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Electrophysiological correlates of the emotional response on brain activity in adolescents

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ABSTRACT

Many studies have attempted to analyze the main neurophysiological characteristics of emotional response, but few have been carried out at early ages, including adolescence or early adulthood. The main objective of the present study is to assess the electrophysiological correlates of emotional response in adolescents and young adults through electroencephalography (EEG) measures. Sample, composed of 25 subjects (18.44 ± 0.71 years old), were exposed to different sequences of images belonging to the IAPS, which were selected following the dimensional model, based on their valence and arousal, while their neural activity was evaluated through EEG. Results indicated differences in cortical neural activity in response to the valence of the images and the level of arousal. Specifically, we observed that exposure to positive images (high valence) with high arousal produced an increase in alpha, beta, and delta wave activity but not in theta activity. In the case of positive images with low arousal, however, the results indicated an increase in beta waves only and a decrease in alpha, delta, and theta activity. For negative images (low valence) with high arousal, an increase in alpha, beta, and delta waves but not in theta was observed, while negative images with low arousal induced an increase in beta, delta, and theta wave response. This study demonstrates that activated cortical areas indicated significant differences based on the different emotional responses in adolescents and young adults.

1. Introduction

Emotions are an essential physiological and behavioral response. They are based on complex and structured reactions that have a direct effect on behavior and perform an important function in human life [21,18,40]). Different models and theories have attempted to explain emotions as well as their categorization and characteristics. Following a categorical perspective, Paul Ekman [19] established the six basic emotions (happiness, sadness, anger, fear, disgust, and surprise) and their relationship with facial expressions [20]. Afterwards, Lang [28] proposed a model from the dimensional perspective that defined emotions as the state of preparation for conduct, which provokes diverse effects at the physiological, cognitive, and behavioral level and organizes them based on the affective dimensions of valence (pleasant/unpleasant), arousal (activation/calm), and dominance (high/low control). Later, Lang et al. (Lang et al. 1999; [29] developed a standardized scale with thousands of images that have been validated. It is one of the most widely used and standardized scales in experimentation on emotions and is known as the International Affective Picture System (IAPS). This system includes positive, negative, and neutral images, that are classified on the basis of valence, arousal, and dominance (Lang et al., 1999; [29,35,24]). These images have been used to analyze the brain's processing of emotions [8], and it has been hypothesized that exposure to such images may elicit neurobiological responses related to defensive and appetitive behaviors, among others [28,42].

The emotional state of people affects many areas of their lives, including cognitive performance, decision making, physical and mental health, and behavior in daily life situations [7,41,18,36,44]. Considering the influence that emotional states have on these aspects, research has been directed towards the analysis of emotional recognition using different behavioral and psychophysiological parameters related to emotional response. The assessment of emotions through questionnaires or behavioral observation techniques has been used in various contexts, but the responses obtained are usually voluntarily controlled by the

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subjects being assessed, and therefore could sometimes provide erroneous or confusing results about their emotional state. In fact, despite the number of studies that have been conducted, the results in some cases are not conclusive and knowledge about emotions in humans is still limited [44,48].

Nevertheless, the study of emotional recognition through the analysis of physiological parameters has shown great effectiveness and validity and produced various methodologies, which include the use of techniques such as electroencephalography (EEG), body temperature, galvanic skin response (GSR), electrocardiogram (ECG), electromyography (EMG), etc. [42,41]. The reason for the use of these techniques compared to more traditional methods is that they offer more objective information since the analysis of physiological responses is usually not voluntarily controlled by the subjects [44]¸ [48]. In fact, the emotional response is often associated with relevant physiological changes, the recognition and analysis of which is of particular relevance [41].

The scientific literature of recent decades has included a wide variety of studies conducted using EEG in the research of emotion recognition [13].The use of EEG techniques allows the electrophysiological activity of the neurons located in the cerebral cortex to be observed while the subject is performing a task, so it offers valuable information about the way the brain works [10,24,30,32]. EEG records the electrical activity about brain network communications in the frontal, temporal, parietal, and occipital cortex lobes [22]. Some of the most important advantages of EEG techniques are: it allows the brain activity of the subjects to be analyzed at the same moment in which the subject is performing it; it is inexpensive and portable; and it offers objective and involuntary information about emotional and cognitive processing [8,10,12,41]. Most of the studies in the area include the analysis of Event Related Potentials (ERPs) as a measure of the brain's response to a specific event or stimulus [45]. Compared to other recording techniques, such as neuroimaging techniques, the use of ERPs through EEG has a better temporal resolution, but it has a lower spatial resolution, which limits the identification of the brain areas involved in this response [8]. It should be noted that the variability of the study techniques used, as well as the strong individual differences in the neurophysiological response to emotions have led to the publication of different databases available [25]. For example, one of the most widely used is the database published by Koelstra et al. [27], called DEAP (Database for Emotion Analysis using Physiological Signals). This database was made through the responses obtained from 32 subjects exposed to music videos for the analysis of spontaneous emotional response from physiological signals.

As indicated above, in recent years, there have been several studies aimed at analyzing emotional response based on electrophysiological variables through EEG techniques. Some of the main results obtained in the different studies indicate that there are indeed changes in neural activity in response to different emotions, with the IAPS system being one of the most widely used to induce the emotional response. In a study conducted by Balconi et al. [8], band frequency was analyzed in relation to cortical areas involved in emotional recognition of IAPS images in adults. Among the main results obtained, it was observed that the brain activity of low-frequency waves showed a significant response to emotional stimuli with respect to high-frequency waves. Specifically, there was an increase in delta (0–3 Hz) and theta (4–7 Hz) wave activity in response to images with negative valence stimuli which was lateralized in the right hemisphere of the participants. In addition, the analysis of the activity shown by the subjects in terms of alpha (8–12 Hz) and beta (13–20 Hz) waves did not indicate significant differences. Similarly, another study conducted with IAPS images by Reali et al. [39] with healthy adults showed an increase in theta wave activity upon exposure to high valence and high arousal images. In another study, which was carried out to analyze possible differences in cortical activation based on exposure to different emotional stimuli (using the IAPS), it was observed that unpleasant images induced greater cortical activation than pleasant images [7]. Another study carried out by Orgo et al. [37] analyzed the emotional response to IAPS images through the EEG spectral asymmetry index (SASI) in healthy adults. In this case, it was observed that the asymmetry obtained in the SASI allowed discriminating between the emotional response to positive, negative, and neutral images. There was an increase in the asymmetry in the case of negative images and a decrease in the asymmetry in the case of positive ones (compared to neutral images).

Currently there is great heterogeneity in the methodology used in the existing studies in this area. For instance, images are not the only stimuli that have been used to induce emotions and evaluate the brain response of subjects. Some research has used other types of audiovisual stimuli such as videos, movies, or music. Eijlers et al. [18] evaluated the different patterns of brain activity in response to videos inducing the emotional responses of happiness, sadness, fear, or disgust. Interesting results were obtained, showing a decrease in gamma waves in the temporal and frontal areas in response to videos evoking happiness, while disgust was associated with an increase in gamma waves in the temporal area only. There was an increase in alpha waves in the sadness response, and there was a decrease when the induced response was fear. In other study, Maffei et al. [31] examined the cortical brain response in women before eliciting emotions using movie clips. In addition, they analyzed whether the degree of empathy of the women affected their emotional response. They observed that women with high empathy showed higher gamma waves activity than women with low empathy in response to movie clips, with either positive or negative emotional content (when compared to neutral content). For women with low empathy, this gamma wave activity was only observed in response to movie clips with negative emotional content. Other recent studies, however, have focused on inducing emotions through multisensory stimulation, adding olfaction. In this way, they have developed databases based on physiological odor and video signals [48,49]. In these studies, conducted with healthy adults, increased activation of beta and gamma waves in the temporal cortex has been observed in the emotional response. Exposure to odors has induced increased activation of delta and theta waves in the prefrontal area. The relevance of these databases lies in the use of multisensory stimuli that increase emotional responses and generate situations more similar to real life.

