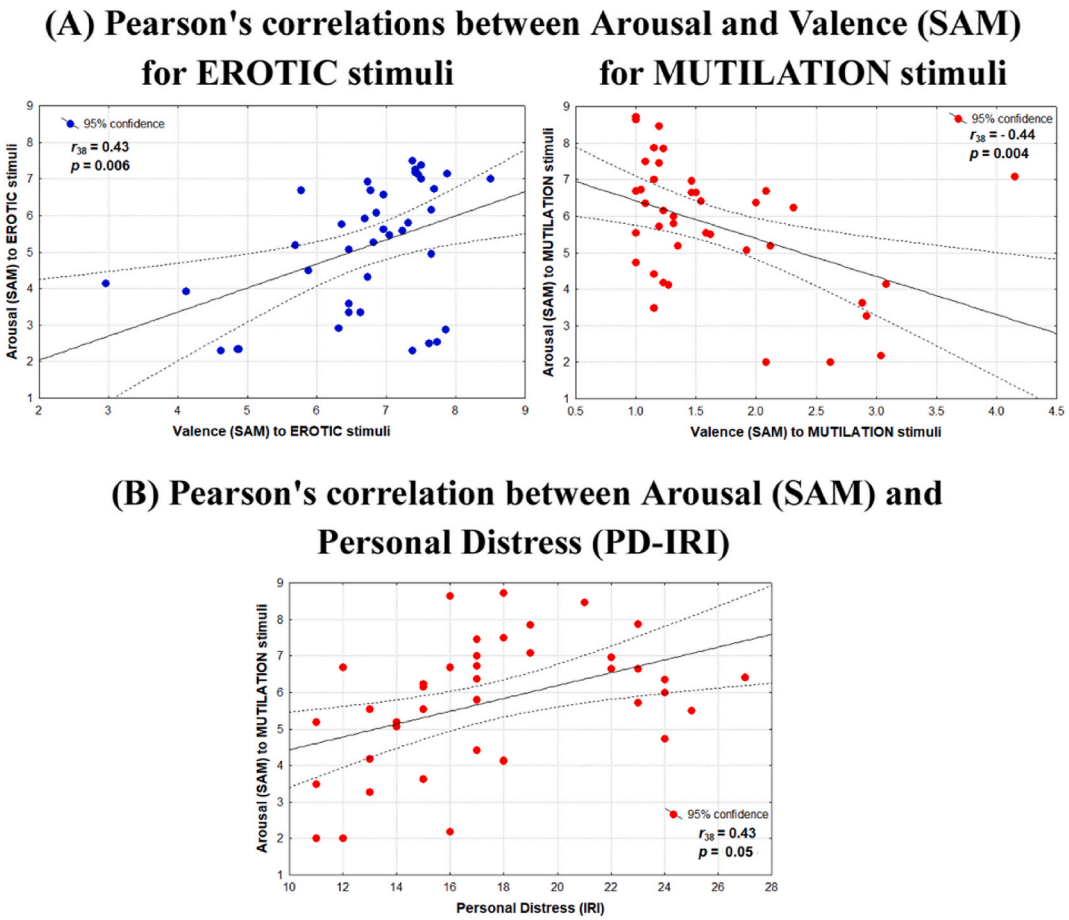

Fig. 3. Correlations between (A) valence and arousal SAM scores for erotic (left panel) and mutilation (right panel) stimuli, and (B) arousal (SAM) scores for mutilation stimuli and personal distress (PD-IRI) scores (FDR-corrected).

are those who attribute higher arousal to mutilation pictures.

Notably, the debriefing interview revealed that none of the participants reported feeling upset or disturbed by the content seen during the experiment.

2.2. EEG source analyses

Neural generators were estimated for emotional and non-emotional conditions (presentation of erotic, mutilation and neutral pictures) and correlated with empathy scores (IRI total score, perspective taking, fantasy scale, empathic concern and personal distress) and subjective ratings (valence and arousal), within the delta and theta frequency ranges. To verify a potential effect in other EEG rhythms, source analysis was also conducted within alpha, high-beta and gamma bands.

No significant correlations emerged when the delta, alpha, high-beta and gamma bands were analyzed. Furthermore, the EEG activity (all bands) for neutral pictures was not correlated with any variable of interest.

