Assessing Emotion-Induced Variations of Event-Related Potentials and Heart Rate During Affective Picture Processing

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Abstract: Emotions are psychological responses to stimuli that can induce measurable variations in physiological parameters. While actual emotions span a continuum spectrum, they can be grouped into a finite number of classes or modeled in terms of independent dimensions, the most common of which are arousal (low to high) and valence (positive, neutral, and negative). In this work, we investigated the modulation of physiological parameters related to both the central (CNS) and the autonomic (ANS) nervous systems induced by passive and sustained affective stimulation. Specifically, an Event-Related Potential (ERP) analysis was conducted to explore the effect of the arousal and valence dimensions on cortical activation. Meanwhile, their influence on the ANS activity was evaluated through time-domain heart rate (HR) parameters. When high arousal stimuli are delivered, the experiment revealed that specific ERP components (i.e., P300 and the late positive potential, LPP) are modulated by the valence dimension, with positive and negative images inducing a stronger response than neutral stimuli. Instead, the early posterior negativity (EPN) was found to be influenced by the stimulus arousal but not by the valence of the processed pictures. Finally, HR parameters were principally modulated by the valence of the stimulation, in line with the observed ERP changes and expectations from the literature.

1 INTRODUCTION

Emotions can be described as the responses to external or internal stimuli influenced by individual experiences that are able to induce physiological changes (Reali et al., 2018b). Both the central nervous system (CNS) and the autonomic nervous system (ANS) have a fundamental role in the ability to regulate emotions during the processing of affective stimuli (Mizuno-Matsumoto et al., 2020). Despite the great interest in human emotions, few conclusions about the emotional response of these two systems had been drawn until a standardization of the stimulation was proposed. Based on the first affective and psychological research theories and findings, a dimensional model of emotional states has been derived and widely employed. According to this model, all the affective states can be seen as the linear combination of *valence* (pleasant/positive vs unpleasant/negative sensation) and *arousal* (calm/low vs excited/high) components (Russell, 2003). Following this perspective, the International Affective Picture System (IAPS) dataset has been developed, validated, and continuously updated to provide a standardized set of emotional stimuli for affective research (Lang Bradley, M.M., & Cuthbert, B.N., 2008).

The study of brain activity modulations in response to emotional stimuli has a long history in the literature, particularly in the form of event-related potential (ERP) analysis (Olofsson et al., 2008), and has often been paired, or substituted, with the evaluation of changes in parameters related to the ANS (Polo et al., 2023; Reali et al., 2018a; Telles et al., 2019).

In terms of ERP analysis, findings consistently identified the early posterior negativity (EPN) as modulated by the arousal level of the stimulus, the late positive potential (LPP) component as associated with the processing of the emotional information (thus related to the valence dimension), while the P300 peak amplitude appeared modulated by the combination of valence and arousal dimensions (Olofsson et al., 2008; Schindler et al., 2022).

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Regarding a more general assessment of cortical response, a prominent frontal activation, also in terms of an asymmetry in the alpha frequency band, has often been reported in response to positive and negative stimulation (Coan and Allen, 2004; Kop et al., 2011).

However, due to differences in the study protocols (i.e., passive/active viewing, exposure times, pictures or video stimuli, etc.), the objectives, the devices used to deliver the stimuli (e.g., PC monitors, virtual reality visors, immersive settings) or to collect the physiological responses, and, above all, the variability between subjects, results are difficult to replicate across studies.

Heart rate variability (HRV) has often been used as an indicator of the ANS response to emotions, both in the time and frequency domains. Together with other ANS-related parameters, such as respiration rate and electrodermal activity, the heart rate (HR) variations have been used to define emotion classification models (Egger et al., 2019; Polo et al., 2023; Reali et al., 2018a). Moreover, HR parameters in the time domain (i.e., mean and standard deviation) at rest have been explored to determine the emotional regulation ability of the subjects and predict their cortical response to successive emotional stimulations or attentional tasks (Ruiz-Padial and Mercado, 2021; Telles et al., 2019), but rarely they have been analyzed in conjunction with ERPs variations. Indeed, to the best of our knowledge, no studies explored the influence of both valence and arousal factors on ERP components and HR simultaneously.