As described in previous studies, most of the research carried out to analyze differences in neural activity in response to different emotions has been conducted in healthy adults. Few studies have evaluated this response in adolescents, despite the fact that this is a stage of life that is particularly marked by emotions. Adolescence is an important evolutionary stage for the development of socio-emotional skills that could be influenced by different neuropsychological factors) [43]. Several studies observed higher emotional reactivity in adolescents and an increase in the development of neural circuits related to the enhancement of emotional response and its regulation, which decreases with age [11,17]. In addition, adolescents show more difficulties in successful emotional regulation because their prefrontal function is not yet fully developed [23]. Evidently, high levels of efficiency and flexibility in emotion regulation is achieved through the full development of the capacity for cognitive control. Evidence from electrophysiological tests reveals both structural and functional changes in multiple brain regions during adolescence. For instance, changes in the cortical region are related to more emotional reactivity in adolescents [9,17]. A study conducted by Moshirian Farahi et al. [36] assessed the relationship between asymmetric frontal activity, level of neuroticism, and emotion valence in adolescents. The results indicated that neuroticism was positively related to valence for fear, disgust, sadness, and surprise, but not to happiness or anger. In another study, Deng et al [17] have evaluated differences in frontal EEG asymmetry during emotional regulation among adolescents with different level of mindfulness practice and have observed a higher left activation in adolescents with high level of mindfulness during emotional regulation. Greater left asymmetry has been related to more effective regulation of emotional response. In other recent study, Güntekin et al. [24] analyzed changes in EEG connectivity in response to IAPS in university students (the mean age of the participants in this study was 21.64 years old). To do this, they used event-related coherence measures and analyzed possible gender differences. Among their main results, the most notable was a higher delta coherence response to negative images in electrodes located in the fronto-parietal, centro-occipital, and fronto-occipital areas. Negative images also elicited a greater theta coherence value. Women showed greater delta, theta, and alpha wave coherence response than men.

Taking these results into account, the main aim of our study was to evaluate the electrophysiological correlates of emotional response in late adolescence and early adulthood. The EEG was conducted by recording brain activity while the subjects received visual stimuli from IAPS exposure, which included positive, negative, and neutral images. Different studies have evaluated emotion recognition using EEG, but few have performed this measurement on adolescents or young adults. Our study may be useful in the psychophysiological study of emotions at young ages due to the importance of emotional response and processing in adolescence and because this stage of development is critical for the proper definition of identity and emotional stability during adulthood. Given the idea that the cortical area is more emotionally reactive in adolescents and reveals greater activation during emotional response, the hypothesis of our study is that we could identify a response of neural activity related to the emotional response in adolescents and young adults using EEG measures. In addition, we expect to observe differences in neural activity based on the type of emotion elicited.

2. Materials and methods

2.1. Subjects

The sample was composed of 25 university students (21 women and 4 males). The inclusion criteria were: 1) age between 18 years old to 21 years old; 2) absence of cognitive impairment; 3) able to follow instructions. The exclusion criteria were: 1) subjects whose visual or hearing impairment impedes participating adequately in the experiment; 2) subjects who have consumed drinks with caffeine, tobacco, or narcotic substances in the three hours prior to the start of the experiment; 3) subjects suffering from chronic pathology or epilepsy; 4) subjects who take psychopharmacological treatments on a regular basis; 5) subjects with diagnosed mental health disorders, including depression. A convenience sampling procedure was used in this study. The convenience of these sample selection criteria is based on those established by previous studies in which the IAPS scale and the recording of neural activity through EEG techniques have also been used [7,8,37,39]. In all cases, the aim was to avoid as far as possible questions that could alter the emotional processing of the images received or could alter the brain activity recorded.

After the inclusion–exclusion criteria were taken into account, there was a final sample of twenty-five healthy subjects (21 females, 4 males) in the study. Twenty-four subjects were right-handed, only one subject was left-handed. The participants were students from different universities, with an average age of 18.44 years old (SD = 0.71; 88 % female). The age range of the participants was chosen in accordance with the criteria for defining adolescence according to the World Health Organization, which places the adolescent stage between 10 and 19 years old and the early or young adulthood stage between 20 and 24 years old [38].

All of the participants received a full description of the study, and then all of the subjects signed an informed consent form. A 50 € gift card was raffled among the participants in the study. The study was approved by the ethics committee of the university (Procedure number H152865096049), and all of the procedures carried out were in accordance with the Declaration of Helsinki (2013).

2.2. Emotional stimuli

EEG signals were recorded during the visualization of a sequence of images. The images selected for the study came from the International Affective Picture System (IAPS; Lang et al., 1999). As stated in the Introduction, the IAPS is an image bank that contains 1195 color photographs, which are validated and widely used in the field of psychology and emotions. The images of the IAPS are categorized in normative ratings in three dimensions: valence, arousal, and dominance. In this study, we used a Spanish adaptation of the IAPS, with results that are consistent with previous research [34,47,35].

A total of 65 images selected from the IAPS were used in this study. The images selected were classified into five different sets following the dimensional model, according to valence (v) and arousal (a): two sets of positive images (20 pictures); two sets of negative images (20 pictures) and one set of neutral images (25 pictures). The sets used in the experiment are detailed in the following:

- Positive images with high (or pleasant) valence and low arousal (↑v↓a). The images of this set correspond to the following images of the IAPS: 2070,1811, 1460, 4641, 2071, 7502, 2224, 5890, 1463, and 2057.
- Negative images with low (or unpleasant) valence and high arousal (↓v↑a). The images of this set correspond to the following images of the IAPS: 1300, 3181, 2730, 3500, 6550, 9570, 3110, 2688, 3015, and 3160.
- Positive images with high valence (or pleasant) and high arousal (↑v↑a). The images of this set correspond to the following images of the IAPS: 7508, 4698, 8467, 7660, 4311, 8492, 7499, 4604, 8499, and 8206.
- Negative images with low valence (or unpleasant) and low arousal (↓v↓a). The images of this set correspond to the following images of the IAPS: 2039, 2718, 9469, 2301, 9290, 9332, 7520, 9922, 9002, and 2104.
- Neutral images. The images of this set correspond to the following images of the IAPS: 6150, 7100, 7035, 7000, 7130, 2200, 7040, 7700, 2383, 7009, 7500, 7090, 5532, 2440, 7002, 7140, 2210, 7050, 7710, 2385, 7006, 7495, 7080, 5531, and 2381.

In order to randomize the order of appearance of the IAPS images, four different presentations were included in the study and randomly projected for the subjects. Table 1 shows the valence and arousal ratings of the selected pictures taking into account the data related to the Spanish validation of IAPS [34,47,35].

2.3. EEG data acquisition

An Enobio® EEG 3G system (Neuroelectrics®, Spain) with eight channels was used to record the EEG signals. The EEG signals were recorded at a sampling rate of 500 Samples per Second using eight electrodes following the standard 10–20 system. In this experiment, wet electrodes were used to improve the signal acquisition. A comfortable neoprene headcap was used by each participant, and the electrodes were placed in the following positions: Fp1, Fp2, F3, F4, F7, F8, T7, and T8 (see Fig. 1).