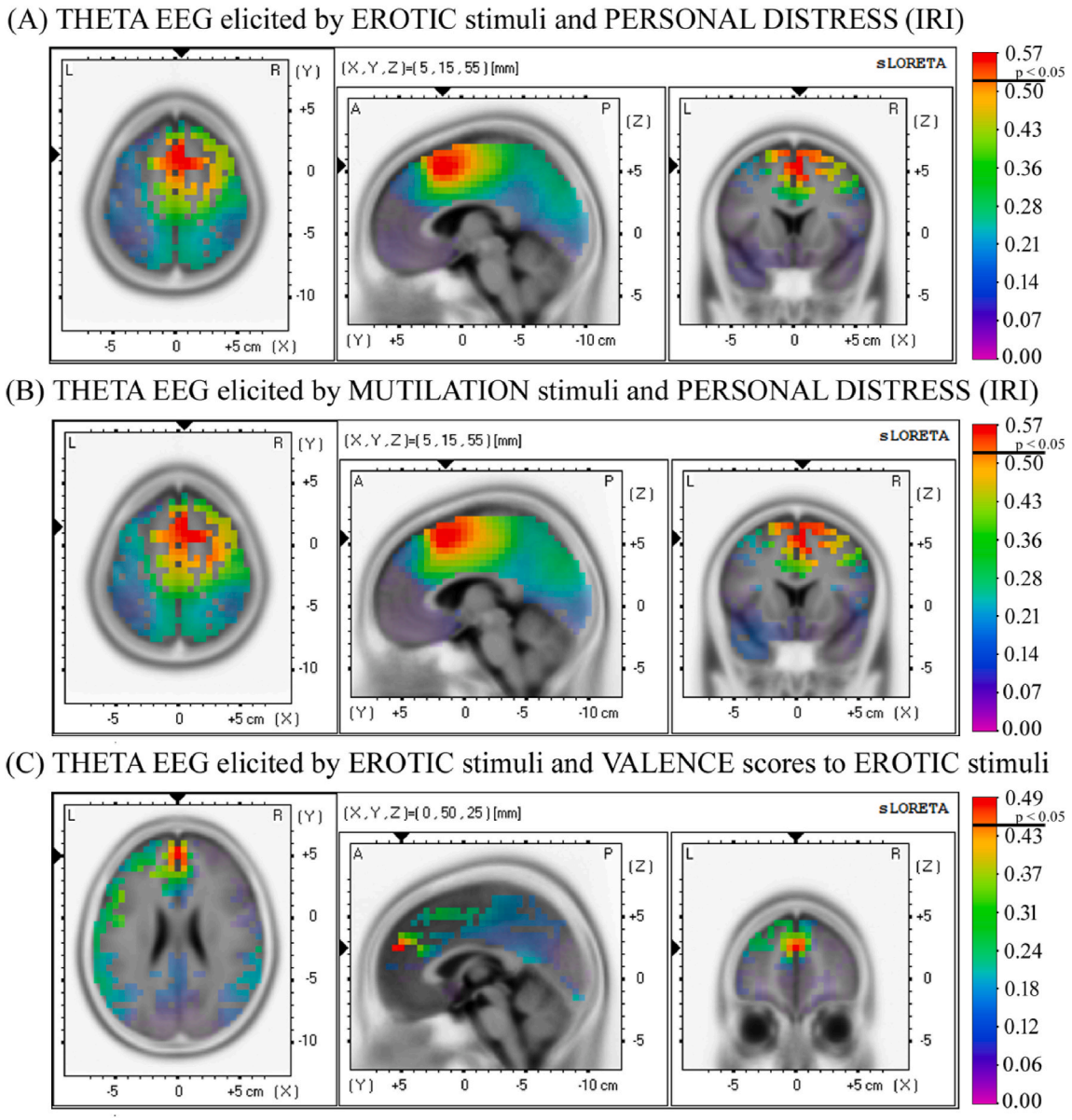

Fig. 4. Correlations between the source of Theta EEG frequency (A) elicited by erotic stimuli and the personal distress (IRI) subscale scores; (B) elicited by mutilation stimuli and the personal distress (IRI) subscale scores; and (C) elicited by erotic stimuli and the corresponding SAM valence scores. X,Y,Z values represent the MNI coordinates. The horizontal black bar in each sLORETA color scale shows the p value (<0.05) for significant correlations.