In this work, we present an ERP analysis and an evaluation of the simultaneous ANS response during affective picture stimulation. Specifically, we designed an IAPS-based passive stimulation protocol featuring sequences of images delivered for an extended exposure time (12 seconds). The goal of such a long exposure, unusual for an ERP analysis, was to allow the volunteer to process each affective stimulus completely and test the effect of this processing rather than the first impression of each picture. Moreover, this was required to properly evaluate ANS variations, as analysis windows of adequate length are needed to accurately estimate HR parameters (Castaldo et al., 2019). As for the ERP analysis, we focused on the late components (EPN, P300, and LPP), which have been associated with the encoding processing phase for emotional stimuli (Olofsson et al., 2008).

2 MATERIALS AND METHODS

2.1 Participants and Procedure

Thirty-one healthy participants (22 males and 9 females) aged between 19 and 27 (mean=20.9; SD=1.5) were recruited for the study. Volunteers were instructed about the protocol and told they could withdraw from the trial at any moment. Before the beginning of each experimental session, participants were asked to sign a written consent to participate in the study.

The experiment was conducted in front of a PC monitor, which was used to provide the visual stimuli. Ninety images were selected from the IAPS database and grouped into three levels of arousal and three of valence. Specifically, the selected arousal ranges were 2.41-3.59 for the “low arousal” (LA) set of pictures, 3.60-5.49 for the “medium arousal” (MA) one, and 5.50-7.35 for the “high arousal” (HA) set. Within each arousal block, three subsets of valence pictures, namely “negative,” “neutral,” and “positive” valence, were selected, containing ten pictures each and showing the following valence ranges: 2.04-5.39 (negative), 5.40-6.19 (neutral), and 6.20-8.28 (positive). Combining these arousal and valence ranges led to nine arousal-valence partitions, each containing ten pictures expected to elicit similar emotions. The above ranges were chosen as a trade-off to maximize the separation among the nine sets of images in terms of arousal and valence while preserving the desired number of pictures (ten) for each of the nine arousal-valence level combinations.

Regarding the stimulation protocol (Figure 1), the nine arousal-valence blocks were presented in order of increasing levels of arousal to keep participants engaged during the experiment. To avoid any other sequence-related bias, the three valence sub-blocks (i.e., negative, neutral, and positive) and the ten pictures of each sequence were presented in a random order. A “neutral image”, a picture intended not to elicit any particular emotion showing a country landscape without any particular subject represented, was shown for 30 seconds between each sequence of ten pictures to reduce the propagation of the physiological response from one arousal-valence block to the following.

Each IAPS image was displayed for 12 seconds; therefore, each condition had a total duration of 2 minutes. A first 90-second neutral image was displayed at the beginning of the protocol to make participants relax and prepare them for the presentation of the first arousal-valence block.

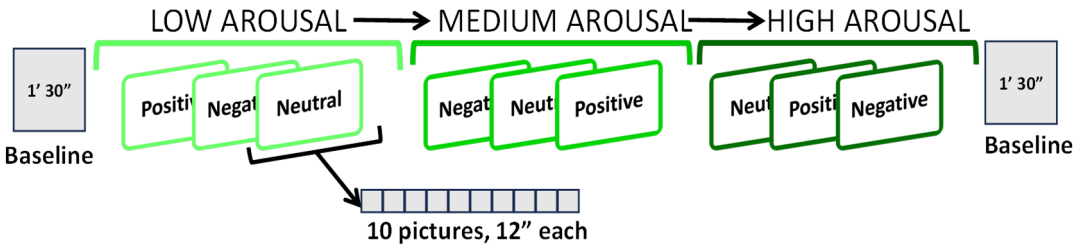

Figure 1: Stimulation sequence. Arousal blocks of pictures were always presented in increasing order. Within each arousal block, the valence sub-blocks were presented in randomized order (i.e., different for each participant). The ten pictures presented within each valence block were also randomized.

Electroencephalographic (EEG) and electrocardiographic (ECG) signals were collected during the entire procedure.

The protocol was approved by the Institutional Ethics Committee of Politecnico di Milano.

2.2 Signal Acquisition

EEG signal was acquired by means of a portable system (SD LTM Express and System Plus Evolution software, Micromed, Italy). Brain signals were recorded from 25 electrodes placed according to the 10/10 system with the following recording channels: Fpz, Fp1, Fp2, AF3, AF4, AF7, AF8, Fz, F1, F2, F3, F4, F5, F6, F7, F8, Cz, C3, C4, T7, T8, P7, P8, O1 and O2. Data were acquired at a sampling rate of 256 Hz, with the reference electrode placed on the pre-cabled cap, between CPz and Pz.