An earlobe electrode (A1) was also used as reference. This study, Version 8 of Enobio was used, which has a converter and an internal amplifier that is suitable for eight simultaneous channels, and a USB Bluetooth receiver.

Table 1
Valence and arousal ratings of selected images from IAPS according to the Spanish validation.

Images	Valence Mean (SD)	Arousal Mean (SD)
Positive (↑v, ↓a)	7.84 (0.55)	4.63 (0.46)
Negative (↓v, ↑a)	2.18 (0.68)	7.03 (0.66)
Positive (↑v, ↑a)	7.15 (0.59)	6.67 (0.55)
Negative (↓v, ↓a)	2.97 (0.74)	4.74 (0.77)
Neutral	5.16 (0.38)	3.52 (0.60)

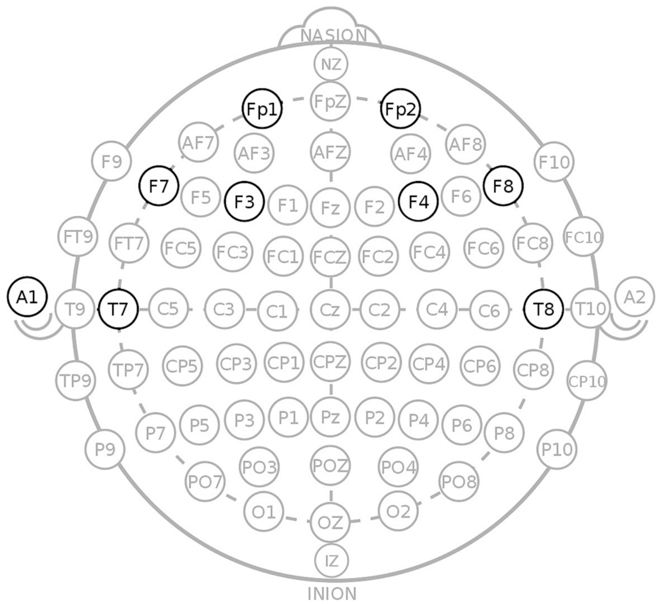

Fig. 1. Placement of the electrodes used in the study following the 10–20 international system.

2.4. EEG preprocessing analysis

The processing of the EEG data obtained with the Enobio 8-electrode used by the participants of the study required the use of different software, including MATLAB and EEGLAB. The protocol followed for each one of the EEG registrations included different steps (see Fig. 2).

First, we used the EEGLAB program for MATLAB [16]to upload the study. Then, we proceeded to eliminate unwanted channels (i.e., the channels associated with the accelerometers X, Y, and Z). The channels that were associated with the electrodes used for the study were Fp1, Fp2, F3, F4, F7, F8, T7, and T8. Then, we input the location of the electrodes used to be able to draw 2D maps later. To ensure accuracy, we also checked to see if this location was correct. After this step, we applied a band pass filter (0.1 Hz. – 45 Hz.) in order to eliminate the environmental noise in the captured signals. The channels were re-referenced with the average of all the electrodes.

Subsequently, we used a MATLAB script that we had programmed ourselves to perform the 'placement of the marks'. This step allowed us to insert the exact moments in which the different types of emotional images were used in the signals obtained. This step facilitated the next action, which consisted of manually cleaning the most obvious artifacts, i.e., those artifacts associated with experimental errors, such as involuntary movements of the electrodes, or some noises, and muscular movements by the subjects.

After cleaning the signal artifacts, we applied Independent Component Analysis (ICA) in order to obtain independent components or artifacts (movements or blinking of eyes). We also applied ICLabel to determine the components that should be removed. We then eliminated the components related to physiological errors in the signal (movement, blinking of eyes, or cardiac activity). Finally, using the MATLAB script that we ourselves programmed, we proceeded to perform the 'calculation of powers', which is a step that creates an Excel file with the information obtained in the process.

The method used in the calculation of powers was Fast Fourier Transform (FFT). The FFT was calculated for a frequency range from 0 Hz to 40 Hz, with a window size of 128 data points. We used Hamming windows for the power spectral density estimation because they provide better spectral resolution than other types of windows such as Blackman-Harris windows, because the Hamming windows made the best mean squared error [33]. To reduce the effect of windowing, we applied a window overlap of 64 data points (50 %). We used the 100 % of the data to sample for computing the spectra. Specifically, we calculated the power obtained by each electrode in each frequency range (alpha, beta, delta, theta) for each one of the marks used in the

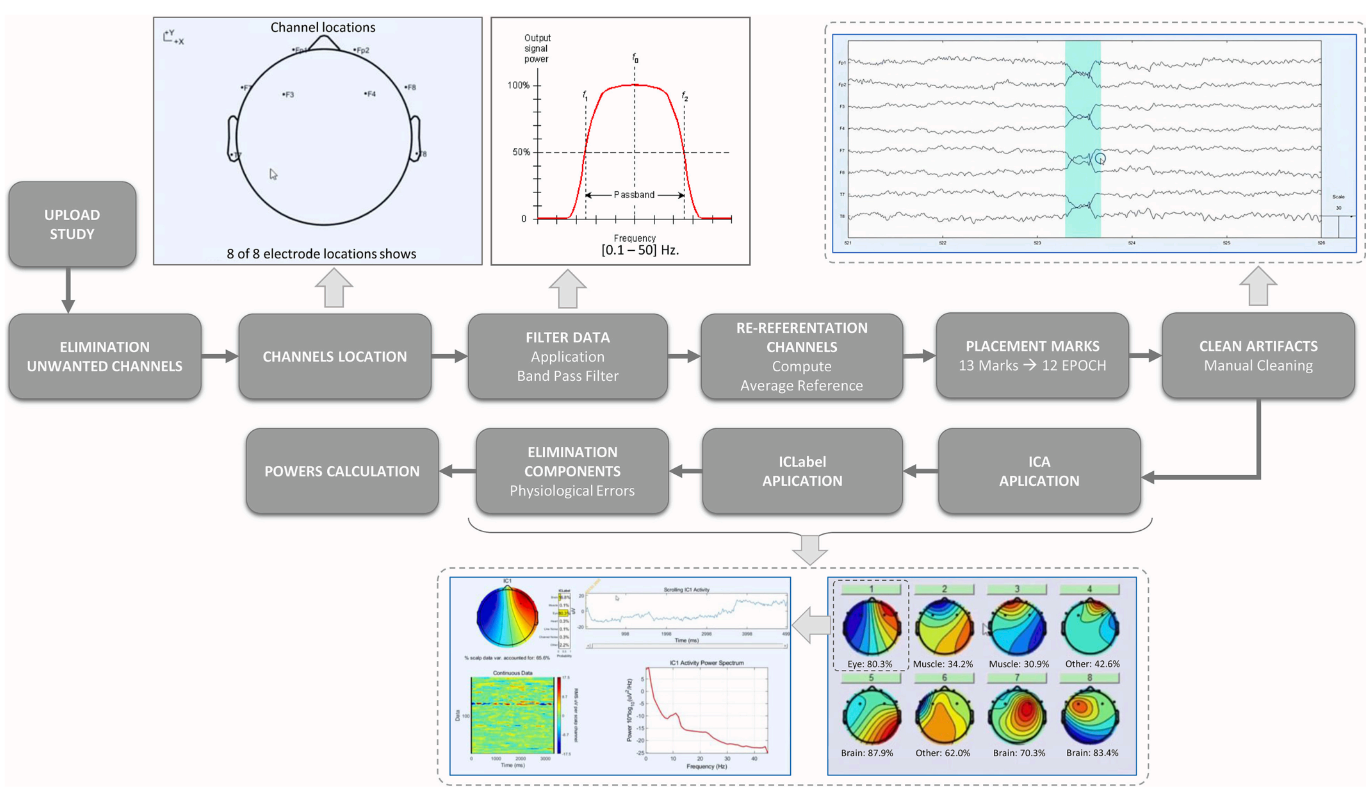

Fig. 2. Procedure for EEG signal processing.

study performed. Thus, we explored the variability of the power of the different brain waves in the frequency domain of delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (13–30 Hz).