The analysis of the theta band elicited by emotional stimuli revealed interesting correlations with empathy and emotional reactions. Source analysis showed significant positive associations between the modulation of theta activity during the presentation of erotic and mutilation stimuli and personal distress scores in the superior frontal gyrus (Brodmann area: 8; MNI coordinates: X = 5, Y = 15, Z = 55). These results revealed that the higher the theta activity in the superior frontal cortex (Fig. 4A and B), the greater participant's personal distress (i.e., the tendency to experience distress, discomfort, and anxiety in emergency situations). This pattern was observed for both erotic and mutilation pictures ($r_{38} = 0.57$, $p = 0.018$, Fig. 4A, and $r_{38} = 0.55$, $p = 0.033$, Fig. 4B, respectively), showing that frontal theta oscillations mediate the relation between emotions and empathy, regardless of the positive or negative stimulus valence.

The modulation of the theta band during the processing of erotic stimuli was also correlated with the corresponding valence scores. We found a positive association between theta activity and the valence rated for erotic pictures in the middle frontal gyrus (Broadmann area: 9; MNI coordinate: X = 0, Y = 50, Z = 25): the greater the theta modulation in this region, the greater the corresponding valence evaluations, for erotic pictures only ($r_{38} = 0.49$, $p = 0.013$, Fig. 4C).

No correlations have been observed between theta activity modulation and arousal for positive or negative pictures.

3. Discussion

Notwithstanding emotional reactions to salient stimuli are well documented in psychophysiological research [37–40], some variables that can affect people's emotional state have been poorly studied, including empathy traits. To fill this gap, the present study aimed at investigating the relationship between empathy and emotional processing by combining behavioral and electrophysiological data. The first goal was to explore the effect of empathic disposition on self-perceived valence and arousal to emotional pictures. The second aim was to examine whether slow EEG frequencies (i.e., delta and theta), known to be sensitive to high arousing emotional stimuli [7–10], are also modulated by empathy levels.

The separate analyses carried out on trait anxiety (STAI-Y2) and empathy dimensions, as well as subjective evaluations of emotional pictures revealed their typical tendency. Our behavioral analysis showed that participants had levels of trait anxiety similar to standardized data [36]. Trait anxiety is considered a stable personality characteristic because it is not influenced by a specific event. In contrast, state anxiety (STAI-Y1) refers to how individuals feel in a particular situation: in our case, we asked participant to answer specifically considering their level of anxiety with respect to the experimental context. We found significant differences between our participants and normative data for state anxiety scores, as participants showed lower levels of state anxiety than the general Italian population, suggesting that the laboratory environment did not induce negative feelings. Importantly, STAI-Y1 was administered before the EEG session to verify that each participant did not show signs of anxiety related to the context of the experiment. Since trait anxiety measures were in line with normative data, and no participants showed an increased level of anxiety at the time of the experiment, we believe that our results were not altered by this trend. The short debriefing interview carried out at the end of the whole experiment (to ensure participants' wellbeing after the emotional processing of negative contents, in particular) support this interpretation. All IRI subscales were highly correlated with the total score: this was an expected result, because the internal consistency Cronbach's alpha for the total score and the four IRI subscales ranges between 0.68 and 0.79, according to the Italian validation of the Interpersonal Reactivity Index [41]. These correlations suggest that each subscale assesses important aspects of the global empathic domain. Similarly, the positive association between valence and arousal of erotic pictures and the negative association between valence and arousal of mutilation pictures confirmed that the stimuli we used were effective in eliciting the expected emotional reactions. Indeed, positive IAPS stimuli usually induce high valence and arousal, whereas negative IAPS stimuli induce low valence and high arousal [3]. These patterns appeared notwithstanding the overall ratings of valence and arousal were consistently lower for most of the IAPS contents, when compared with standardized data. This is not an isolated incident, as this phenomenon has recently been observed in emotion research. As discussed in a recent review [42], IAPS database has been validated in different countries showing good correlations with the original American data. However, it is common to observe some discrepancy in average ratings of valence, arousal, and dominance probably due to cultural differences. Furthermore, the IAPS images were validated more than 30 years ago in a large American sample, and therefore the presence of some differences could be due to changes in society and lifestyle. For example, young people today are more frequently exposed to erotic or violent stimuli, such as injury or mutilation. Easy access to this type of materials can therefore induce decreased valence and arousal reactions compared to previously collected data. This suggests that a reevaluation of IAPS stimuli is certainly necessary, together with the use of more ecological stimuli (such as videoclips). Despite this difference in 'absolute values', the distribution of our data still shows trends in line with previous research (i.e., lower valence for unpleasant stimuli, greater valence for pleasant stimuli and greater arousal for emotional stimuli compared to neutral ones).

