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Differentiating neural responses to emotional pictures: Evidence from temporal-spatial PCA

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Abstract

Consistent with the notion that emotional stimuli receive preferential attention and perceptual processing, many event-related potential (ERP) components appear sensitive to emotional stimuli. In an effort to differentiate components that are sensitive to emotional versus neutral stimuli, the current study utilized temporospatial principal components analysis to analyze ERPs from a large sample ($N = 82$) while pleasant, neutral, and unpleasant images were passively viewed. Several factors sensitive to emotional stimuli were identified—corresponding to the N1, early posterior negativity (EPN), and P3; multiple factors resembling the late positive potential (LPP) emerged. Results indicate that the N1 represents the earliest component modulated by emotional stimuli; the EPN and the LPP represent unique components; the scalp-recorded LPP appears to include a P3-like positivity as well as additional positivities at occipital and central recording sites.

Descriptors: Emotion, Normal volunteers, EEG/ERP

Emotions can be conceptualized as complex constellations of psychological and physiological states that reflect an organism's appraisal of the meaning, relevance, and value of events in the world (Dolan, 2002). Our emotional responses function to guide our thoughts and behavior in response to the immediate demands of the environment, and, in fact, it appears that environmental events that elicit emotional responses receive preferential perceptual processing. There is consistent evidence that emotional stimuli automatically capture attention (Armony & Dolan, 2002; Mogg, Bradley, de Bono, & Painter, 1997; Ohman, Flykt, & Esteves, 2001), are the target of increased processing even in the absence of attention (Anderson & Phelps, 2001; Esteves, Parra, Dimberg, & Ohman, 1994), and benefit from enhanced later recall (Hamann, Cahill, McGaugh, & Squire, 1997; Hamann, Ely, Grafton, & Kilts, 1999; Phelps, LaBar, & Spencer, 1997).

Neuroimaging studies have enhanced our understanding of how emotions operate within the brain at an anatomical level, and regions including the medial prefrontal cortex, amygdala, occipital cortex, and anterior cingulate cortex have all been identified as being involved in the processing of emotional stimuli, with only limited evidence for lateralization (for meta-analyses, see Phan, Wager, Taylor, & Liberzon, 2002; Wager, Phan, Liberzon, & Taylor, 2003). In support of the view that emotional stimuli receive facilitated processing, research with primates has demonstrated extensive neuroanatomical connectivity between the amygdala and the visual cortex (Amaral, Price, Pitkanen, & Carmichael, 1992; Freese & Amaral, 2005, 2006). Similarly, in humans, amygdala responses have been shown to predict neural activity in areas of the visual cortex in response to images depicting emotional faces, erotica, mutilation, and threat (Morris et al., 1998; Sabatinelli, Bradley, Fitzsimmons, & Lang, 2005). Conversely, amygdala damage has been linked to decreased activity in the visual cortex in response to emotional stimuli (Vuilleumier, Richardson, Armony, Driver, & Dolan, 2004).

Building upon behavioral and neuroimaging findings, there has been an increasing emphasis on exploring the time course of emotional processing. Davidson (1998) proposed the term *affective chronometry* to encompass this notion, and he suggested that individual differences in threshold for emotional reactivity, peak amplitude of emotional response, rise time to peak, and recovery time are all essential parameters to understanding both ordered and disordered emotional processing. Although fMRI and PET studies have provided important insight into those brain structures that are involved in emotional processing, they rely on relatively slow changes in blood flow that make it difficult to quantify how emotional processing unfolds over time. It is in this realm that event-related potentials (ERPs) have proven to be particularly useful, as they offer millisecond temporal resolution of electrocortical activity. Indeed, numerous studies have investigated ERP responses during affective picture viewing (for a review, see Olofsson, Nordin, Sequeira, & Polich, 2008). A wide range of ERP components have been studied in conjunction with emotional processing, and findings have suggested that a broad distinction can be made between early (< 300 ms) processing that

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reflects obligatory initial attention capture, and later (> 300 ms) processing that is driven more by the motivational relevance of stimuli and may be related to elaborative processing and memory encoding (Codispoti, Ferrari, & Bradley, 2007; Dolcos & Cabeza, 2002; Olofsson & Polich, 2007).