2.5. Procedure

The data was collected in an individual session that lasted approximately 30 min. Upon arrival at the session, the subjects were given a full explanation of the study, and their doubts were resolved. Then, they read and signed the informed consent form. Afterwards, they completed another brief form to collect sociodemographic information of interest, and they were asked a few questions to verify compliance with the inclusion / exclusion criteria.

All of the participants then received a brief description of the instructions for completing the study. Once the electrodes were placed and calibrated, the experiment began. The study was carried out in a quiet room with little lighting and no external stimuli, and the participants were seated in front of a monitor, where a sequence of 13 sets of images was shown. Each presentation of these 13 sets of images belonged to one of the categories described before and followed the order shown in Fig. 3.

In order to minimize the impact of the order in which the categories were shown in the experiment and to randomize it, four different sequences (with 13 sets of images each) were used in the study:

- Sequence 1: I-OE-CE-0–1-0–2-0–3-0–4-0-CE.
- Sequence 2: I-OE-CE-0–2-0–3-0–4-0–1-0-CE.
- Sequence 3: I-OE-CE-0–3-0–4-0–1-0–2-0-CE.
- Sequence 4: I-OE-CE-0–4-0–1-0–2-0–3-0-CE.

The sequence of images shown to each subject was established a priori in a random and balanced way. The total presentation time of each sequence of images was approximately 23 min (1365 sec). The time of exposure of each type and the number of images that composed each sequence are shown in Fig. 3. In each sequence, the subjects first read the instructions on the screen for 15 sec (I). This was followed by an eyes-open (OE) for 15 sec and eyes-closed (CE) for 180 sec time frame. Then, they began viewing the images in different randomized sequences. To reduce the effect of biased transition probability based on the emotions elicited previously [26], all sets of emotional images were preceded and followed by a set of neutral images. Upon completion, the subjects were again asked to keep their eyes closed for 180 sec.

2.6. Statistical analysis

All of the statistical analyses were carried out using IBM SPSS® Statistics (Version 24.0) for Windows. The normal distribution of the data was analyzed by Kolmogorov Smirnov ($p < 0.05$), and nonparametric statistics were applied due to the results obtained. The Wilcoxon Rank-sum test was used to determine the possible event-related oscillation differences among the averages of data about the alpha, beta, delta, and theta waves registered by the different electrodes in response to positive and negative emotional images. The within-subject factors included in the analysis were five types of emotional images (neutral; positive ↑v, ↓a; negative ↓v, ↑a; positive ↑v, ↑a; and negative ↓v, ↓a) and eight electrodes positions (Fp1, Fp2, F3, F4, F7, F8, T7, and T8).

3. Results

3.1. Results of event-related data of delta waves

The results obtained for event-related delta waves indicated significant differences in the following measures (see Fig. 4). The data obtained indicated that the positive images related to low arousal (↑v, ↓a) induced lower delta activity in the Fp2 location than the positive images related to high arousal response (↑v, ↑a) ($p = .030$).

For the F7 and F8 location, the data also indicated statistically significant differences. In the F7 location, event-related data indicated that the positive images (↑v, ↓a) induced lower delta activity than the other positive images (↑v, ↑a) ($p = .028$) and negative images (↓v, ↑a) ($p = .05$). The results for the F8 location, the data showed that the neutral images induced lower delta brain activity than the positive images (↑v, ↑a) ($p = .008$) and the negative images (↓v, ↑a) ($p = .037$).

3.2. Results of event-related data of theta waves

The results obtained for event-related delta waves indicated significant differences in the F7 and F8 locations (see Fig. 5). Specifically, the results for the F7 location showed that the positive images (↑v, ↓a) induced a lower theta activity response than the other positive images (↑v, ↑a) ($p = .003$) and the negative images (↓v, ↑a) ($p = .04$). The F7 location also shown less theta activity for the negative images (↓v, ↓a) than for the negative images (↓v, ↑a) ($p = .03$) and the positive images (↑v, ↑a) ($p = .009$).

For the F8 location, the data indicated lower brain activity in response to the neutral images than the positive images (↑v, ↑a) ($p = .013$) and the negative images (↓v, ↑a) ($p = 0.10$). There was also a significant lower theta wave activity between the positive images (↓v, ↑a) and the other positive images (↑v, ↑a) ($p = .016$), as well as the negative images (↓v, ↓a) ($p = .02$).

3.3. Results of event-related data of alpha waves

The results obtained for event-related alpha waves indicated significant differences in the following measures (see Fig. 6). For the F7 location, alpha waves showed significant differences between positive and negative emotional images. The alpha response was significantly lower for positive images (↑v, ↓a) than for the other type of positive images (↑v, ↑a) ($p = .012$). Moreover, negative images (↓v, ↓a) induced a significantly lower alpha response than the other negative images (↓v, ↑a) ($p = .009$) and also the positive images (↑v, ↑a) ($p = .03$).

For the F8 location, the data showed that there were significant differences in the alpha wave response, indicating that the neutral images induced lower alpha waves than the negative images (↓v, ↑a) ($p = .003$) and also the positive images (↑v, ↑a) ($p = .025$). Another difference that was observed indicated that the positive images (↑v, ↓a) elicited a lower alpha response than the other positive images (↑v, ↑a) ($p = .028$) and also the negative images (↓v, ↑a) ($p = .04$).

For the T8 location, the data indicated differences for alpha waves. Specifically, the neutral images induced a statistically lower alpha response than the positive images (↑v, ↑a) ($p = .028$).

3.4. Results of event-related data of beta waves

The results obtained for event-related beta waves indicated

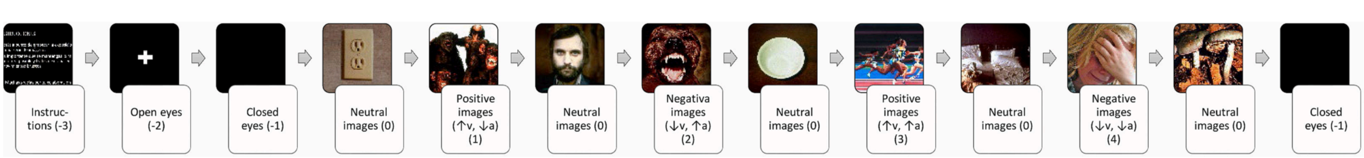

Fig. 3. Example of the presentation of the image sequence used in the study.