The ProComp Infiniti system (Thought Technology Ltd., Canada), a battery-powered device, was used to record a single lead ECG at the default sampling rate of 2048 Hz, with three pre-gelled disposable electrodes placed in lead II configuration.

2.3 ECG and EEG Signal Analysis

The collected ECG and EEG signals were imported and processed in MATLAB (R2019B).

The Pan-Tompkins algorithm(Pan and Tompkins, 1985) was applied to the ECG traces to detect the R peaks and obtain the RR time series. Such a well-known algorithm comprises an initial band-pass finite impulse response (FIR) filter to reduce baseline wander and high-frequency noise, followed by additional steps to enhance the QRS complexes and enable R peak identification. After finding the approximate location of the R peaks on the filtered signals, their exact positions were determined by finding the closest local maxima on the original ECG signals. Finally, the identified R peaks were visually inspected to avoid false detections or missed beats. For each stimulation block (i.e., ten-picture sequence), the mean RR interval and the related standard deviation were extracted. The entire duration of each stimulation block (2 minutes) was considered for the calculation of these features, given the temporal requirements for accurate estimation of time-domain HR indices (Castaldo et al., 2019).

EEG signals were pre-processed using the EEGLAB toolbox [https://eeglab.org/] and custom scripts optimized for the study aim (Cassani et al., 2022; Coelli et al., 2024). First, data were band-pass filtered between 1 Hz and 45 Hz with a FIR (order = 400), zero-phase filter, and bad channels were visually selected and removed (i.e., low signal quality due to low electrode adherence).

Signals were segmented into epochs from -1 to +4 seconds with respect to each stimulus presentation. The extended Infomax independent component analysis (ICA) algorithm was applied to the concatenated epochs and, with the support of the IClabel plugin (Pion-Tonachini et al., 2019), the sources of artifacts (i.e., ocular, heart, muscular and residual power line noises) were identified and removed. The previously rejected bad channels (if any) were interpolated using spherical spline interpolation, and signals were re-referenced to the infinite reference using the Reference Electrode Standardization Technique (REST plugin) (Yao, 2001). Finally, epochs with residual artifacts were visually checked and rejected, obtaining 9.14 ± 1.07 valid trials for each participant and condition.

ERPs were obtained for each of the nine conditions of stimulation at each EEG channel by applying the synchronous averaging method and using the 100 ms preceding the stimulus presentation for baseline correction. ERP components were extracted using a fixed time window, as suggested in the literature (Schindler et al., 2022; Schupp et al., 2012). We further explored specific ERP components that have been previously correlated with emotion perception and processing: P300 [270 - 340 ms], EPN [200-300 ms], and the early LPP [400-700 ms]. Specifically, we identified the peak amplitude for the

P300 and the area under the curve (AUC) for both EPN and LPP, since these latter components cannot be described by considering individual peaks alone.

Given that the polarity of the ERP depends on the channel position, both the peak amplitudes and the AUC were computed by maintaining the original polarity. In fact, negative AUC may be obtained because the areas corresponding to the downstate of the ERP (negative polarity) are subtracted from the positive one (if present). The extracted ERP and parameters were averaged on clusters of channels: Centrals (C3-Cz-C4), Posteriors (P7-P8-O1-O2), Frontal Left (FP1-F1-F3), and Frontal Right (FP2-F2-F4).

Statistical analysis was performed in R to compare the variations in HR and ERP indices across the different stimulation blocks.

3 RESULTS

3.1 Heart Rate Analysis Results

HR variations were analyzed considering the mean (RRmean) and standard deviation (RRstd) of the RR intervals. Since most of the data distributions did not pass the Shapiro-Wilk normality test, the non-parametric Friedman's test and Wilcoxon's Bonferroni-corrected post hoc tests were used to compare the RRmean and RRstd values among the three valence and arousal levels separately (Figure 2). In fact, we did not find any evidence of an interaction between the two factors (Valence*Arousal).

Friedman's test found significant differences for the RRmean values across valence levels ($p = 0.027$), while no significant differences were found for the Arousal main effect. The significant effect of Valence was further explored through pairwise comparisons, which highlighted a significant difference between the positive stimulation against the neutral one ($p = 0.008$) and between the negative and neutral stimulations ($p = 0.008$).