Interestingly, when we combined the empathy dimensions with the emotional self-perceived evaluations, we found that only the personal distress scale was positively correlated with the arousal ratings of mutilation pictures. Individuals with high personal distress usually feel discomfort because of what could happen to oneself [43] and, according to our results, they are particularly sensitive to pictures depicting dangerous situations (i.e., mutilations). Across all dimensions of empathy, personal distress was the only one associated with explicit, negatively-valenced emotional judgments. This result is in line with previous data showing that personal distress is characterized by higher levels of arousal compared to other empathy domains (i.e., empathic concern) [44]. Other research investigated the relation between unpleasant situations (i.e., physical and psychological pain) and the empathic responses. It has been shown that while psychological pain can cause more empathic concern or personal distress (depending on whether the focus is on oneself or on the other), physical pain led to increased personal distress in the observer [45–48]. Our results revealed that mutilation pictures are particularly effective in inducing a negative emotional response (i.e., low valence and high arousal). Furthermore, mutilations represent a salient and biologically relevant stimulus, depicting a situation of extreme pain and physical danger. Thus, it is

noteworthy that these stimuli mainly activated the participants with the greatest disposition to personal distress. This result suggests that specific dimensions of empathy may have an impact on emotional experience.

The relation between empathy and emotional processing is also supported by electrophysiological data. Source localization analysis showed positive correlations between theta EEG activity in the superior frontal gyrus elicited by erotic and mutilation pictures and the level of personal distress. These results suggested a series of important remarks.

First, theta waves were elicited by emotional stimuli and were correlated with personal distress dimension of empathy. As previously reported, there is evidence that theta band is involved in the processing of high arousing information and underlies many cognitive-affective processes [9,19,49]. Contrary to our expectations, no significant activations were found within the delta range. Although delta has been associated with the processing of arousing emotional stimuli [9,13], theta rhythm primarily characterizes the relation between emotional processing and empathy. Indeed, our data show that theta band has not only a key role in the discrimination between emotional and non-emotional stimuli, but it is also modulated by the level of personal distress. Second, identical patterns of theta activation were found for erotic and mutilation pictures, but not for neutral stimuli. This finding confirmed that erotic and mutilation contents represent biologically relevant stimuli that elicit greater brain responses compared to other kinds of visual stimuli [3]. Furthermore, in agreement with past literature reporting increased theta power for emotional vs. non-emotional stimuli [2,9,13,19], our findings show that theta band on the one hand is sensitive to affective contents regardless of their valence, and on the other hand also mediates the relation between personal distress levels and pleasant and unpleasant emotional processing. Third, source analyses allowed us to localize the area of the brain that underlie the association between empathy and emotional processing: the central portion of the superior frontal gyrus (SFG). This cortical region is connected with several brain networks, and it is thus involved in different functions, such as working memory, motor activity, cognitive controls and introspection [50–54]. However, the prefrontal cortex, which includes the superior frontal gyrus, has also been associated with the generation and regulation of emotions [55]. A meta-analysis of functional magnetic resonance imaging (fMRI) data showed that the SFG, together with the cingulate and premotor areas, is a core brain region for emotion regulation-related processes [56]. Moreover, an fMRI study found that the connectivity between the posterior insula and the dorsomedial part of the prefrontal cortex was positively correlated with the personal distress [57]. Overall, these contributions suggest that the prefrontal cortex is a critical hub for both emotional processing and empathy traits, although these latter dimensions were never investigated within the same research. The present study, the first one that aimed to identify a shared neural correlate of empathy and emotions, allowed us to clarify the role of the prefrontal cortex and its subregions. Specifically, our findings revealed that individuals with high personal distress activated a specific cortical circuitry (i.e., the superior frontal gyrus) during the processing of emotionally salient information.