Early visual ERP components that have been examined during affective picture processing include the P1, N1, and P2, all of which peak between 100 and 200 ms following stimulus onset. Results from these components suggest that they are generally larger for emotional relative to neutral stimuli (Batty & Taylor, 2003; Carretie, Hinojosa, Martin-Loeches, Mercado, & Tapia, 2004; Keil et al., 2001). A number of studies, however, have also reported an enhancement for unpleasant relative to pleasant stimuli, which has been interpreted as a "negativity bias," or an automatic initial sensitivity to threatening stimuli (Carretie, Hinojosa, Albert, & Mercado, 2006; Carretie, Martin-Loeches, Hinojosa, & Mercado, 2001; Delplanque, Lavoie, Hot, Silvert, & Sequeira, 2004; Smith, Cacioppo, Larsen, & Chartrand, 2003). Although these findings generally suggest that the emotional modulation of ERPs begins quite early, there is considerable variability between studies in terms of which components show an effect of emotion and at what latencies. A remaining question, then, is identifying which ERP component is the earliest to be sensitive to emotional versus non-emotional stimuli.

In addition to these early visual components, two additional components have frequently been studied in the context of emotional picture viewing: the early posterior negativity (EPN) and the late positive potential (LPP). The EPN is a relative temporo-occipital negativity to emotional pictures that is maximal within the 200–300-ms time range and has been linked to the early selective processing of emotional stimuli (Schupp, Flaisch, Stockburger, & Junghofer, 2006; Schupp, Junghofer, Weike, & Hamm, 2003a, 2003b, 2004; Schupp, Stockburger, et al., 2006). The LPP, by comparison, is a sustained relative positivity to emotional pictures that begins as early as 300 ms and is maximal at posterior-superior sites (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000; Schupp et al., 2000; Schupp, Junghofer, et al., 2004). The LPP has been shown to relate to subjective ratings of emotional intensity and to persist for as long as the affective stimulus is presented (Cuthbert et al., 2000). There is also data demonstrating an enhanced LPP after emotional picture offset, suggesting that it reflects the continued allocation of attention to emotional stimuli (Hajcak & Olvet, 2008). In addition, the LPP has been shown to correlate with neural activity in the lateral occipital, inferotemporal, and parietal visual areas (Sabatinelli, Lang, Keil, & Bradley, 2007), and relate to subsequent recall of pictures (Dolcos & Cabeza, 2002)—both findings that support the notion that the LPP reflects facilitated processing and encoding of motivationally relevant, emotional stimuli.

The LPP has also been used in studies of emotion regulation, particularly in tasks investigating the mechanisms of cognitive reappraisal in which unpleasant stimuli are reinterpreted to be less negative. Instructions to reappraise unpleasant stimuli have repeatedly been shown to decrease the magnitude of the LPP (Hajcak & Nieuwenhuis, 2006; Krompinger, Moser, & Simons, 2008; Moser, Hajcak, Bukay, & Simons, 2006), and data from our own laboratory suggests that this effect is not due to cognitive load (Hajcak, Dunning, & Foti, 2007) but instead due to changing the motivational context in which pictures are viewed (Foti & Hajcak, 2008).

Overall, a multitude of studies have demonstrated that a wide range of ERP components are sensitive to emotion and that the modulation of different components may, in fact, capture different stages within emotional processing. There remain, however, several important theoretical and empirical questions regarding the interpretation of these findings. One fundamental question pertaining to the LPP is whether or not it reflects a single, prolonged cognitive process, or, rather, multiple overlapping processes. In particular, it has been proposed that the LPP reflects the same underlying mental process as another component, the P3 (Kok, 1997). The P3 is a parietally maximal component that peaks at approximately 300–400 ms and has been found to be generally sensitive to stimuli that are task relevant and of motivational significance (Polich & Kok, 1995). Indeed, studies have investigated the emotional modulation of the P3 and have generally found it to be enhanced for emotional images compared to neutral images in both passive viewing (Keil et al., 2002; Mini, Palomba, Angrilli, & Bravi, 1996) and oddball paradigms (Delplanque et al., 2004; Delplanque, Silvert, Hot, Rigoulot, & Sequeira, 2006; Delplanque, Silvert, Hot, & Sequeira, 2005). Unlike the P3, however, the LPP has been shown to be sustained throughout and even following picture presentation (Cuthbert et al., 2000; Hajcak & Olvet, 2008). Furthermore, in data from our own laboratory we have observed an apparent scalp topography shift in the LPP from a parietal positivity in the 400–1000-ms range to a more broadly superior positivity in the 1000–2000-ms range (Foti & Hajcak, 2008; Hajcak et al., 2007), which would not be the case if the LPP were merely a sustained P3. This raises the questions of how the LPP can be functionally distinguished from the P3 and whether the frontalization of the LPP over time is indicative of other, overlapping ERP components.