Conversely, for the RRstd values, Friedman's test found a significant difference when comparing the arousal levels ($p = 0.004$) but not for the valence ones. Specifically, HA stimuli significantly differed from the LA ones ($p = 0.019$). Observing an increasing trend of the RRstd from LA to HA, we cannot exclude an influence of the protocol sequence on this finding, given that the IAPS pictures were presented in increasing order of arousal.

3.2 Event Related Potential Results

Figure 3 displays the grand average of the ERP time course for each cluster of channels (rows) grouped by arousal level (columns). Valence levels are directly compared in each subplot.

Since all the computed ERP indices were found to be approximately normally distributed, a repeated measures analysis of variance (ANOVA) with two within factors (Valence and Arousal) was performed for each cluster of channels. The ANOVA was followed by post hoc tests to evaluate simple main effects when needed.

3.2.1 P300

P300 peak amplitude results are shown in Figure 4. A significant interaction Valence*Arousal was found in the Frontal-Right ($F(4,116) = 3.391$; $p = 0.012$) and Frontal-Left clusters ($F(4,116) = 4.17$; $p = 0.003$). On the right hemisphere, significantly larger peaks were detected in the HA block for positive and negative valence with respect to neutral stimuli ($p_{Neut\ vs\ Pos}=0.005$, $p_{Neut\ vs\ Neg}=0.0002$), and differences were observed between HA and MA when the valence was neutral ($p_{HA\ vs\ MA}=0.008$). The same significant differences were found in the left hemisphere during HA stimulation ($p_{Neut\ vs\ Pos}=0.005$, $p_{Neut\ vs\ Neg}=0.002$), and between HA and LA with neutral stimuli ($p_{HA\ vs\ LA}=0.007$).

For the posterior cluster, results followed the same pattern: a significant interaction was found

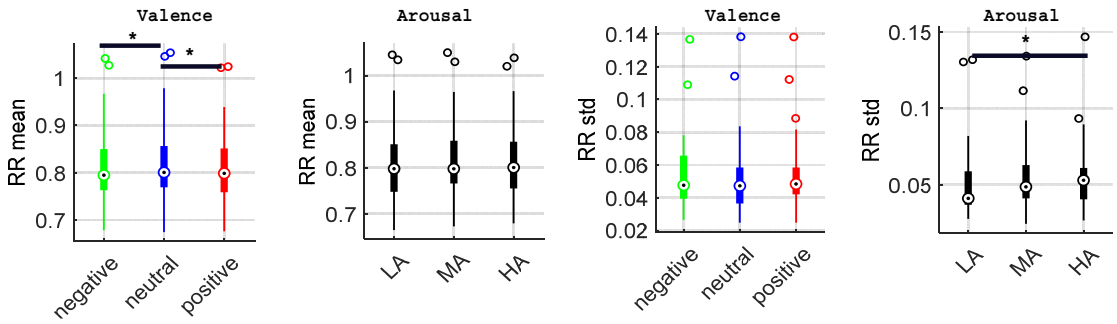

Figure 2: RR mean and standard deviation parameters compared by valence (colors) and arousal (black) levels.