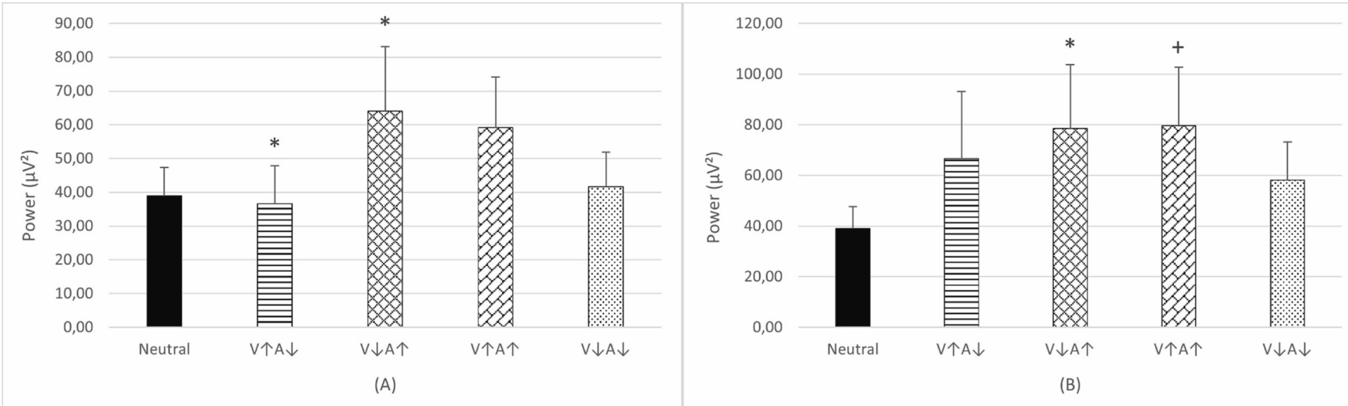

Fig. 4. Results obtained for event-related delta waves power (μv2) obtained for the (A) F7 electrode location, and (B) F8 electrode location. Data are presented as mean ± SEM. (A)(*) $p < 0.05$; positive images (↑v, ↓a) vs. negative images (↓v, ↑a) and positive images (↑v, ↑a); negative images (↓v, ↑a) vs. negative images (↓v, ↓a). (B)(*) $p < 0.05$; negative images (↓v, ↑a) vs. neutral images. (+) $p < 0.01$; positive images (↑v, ↑a) vs. neutral images.

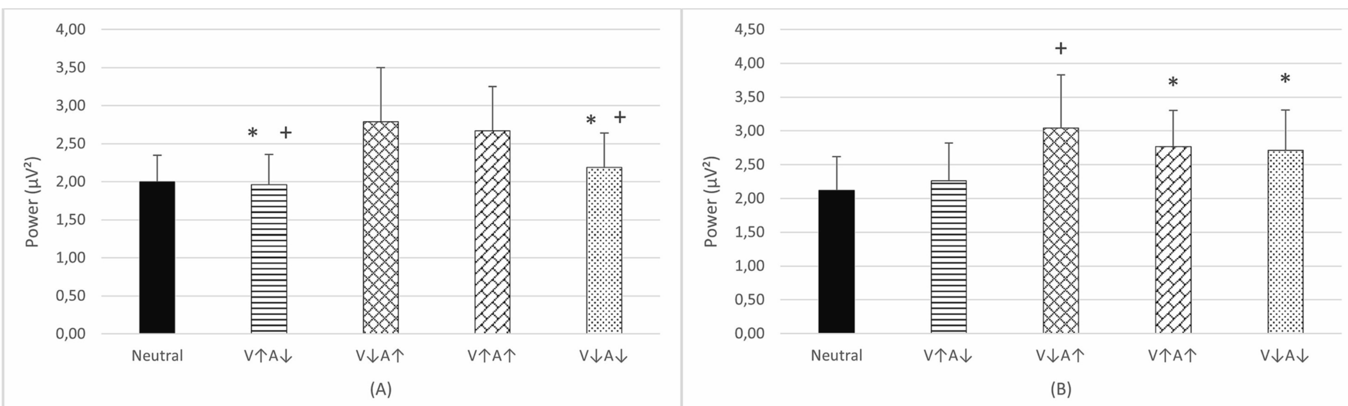

Fig. 5. Results obtained for event-related theta waves power (μv2) obtained for the (A) F7 electrode location, and (B) F8 electrode location. Data are presented as mean ± SEM (A)(*) $p < 0.05$; positive images (↑v, ↓a) vs. negative images (↓v, ↑a); negative images (↓v, ↓a) vs. positive images (↑v, ↑a). (+) $p < 0.01$; positive images (↑v, ↓a) vs. positive images (↑v, ↑a); negative images (↓v, ↓a) vs. negative images (↓v, ↑a). (B)(*) $p < 0.05$; positive images (↑v, ↑a) vs. positive images (↑v, ↓a) and neutral images; negative images (↓v, ↓a) vs. positive images (↑v, ↓a). (+) $p < 0.01$; negative images (↓v, ↑a) vs. neutral images.

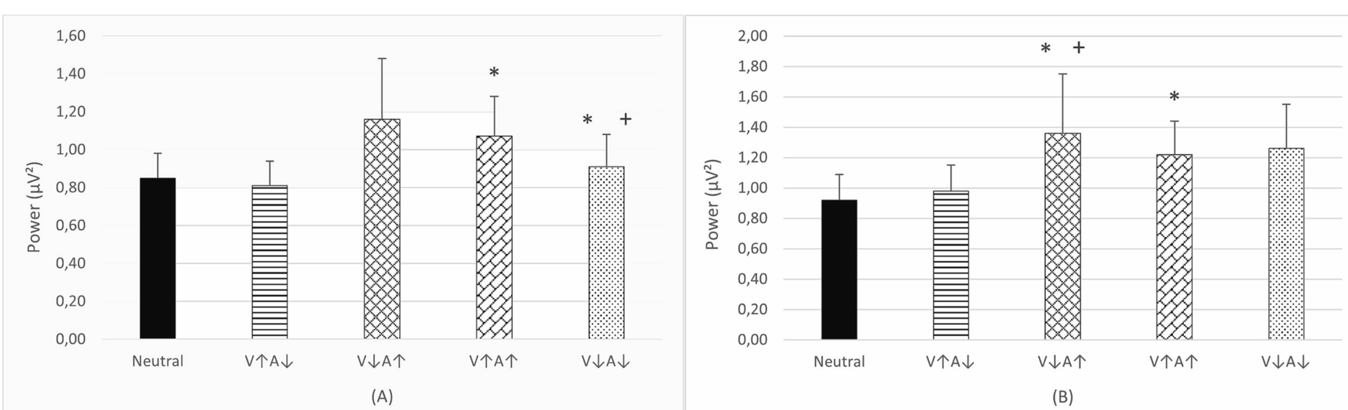

Fig. 6. Results obtained for event-related alpha waves power (μv2) obtained for the (A) F7 electrode location, and (B) F8 electrode location. Data are presented as mean ± SEM. (A)(*) $p < 0.05$; positive images (↑v, ↑a) vs. positive images (↑v, ↓a). (B)(*) $p < 0.05$; negative images (↓v, ↓a) vs. negative images (↑v, ↑a). (+) $p < 0.01$; negative images (↓v, ↓a) vs. negative images (↓v, ↑a).

significant differences in almost all the locations of the EEG electrodes (except in the F4 and F7 locations) (see Figs. 7 and 8). The differences obtained in the Fp1 location indicated that the neutral images induced a lower beta response than the two types of positive images (↑v, ↓a) ($p = .01$) and (↑v, ↑a) ($p = .006$), as well as the two types of the negative images (↓v, ↑a) ($p = .004$) and (↓v, ↓a) ($p = .026$).