Source localization analysis also revealed a positive correlation between theta activity in the middle frontal gyrus elicited by erotic stimulus processing and the valence elicited by the erotic pictures. Among the various functions attributed to the medial frontal cortex, it has also been shown to be involved in processes of emotional regulation, in the evaluation of the relevance and salience of emotional information and in the attribution of the affective meaning [58–60]. In our study, its activity was associated with a greater perceived pleasantness to positive pictures. Erotic stimuli are particularly effective in inducing an increase in valence, given their biological relevance for the evolution. In addition, all the erotic pictures administered in the present study were characterized by the presence of heterosexual couples: as we chose heterosexual participants only (see exclusion criteria in the methods section), they were probably familiar with this kind of stimuli as part of their everyday life. Therefore, it is plausible that erotic materials engage the middle frontal gyrus, an important brain area for emotional decoding.

4. Conclusions and limitations

In summary, high levels of personal distress can modify the behavioral reactions to negative information, such as increasing the associated self-perceived arousal. At the electrophysiological level, the interplay between emotions and empathy is supported by theta oscillations. We provided evidence that different portions of the frontal cortex contribute to the emotional phenomenon. Specifically, the middle frontal gyrus is more involved in the judgement of positive stimuli, whereas the superior frontal gyrus mediates the relationship between the processing of positive and negative emotions and personal distress in individuals who usually feel discomfort because of what could happen to oneself [43]. Overall, our data support the hypothesis that empathy is a relevant component of the affective experience, and therefore should be carefully evaluated in emotional research.

The present study has some limitations. First, it did not include other physiological indices usually recorded in research on emotions (such as skin conductance or heart rate). Given the complementary information provided by these measures, future research should consider recording them during the experimental stimulation. Second, although previous research showed gender-related differences on both the emotional reactivity [5,61,62] and the empathic continuum [63,64], in the present study we did not consider its potential effect, tacitly assuming that men and women process affective stimuli in a similar way and are similarly touched along the empathic dimensions. As a future direction this could be probed.

Notwithstanding these limiting factors, the experimental protocol administered in the present study ensures ecological validity, representing appetitive stimuli which are familiar to real-world experiences (i.e., erotic contents) and aversive stimuli, biologically-relevant for survival (i.e., mutilation images). Notably, novel evidence of the special role of a specific empathic dimension – the personal distress – as a critical variable that can affect people's emotional state has been here provided for the first time.

6. Methods

6.1. Materials and methods

6.1.1. Participants

An online screening was completed by 215 young and healthy adults to collect information on age, years of education, drug use and the presence of psychiatric/neurological disorders. Furthermore, the level of empathy and the presence of phobias were assessed using the Interpersonal Reactivity Index (IRI) questionnaire and the Fear Survey (short Italian version) [29,65]. IRI questionnaire comprises four subscales: Perspective Taking (the propensity to unintentionally adopt the viewpoint of another person); Fantasy Scale (the ability to self-identify with fictional characters); Empathic Concern (the "other-oriented" feelings for disadvantage people) and Personal Distress (the stress that a person may experience in a challenging interpersonal situation). For each subscale, an individual score is calculated and the IRI total score is given by their sum. Participants were excluded from the study if they: a) were homosexual or bisexual or preferred not to specify their sexual orientation (as our erotic emotional stimuli were characterized by the presence of heterosexual couples only); b) had specific phobias (e.g., phobia for firearms, knives, blood, as some negative-valenced stimuli represented these contents); and c) had neurological or psychiatric disorders. The final sample consisted of 40 participants (20 women; mean age ± standard deviation [SD] = 22.40 ± 2.24 years). The sample size was computed using G power software [66]. In a pilot study, we observed a correlation between emphatic concern scores and arousal reported to fear pictures ($r(18) = -0.45$, $p = 0.049$) in a group of young women. Not having found other studies in which empathy and subjective emotional reactions were correlated, we used these parameters to determine the size of our cohort. Specifically, with an $r = 0.45$, an alpha = 0.05, an expected power of 0.80, the estimated sample size needed was of $n = 36$ (two-tailed). All participants had normal or corrected-to-normal vision and gave their written informed consent to take part in the study, according to the Declaration of Helsinki. This study was approved by the Psychology Ethics Committee of the University of Padova (Protocol n. 4440).

6.1.2. Experimental procedure

On the day of the experiment, each participant completed two questionnaires: the State-Trait Anxiety Inventory (STAI Y1 and Y2), which measures trait and state anxiety and the Positive and Negative Affect Schedule (PANAS), which assesses positive and negative feelings [67,68]. STAI (Y1 and Y2) and PANAS were administered in a quiet area of the laboratory and participants were given the time they needed to complete the questionnaires. Before starting the EEG session, the experimenters computed the scores of the STAI-Y1 to ensure that the participants did not experience anxiety induced by the experimental setting.