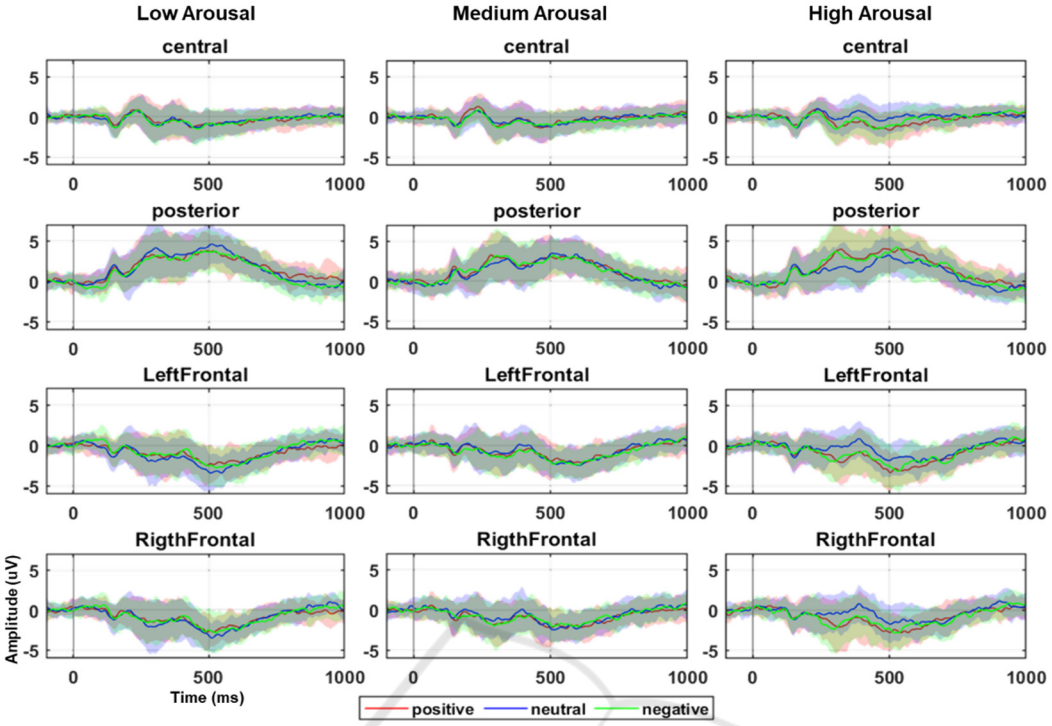

Figure 3: ERP time course averaged across clusters of channels and volunteers for each arousal/valence condition. Solid lines represent the group mean and shaded areas display the standard deviation.

(F(4,116) = 4.794; p = 0.001), and, dividing by factors, we obtained significantly higher peaks in the HA block for both positive and negative valence with respect to neutral images ($p_{Neut\ vs\ Pos}$=0.004, $p_{Neut\ vs\ Neg}$=0.001) and, at neutral valence level, between HA and LA ($p_{HA\ vs\ LA}$=0.0002). Finally, in the central cluster, the interaction was again significant (F(4,116) = 2.653; p = 0.037), and stronger P300 were elicited in the HA block for the negative and positive valence with respect to the neutral ($p_{Neut\ vs\ Pos}$=0.002, $p_{Neut\ vs\ Neg}$=0.0006), and between arousal levels when the valence was neutral ($p_{HA\ vs\ MA}$=0.029, $p_{HA\ vs\ LA}$=0.002).

3.2.2 EPN

No significant interactions between Valence and Arousal factors were identified in any cluster of channels. Only the main effect of Arousal was found significant at the posterior site (F(2,58) = 4.183; p = 0.02), and the post hoc analysis identified differences between LA and MA and between LA and HA ($p_{LA\ vs\ MA}$=0.014, $p_{HA\ vs\ LA}$=0.024).

3.2.3 LPP

Distributions of the LPP area values are displayed in Figure 5.

In the left frontal lobe, the two-factor interaction was significant (F(4,116) =3.747; p = 0.007), and, breaking down by Arousal levels, we found that the positive stimuli elicited a stronger LPP with respect to neutral stimulation ($p_{Neut\ vs\ Pos}$=0.003) in the HA condition. While analyzing the Valence simple main effects, a difference was found in the positive stimulation between HA and MA ($p_{HA\ vs\ MA}$=0.032), whereas HA was different from LA when the stimulation was neutral ($p_{HA\ vs\ LA}$=0.025). In the right frontal lobe, only the main effect of Arousal was found significant (F(2,58) = 3.19; p = 0.048); precisely, LA was different from MA (p = 0.034).

At posterior sites, only the main effect of Arousal was significant (F(2,58) = 3.173; p = 0.049) with a significant pairwise difference between MA and LA ($p_{MA\ vs\ LA}$=0.01). Finally, in the central cluster, the interaction was again significant (F(4,116) = 3.142; p = 0.017), and larger LPP were elicited in the HA block for the negative and positive valence with respect to the neutral ($p_{Neut\ vs\ Pos}$<0.0001, $p_{Neut\ vs\ Neg}$=0.001) and between arousal levels when the valence was neutral ($p_{HA\ vs\ MA}$=0.016, $p_{HA\ vs\ LA}$=0.007).