The results obtained for the brain activity registered in the Fp2 location indicated similar information as that observed for Fp1. The neutral images induced significantly lower beta activity in this brain area than the two types of positive images (↑v, ↓a) ($p = .014$) and (↑v, ↑a)

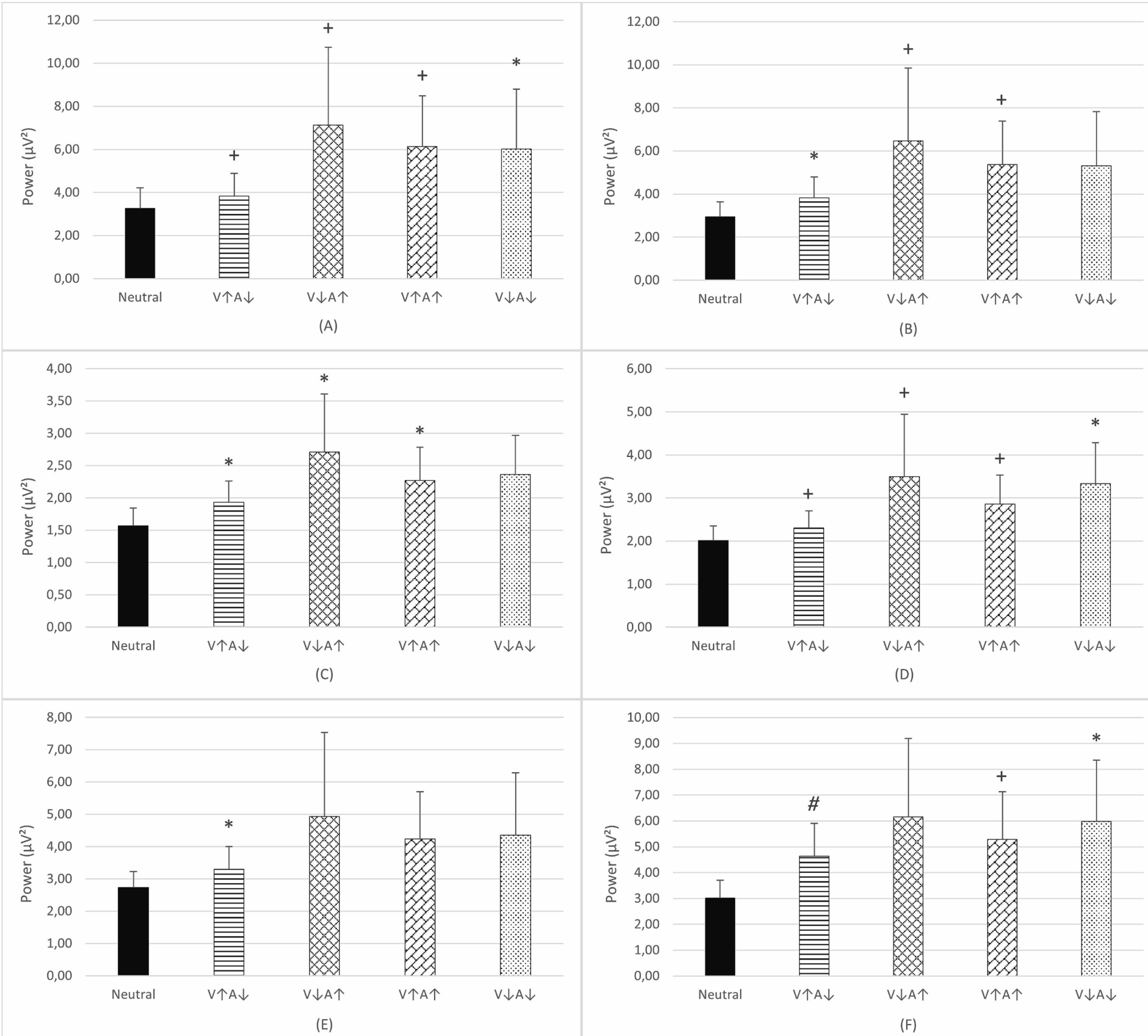

Fig. 7. Results obtained for event-related beta waves power (μv2) obtained for the (A) Fp1 electrode location, (B) Fp2 electrode location, (C) F3 electrode location, (D) F8 electrode location, (E) T7 electrode location, and (F) T8 electrode location. Data are presented as mean ± SEM. (A)(*) $p < 0.05$; negative images (↓v, ↓a) vs. neutral images. (+) $p < 0.01$; positive images (↑v, ↓a) and (↑v, ↑a) vs. neutral images; negative images (↓v, ↑a) vs. neutral images. (B)(*) $p < 0.05$; positive images (↑v, ↓a) vs. neutral images. (+) $p < 0.01$; negative images (↓v, ↑a) vs. neutral images; positive images (↑v, ↑a) vs. neutral images. (C)(*) $p < 0.05$; positive images (↑v, ↓a) and (↑v, ↑a) vs. neutral images; negative images (↓v, ↑a) vs. neutral images. (D)(*) $p < 0.05$; negative images (↓v, ↓a) vs. neutral images. (+) $p < 0.01$; positive images (↑v, ↓a) and (↑v, ↑a) vs. neutral images; negative images (↓v, ↑a) vs. neutral images. (E)(*) $p < 0.05$; positive images (↑v, ↓a) vs. neutral images. (F)(*) $p < 0.05$; negative images (↓v, ↓a) vs. neutral images. (+) $p < 0.01$; positive images (↑v, ↑a) vs. neutral images. (#) $p < 0.0001$; positive images (↑v, ↓a) vs. neutral images.

(p =.005) and the negative images (↓v, ↑a) (p =.008).

For the F3 location, the data also shown significant differences between the neutral images and the positive and negative images. The data indicated that the subjects presented a lower beta response to neutral images than the two types of positive images (↑v, ↓a) (p =.01) and (↑v, ↑a) (p =.019) and the negative images (↓v, ↑a) (p =.048).

The data obtained for brain activity registered by the F8 location indicated that there was lower beta wave activity for the neutral images than for all of the other images, i.e., the two types of positive images (↑v, ↓a) (p =.003) and (↑v, ↑a) (p =.007), as well as the two types of negative images (↓v, ↑a) (p =.008) and (↓v, ↓a) (p =.021).

The brain activity of beta waves registered in the T7 and T8 locations showed some differences with the other locations. When beta waves were analyzed in the temporal lobe, there was a lower response to the neutral images than to the positive images (↑v, ↓a) (p =.023) in the T7 location, and a lower beta response to the neutral images than to the positive images (↑v, ↑a) (p =.028) in the T8 location.

4. Discussion

This research study, which is aimed at analyzing the neurophysiological response in late adolescents and young adults to emotional stimuli that vary according to their valence and arousal, has yielded interesting results. Specifically, the data obtained has shown differences in the functioning and activation of different brain waves in response to images with positive or negative emotional content as well as according