The experiment consisted in the passive viewing of 130 pictures with emotional or neutral content, during the simultaneous recording of electrophysiological activity. Each picture was presented in full-screen mode for 2 s, followed by a black screen (inter-stimulus duration ranging between 1 and 3 s). The stimuli were all part of the International Affective Picture System (IAPS) and comprised two positive emotional categories (i.e., 26 Erotic and 26 Sport pictures), two negative emotional categories (i.e., 26 Mutilation and 26 Fear images) and neutral pictures ($n = 26$) depicting objects used in everyday life activities [34]. Pictures were randomly presented, but the same order was maintained for all participants. At the end of the experiment, participants were asked to self-evaluate valence and arousal elicited by each picture using the Self-Assessment Manikin (SAM), including a scale ranging from 1 (low) to 9 (high).

Finally, a short debriefing interview was carried out to ensure that participants felt good, especially with respect to the vision of particularly bloody and violent negative emotional contents.

6.1.3. Behavioral statistical analysis

As most of the existing literature on emotional processing with IAPS stimuli focused on erotic and mutilation pictures as the most representative contents for positive/appetitive and negative/aversive stimuli [69–72], respectively statistical analyses were carried out on these two emotional contents, and neutral pictures.

We carried a series of Pearson's correlations between the empathy traits (total score, perspective taking, fantasy scale, empathic concern and personal distress), between valence and arousal elicited by erotic and mutilation stimuli and between empathy traits (total and subscales scores) and valence and arousal ratings to erotic and mutilation pictures. All p-values were adjusted by means of FDR correction.

6.1.4. EEG preprocessing

EEG data were collected using a standard 64-channel cap (Acticap, BrainProduct System) according to the international 10–20 system. The EEG was recorded in DC mode and the activity of each electrode was online referred to FCz. The sampling rate was set at 1000 Hz (Hz), and the impedance was kept below 5 Kiloohm (kΩ) throughout the recording. The activity of FCz was off-line reconstructed and data were re-referenced to the average reference. Bad channels were identified and interpolated using the triangulation and linear interpolation method provided in BrainVision Analyzer software (BrainProduct GmbH, Germany). All the other preprocessing steps were computed through the Brainstorm toolbox [73]. After data filtering (lower cutoff = 0.5 Hz; upper cutoff = 125 Hz; stop-band attenuation = 60 dB), an Independent Component Analysis (ICA; method = Infomax EEGLAB/RunICA) was computed to identify and then remove artifactual components (i.e., ocular and/or muscles artifacts). Then, epochs with residual noise were deleted first by using a peak-to-peak procedure (threshold value = ± 150 μV, μV) that rejected the entire epoch, and lastly by visually inspecting the residual artifact-free epochs. On average, 75 % of all epochs were accepted (73 % of erotic stimuli, 77 % of neutral stimuli and 74 % of mutilation stimuli).

6.1.5. EEG source localization

Source localization analysis was performed using the sLORETA software, based on the standardized low resolution brain electromagnetic tomography method [74]. sLORETA estimates the smoothest possible 3D distributed source density solution in gray matter after 5,000 permutations. Starting from all cleaned epochs available from each participant and category (neutral, erotic, mutilation IAPS pictures), a single 64 × 64 complex-valued, cross-spectral matrix for each participant was computed for the delta (0.5–4 Hz) and theta (4–7 Hz) frequency ranges. To investigate the association between the brain responses to emotional stimuli and (i) the empathy levels and (ii) the subjective emotional state, we computed separate sLORETA correlation analyses between the delta and theta bands (during the presentation of neutral, erotic or mutilation pictures) and (i) the IRI questionnaire (total score, perspective taking, fantasy scale, empathic concern and personal distress) and (ii) SAM ratings (valence and arousal). All results are reported in MNI coordinates. A control analysis was also computed on the alpha (8–12 Hz), high-beta (20–35 Hz) and gamma (35.5–64 Hz) bands to verify a possible effect in other frequency ranges.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors. The data are not publicly available due to privacy or ethical restrictions.

CRediT authorship contribution statement

Zaira Romeo: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Chiara Spironelli:** Writing – review & editing, Resources, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgments

The study was funded by a PRIN grant from the Italian Ministry for University and Research (MIUR) to CS (20178NNRCR_003).

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