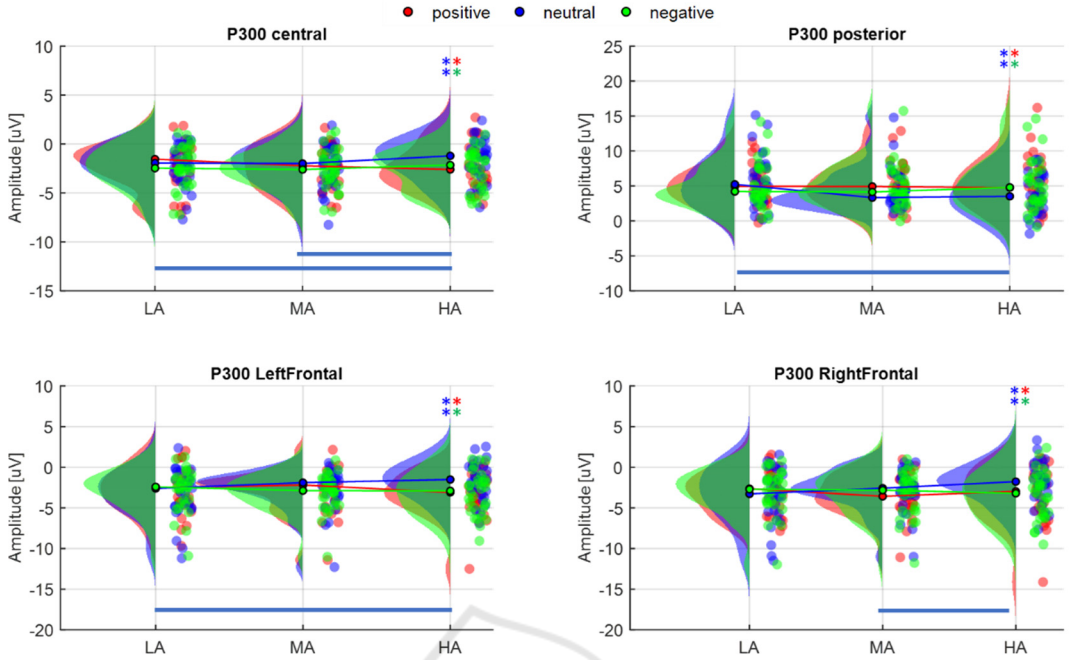

Figure 4: Comparison of P300 amplitude values across valence (colours) and arousal levels (LA, MA, HA). Pairs of * indicate significant differences between valence levels at the corresponding arousal block (e.g., *blue-*red: difference between positive and neutral stimulation). The coloured lines indicate the presence of a significant difference between arousal blocks at the corresponding valence level (e.g., a blue line marks differences between arousal blocks at neutral valence).

4 DISCUSSION

In this work, we presented a classical ERP components analysis applied to an unusual stimulation protocol, justified by our intention to also evaluate the slower response of the ANS through the analysis of the RR series. Moreover, the long picture exposure allowed us to observe the cognitive processing of the presented stimuli (Olofsson et al., 2008) and the associated modulations of both CNS and ANS.

Indeed, a first interesting result was the achievement of an expected cortical stimulation provided by the protocol and demonstrated by the clear ERP patterns obtained for each stimulation condition in the different cortical regions, as defined by clusters of channels. Specifically, ERP waves were found prominent at posterior positions, indicating a primary response of the visual cortex and an early processing of the stimulus at posterior sites (Schupp et al., 2012). Clear ERP patterns were also observed in the frontal regions where effective content is supposed to be further processed (Gable et al., 2014).

The interaction between the arousal and valence emotional dimensions was significant in most cases, particularly highlighting differences during the HA block. Specifically, P300 and LPP were significantly modulated by the valence of the pictures only when the arousal level was high. In line with the literature (Gable et al., 2014; Schindler et al., 2022; Schupp et al., 2012), we found a stronger response to both positive and negative pictures with respect to neutral ones, but these were not different between them.

Unexpectedly, we found that neutral valence images elicited weaker ERP responses in the HA condition when compared to lower arousal levels. This outcome might be explained by the arousal-increasing sequence that could result in a habituation effect, not affecting, interestingly, the volunteers' perception of positive and negative emotions. Moreover, such a perception was not influenced by the presentation sequence, likely thanks to the randomization of the different valence sub-blocks.

The EPN is often identified as a negative deflection over fronto-central sites and a positive waveform at lateral and posterior channels, principally modulated by the arousal dimension of stimulating images (Olofsson et al., 2008). Indeed, our results confirm this statement as we coherently found a modulation of the EPN at posterior sites induced by the arousal dimension as a main effect.