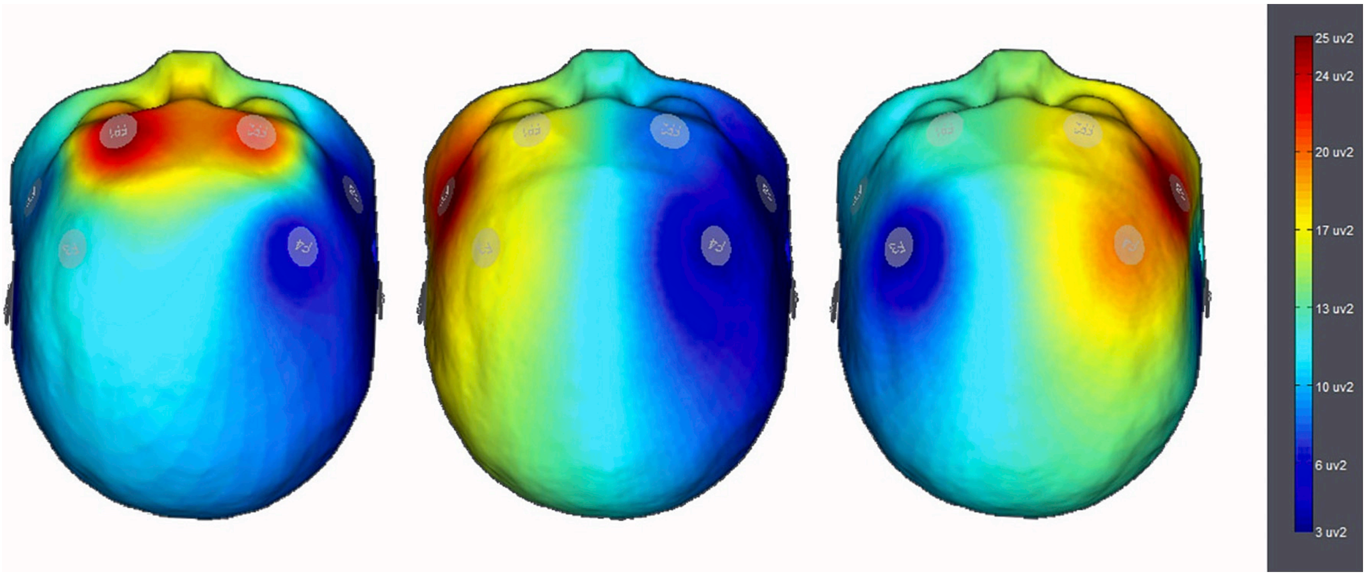

Fig. 8. Example of EEG maps of the brain activity obtained from a participant of the study in response to positive images, from left to right: for beta waves power (note the activation in the Fp1 and Fp2 electrodes position); for alpha waves power (note the activation in the F7 electrode position); and for theta waves power (note the activation in the F8 electrode position).

to the level of arousal elicited by them. Since emotions have been related to synchronized changes in functions such as cognitive processing, behavioral responses, subjective feelings, and physiological reactions [50], it would be useful to know more about the functioning of the emotions when defining the relationship between emotional response and physiological reactivity. The selection of the images used was made following the two-dimensional model, which is based on the valence and arousal analyzed in the IAPS images for the Spanish population [34,47,35]. Based on this classification, we selected images that evoke positive emotions (high valence) with high arousal (e.g., surprise or happiness) and those with low arousal (e.g., satisfaction or relaxation). A distinction was also made between images that evoke negative emotions (low valence) with high arousal (e.g., fear or anger), and those with low arousal (e.g., disgust or sadness). It should be recalled that the cortical activity recorded by EEG in this study was focused on the analysis of the data collected through eight electrodes that were distributed among the prefrontal (Fp1 and Fp2), frontal (F3, F4, F7, and F8), and temporal (T7 and T8) lobes.

In the following, the main results obtained are shown and discussed according to the differences in neural activity depending on the type of emotional images (i.e., their valence and arousal). According to this criterion for the positive images with high arousal (↑v, ↑a) there was an increase in beta wave activity in the prefrontal lobe and the right temporal cortex (see an example of this activity in Fig. 8). There was also an increase in alpha and delta waves in the frontal lobe. In addition, there was also an increase in delta waves in the right prefrontal lobe and increased theta activity in the electrode located in the right temporal cortex. For the positive images with low arousal (↑v, ↓a), different results were observed. There was an increase in beta waves in the prefrontal, frontal, and right temporal lobes. There was also less alpha, delta, and theta wave activity (principally in the frontal lobe).

With regard to the negative images, differences based on the arousal level were also observed. For negative images with high arousal (↓v, ↑a) there were also an increase in beta waves in the prefrontal and frontal lobes. Increased alpha and delta wave activity was also observed in the frontal cortex in response to these images. There was an increase for the theta wave response that was observed only in the right frontal lobe. For the negative and low arousal images (↓v, ↓a), increased beta wave activity was observed in the frontal cortex and the left prefrontal cortex. There was also increased delta and theta wave activity in the right frontal cortex and a decrease alpha waves in the left frontal cortex.

Studies by other authors have obtained slightly different results regarding brain wave variations in response to IAPS imaging. In line with our results, Reali et al. [39] observed in young adults an increase in theta wave activity in response to high-valence, high-arousal imagery. For their part, Balconi et al. [8] obtained in adults evidence related to an increase in theta and delta waves in response to negative imagery, which is related with our results, obtaining no significant differences in alpha and beta wave activity. In contrast to this result, in our study we did observe significant differences in alpha and beta wave activity in response to negative images, mainly in the frontal lobe area. In another study conducted with adult men, a differential pattern of cortical activity in response to positive and negative images was obtained, with a higher level of brain activity observed in response to positive images and lower brain activity in response to negative images [7]. This result also does not agree exactly with what was obtained in our study, since, as can be seen in our results, the differences in brain activation occurred in response to both positive and negative images. Possibly, the observed difference is influenced by the age of the subjects, since as we have seen previously, it has been observed that in adolescents there is a greater cortical response in relation to emotional reactivity [9,17]. Thus, a closer correspondence with the results obtained in samples of a similar age to the one used in our study (i.e., [39] is observed, whereas in studies conducted with adults a lower cortical reactivity to negative emotional stimuli seems to be observed. In research conducted by Orgo et al. [37], an increase of asymmetric activity was observed in response to negative images in the frontocentral, central, centroparietal, parietal, and occipital areas. In response to positive images, Orgo et al. [37] observed a decrease in asymmetric activity in the temporal, centroparietal, parietal, and occipital areas. Taking into account that brain asymmetry was not evaluated in our study, we consider these results very interesting in order to propose future studies that will help us to advance in the knowledge of the brain response to emotions. The use of the images contained in the IAPS has been very widespread in the different studies analyzed. Certainly, the thorough analysis of the images contained therein indicates that, in some cases, the images can be very useful. Nevertheless, depending on the sample in which they are to be used, some of the images may require some type of update. The advance of new technologies allows some of these techniques to be updated through the development and design of more realistic situations, with techniques based on virtual reality being the most frequently used for this purpose [41].

Other studies have indicated that our brain is more sensitive and responsive to negative and low-valence stimuli and emotions because this response favors our survival [31,2,6]. If we look at the results obtained in our study, we do not clearly observe this relationship since the brain response obtained shows a more evident relationship with the level of arousal of the emotions elicited than with their emotional valence. In fact, in the study carried out by Maffei and colleagues [31], it can be observed that the characteristics of the subjects evaluated in relation to empathy can modulate the brain response obtained according to the elicited emotions. This is particularly relevant for evaluating the way in which certain personality factors and individual differences can modify the brain responses obtained to the same emotional stimuli. At a stage such as adolescence, this type of study can provide more complete and through information that would be very relevant for future research in this area.

Some pioneering studies already showed the importance of lateralization of emotional response. In this line, for example Tucker [46] established a holistic and nonverbal conceptualization of the right hemisphere for emotion. For his part, Davidson [14,15] already observed differences in the frontal processing of emotions, indicating that there is some left frontal asymmetry towards positive emotions, manifested through approach-related behaviors, whereas negative emotions, manifested through withdrawal-related behaviors, seemed to elicit greater right frontal activation. Furthermore, according to these initial studies by Davidson, individual differences in these asymmetrical patterns of brain functioning were related to each person's affective style. In general, our results indicated that most of the differences found with respect to theta wave activity were obtained at electrodes placed in the right frontal cortex (F8 location). In relation to the most current studies that have analyzed brain asymmetry in relation to emotions, it is worth noting that studies by other authors have established that frontal level asymmetries are related to emotion valence, with increased left frontal cortical activity observed in response to positive valence emotions and increased right brain activity in response to negative emotions, which are in line with what was observed by Davidson [14,15]. Specifically, Zhao et al. [50] observed increased right hemisphere frontal alpha activity in response to emotions related to tenderness compared to those related to amusement. These results differ from those obtained in our study. There was a differentiation in alpha wave activity, but it was more related to the level of arousal elicited than to the valence of emotions (positive or negative). Taking the alpha waves that have shown changes in the study by Zhao et al. [50] as a reference, our results show that images eliciting high arousal induce an increase in alpha wave activity at the frontal level in both hemispheres (F7 and F8 locations); whereas exposure to images with low arousal induces a significant decrease in alpha waves in this same area. Zhao et al. [50] also observed that there were differences between negative emotions. When they compared the emotional response to movie scenes evoking anger or fear, there was an increase in theta wave activity in the right hemisphere versus the left hemisphere during the viewing of fear-related images. In line with these results, Balconi et al. [8] concluded that theta activity is related to the response of the amygdala to the emotional contexts, while delta functioning has been related to the motivational system. In view of this finding, Balconi and colleagues observed an increase in theta and delta wave activity in the right hemisphere in response to negative IAPS images. In our study, we found a difference between the neural response of the right hemisphere and the left hemisphere in terms of theta waves. There was a significant increase in theta wave activity at the frontal level (F8 location) in response to negative images with high and low arousal, and also positive images with high arousal. However, for positive images with low arousal, there was a significant decrease in the neural activity of theta waves in the right hemisphere. In the analysis of delta activity, our data indicated an increase in the right hemisphere in response to positive and negative images with low arousal, obtaining a homolateral activity when the images induced high arousal (either positive or negative). Our results are in line with the knowledge that delta and theta activity could be related to the level of arousal of emotional stimuli, regardless of the valence, but they do not agree with the idea suggested by Balconi et al. [8] relating theta and delta activation to emotional and motivational response, respectively.

In the bibliographic analysis of the references reviewed in this study, the most relevant issues that required the most attention are related to the heterogeneity of the processing models of the signals obtained by EEG, the removal of artifacts, and the quantification of the data. Similarly, the placement of the electrodes is highly variable, and most of the contributions limited their studies to one or two type of waves (especially alfa and/or beta). Also, it could be interesting to identify the optimal EEG channels for emotional changes across brain regions, as shown by other studies using a similar approach [1,2,6]). Thus, the disparity in those studies makes it difficult to obtain a general or comparative conclusion. Many of the disparities in the results obtained may be related to the methodological differences observed in the different studies, as indicated in manuscripts published by other authors (e.g., [8]. We used the analysis of event-related oscillations in this study because they have been widely applied in research related to affective image processing. In some previous studies (such as [24]the authors demonstrated the ability to differentiate between different types of images based on the latency recorded, making the brain activity processing more sensitive to emotional stimuli than to neutral stimuli. Another possibility is based on the use of databases that integrate different sensory pathways aimed at evoking positive, negative, and neutral emotions [48,49]. This offers interesting options for the study of the physiological response to emotions, which also allow the standardization of emotional recognition procedures with EEG [25].

With regard to the age of the subjects, few studies have been carried out with late adolescents and young adults. The study of emotional processing and response at this age is especially relevant if we consider the characteristics of this age group and the importance of developing socio-emotional abilities to help them overcome emotional obstacles. Adolescence is a sensitive period of time where the capability to regulate emotions could be influenced by different neuropsychological factors. These include the differences between brain development in adolescence and in adulthood as well as the changes produced in the connections and circuits among the different brain areas. Several studies indicate that adolescence is a particularly important stage in emotional reactivity and in the development of neural circuits related to the development of emotional response and its regulation [11,17]. These factors may influence the observed results, making, adolescents show greater reactivity to certain types of images with emotional content than adults. Güntekin et al. [24] analyzed brain activity (through event-related coherence) in young adults in response to IAPS, obtaining some results that are in line with those obtained in our study. Negative images induced higher delta and theta coherence values. Likewise, it was observed that there was greater brain connectivity in response to emotional images compared to neutral images. Güntekin et al., [24] also considered that in the perception of emotional stimuli, the brain works in a connected way, being especially responsive to exposure to negative images, with higher response in women than men. The fact that gender differences in neural activity in response to emotional stimuli have been observed would be a possible direction for us to take in future studies. Another study carried out in adolescents by [36] indicated that the emotional valence of certain stimuli could be mediated by measures of frontal asymmetry and the degree of neuroticism. Moreover, it was observed that this mid-frontal asymmetry was directly related to neuroticism and to the emotional valence of the fear response, with this being established as a possible indicator of the risk of suffering a psychopathology.

The most important contributions of or study are related to the age of the sample and the establishment of a simple method of quantification of EEG measurements that allows extrapolation to other types of studies.

Our study also extends the analysis to alpha, beta, delta, and theta waves, while other studies limit their analysis to only two types (or even one type) of waves. Despite these issues, the study also has some limitations that should be taken into consideration. The first one is related to the small sample size and the fact that the majority of the participants were female, due to the fact that girls tend to response more positively to the recruitment than boys. Thus, the sample of this study might be biased and only partially representative for the broader population of Spanish adolescents, due to the sampling procedures of convenience and small sample size. Therefore, this study should be extended to include a larger sample and more boys in order to compare the gender differences with the results obtained. Future studies using more boys will make it possible to expand the sample, in order to provide more deterministic data and to allow for a better analysis of possible gender differences. The use of a sample with a balanced distribution of males and females would allow further research on gender differences based on emotional changes by EEG, continuing the research on this subject carried out in other studies [3,4,5]. Second, it would be relevant to analyze the participants' perception of the degree of valence and emotional activation of the projected images in order to determine whether the values obtained in the validations of other studies are maintained or whether they require updating or modification. Perhaps the use of other types of stimuli, such as movie clips, olfactory stimulus, or scenes developed using virtual reality techniques, could provide more effective emotional stimulation in the adolescents of today. In addition, it could be interesting to apply the Self-Assessment Manikin (SAM) self-report scale [29] to assess the emotional perception of the evaluated subjects as well as their possible individual differences. Given the great disparity of existing models and measurements with EEG in the existing scientific literature, in future studies, we are planning to add measures that are related to the connectivity of neural circuits or brain asymmetry, as well as the analysis of the gamma waves. After having reviewed studies in which personality factors may modulate the responses obtained, we also planned to add measurements of this type to review possible interactions and differences. Future studies using comparison groups of different age would help explain the differences in the results obtained by other studies, especially considering comparison with groups of adults.

5. Conclusion

In summary, this study has shown that exposure to different emotional images can induce different cortical brain activity measured by EEG in adolescents and young adults through the analysis of alpha, beta, delta, and theta waves. The main differences observed are based on the valence of the images shown as well as on their arousal level. Using the dimensional model of emotions of Lang [28], the combination of these two dimensions involves four types of emotions that show differences in terms of neurobiological responses of cortical brain activation. This is in line with some of the results obtained in studies of other authors. In addition, when taking the location of the brain areas recorded using EEG into account, effects are also observed in terms of emotional response based on the differential activation of the prefrontal, frontal, and temporal lobes. This study is relevant because it expands knowledge about emotional response at the neurobiological level at a developmental stage that is particularly pertinent to identity formation and emotional stability in adulthood. Moreover, as discussed throughout this work, the wide heterogeneity of EEG quantification procedures and the analysis of the data obtained means that obtaining these results offers new possibilities for analysis and brings new perspectives to the study of emotions. Finally, with respect to the implications of the results obtained, obtaining objective evidence related to emotional response may be of interest when addressing emotional well-being at an early age through new prevention or intervention strategies based on new technologies.

Data access statement.

As part of IARR's encouragement of open research practices, the authors have provided the following information:

- This research was not pre-registered.
- The data used in the research are available.
- The data can be obtained "via email"
- The materials used in the research are available.
- The materials can be obtained "via email"

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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