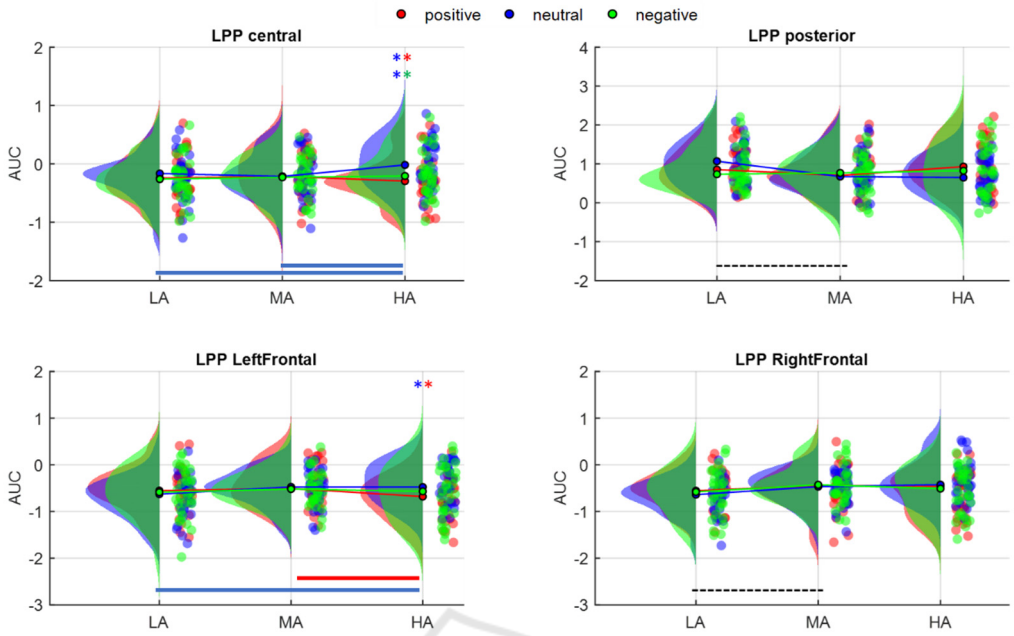

Figure 5: Comparison of LPP areas across valence (colours) and arousal levels (LA, MA, HA). Pairs of * indicate the significant differences between valence levels at the corresponding arousal block (e.g., *blue-*red: difference between positive and neutral stimulation). The coloured lines indicate the presence of a significant difference between arousal blocks at specific valence level. Black lines indicate significant differences between arousal levels when only the main effect of Arousal was found significant.

In line with the EEG results, the analysis of the HR parameters highlighted a modulation of the mean RR due to the valence of the stimulation, resulting in a shorter RR interval during both negative and positive stimuli with respect to neutral ones. The arousal dimension did not modulate the mean RR but its standard deviation, which increased with the arousal level. While the results related to the mean RR are comparable with those from previous studies, where HR features have been found more sensitive to valence variations rather than arousal(Bensafi, 2002; Colomer Granero et al., 2016), changes in RRstd with arousal are not well documented in the literature. Since the picture arousal levels increased over time in our stimulation protocol, we cannot exclude RRstd changes to be an effect of time rather than arousal-dependent. In this sense, even if the protocol was designed with an increasing arousal stimulation to keep the subject engaged, the lack of randomization in the arousal dimension might be considered a limitation of the study. However, a more detailed analysis of the HR data (e.g., including frequency-domain features) is needed to shed light on this peculiar finding. Moreover, to increase the statistical power of our findings, a larger sample size is needed, while to assess the effectiveness of the stimulation, in terms of elicited emotions, the participants' feedback should be collected through questionnaires, and the agreement among them investigated.

5 CONCLUSIONS

In summary, this study confirmed the efficacy of the proposed stimulation protocol as it induced HR variations and ERP responses with similar characteristics to those observed in previous works through different affective stimulation protocols. Thanks to the longer exposure times guaranteed by our protocol, these physiological responses could be assessed both at the CNS and ANS levels through the simultaneous analysis of ERP and HR parameters, respectively. In this work, we focused on a time-domain analysis, both for the cortical and ANS response. Future studies will also include frequency domain analysis to find optimal combinations of EEG and HR features to predict arousal and valence levels from physiological signals.

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