A similar question regards how the LPP relates to the somewhat earlier EPN. Although the EPN has been reported to be maximal in the 200–300-ms range, it also appears to persist beyond this point, suggesting that the EPN and LPP may overlap in time (Schupp, Junghofer, et al., 2004). Furthermore, the EPN has been reported to occur concurrently with a centro-medial positivity that overlaps spatially with the LPP (Schupp et al., 2003b; Schupp, Junghofer, et al., 2004). One possible explanation for this overlap is the frequent use of an average-electrode reference in studies examining the EPN (Schupp et al., 2003a, 2003b; Schupp, Junghofer, et al., 2004; Schupp, Stockburger, et al., 2006) and a mastoid reference in studies examining the LPP (Cuthbert et al., 2000; Foti & Hajcak, 2008; Hajcak et al., 2007; Hajcak, Moser, & Simons, 2006; Hajcak & Nieuwenhuis, 2006; Krompinger et al., 2008; Schupp et al., 2000; although see Schupp, Junghofer, et al., 2004 for the LPP using an average reference). The use of different references in ERP studies can drastically affect the appearance of components (Dien, 1998b; Luck, 2005), making it difficult to directly compare many of the EPN and LPP studies. It is possible, for example, that the EPN and the early portion of the LPP may, in fact, be capturing a single electrical dipole and that the choice of reference determines which of these two components is observed. Overall, then, it remains unclear how many distinct components underlie the apparent emotional modulation of scalp-recorded ERP differences; that is, it remains to be shown whether shifts in individual ERP components such as the P1, N1, P2, EPN, and LPP are unique effects or whether they reflect overlapping processes relevant to emotion.

To investigate these issues, in the present study we conducted an exploratory principal components analysis (PCA) over both time and space using data from a passive affective picture viewing task in a large sample. PCA is a factor-analytic statistical approach that can be used to capture variance across electrode sites and across time points as well as to separate latent components that may not be readily apparent in the ERP averages. For example, PCA has been used previously to effectively distinguish between the P3, Novelty P3, and slow wave components in an auditory oddball task (Simons, Graham, Miles, & Chen, 2001; Spencer, Dien, & Donchin, 2001). Importantly, these papers demonstrated that novel stimuli elicit both a P3 and a Novelty P3 as independent components, a question which had proven difficult to answer based on ERP averages and scalp topographies alone.

A handful of previous studies have employed PCA in the context of emotional picture processing, although they all utilized relatively brief picture duration ($<$ 1000 ms) in a variety of task contexts and have yielded somewhat inconsistent results. For example, there exist conflicting reports of components corresponding to the P1 being enhanced (Delplanque et al., 2004; Hot, Saito, Mandai, Kobayashi, & Sequeira, 2006) or reduced (Rigoulot et al., 2008) for emotional images, as well as reports of P2 components being enhanced at either frontal (Carretie, Hinojosa, Lopez-Martin, & Tapia, 2007) or posterior sites (Delplanque et al., 2004). Similarly, components representing the P3 appear to be sensitive to emotional stimuli (Delplanque et al., 2004, 2006; Hot et al., 2006), although effects of emotion are not always reported in this time range (Carretie et al., 2007; Rigoulot et al., 2008). Some of these inconsistencies may be explained by the use of differing experimental paradigms, such as oddball tasks (Delplanque et al., 2004, 2006) and categorization tasks (Carretie et al., 2007; Rigoulot et al., 2008).

One previous report utilized PCA to examine ERPs elicited during a passive picture viewing task and identified components corresponding to the P1/N1 complex, the EPN, and the P3 (Hot et al., 2006). Although Hot et al. presented pictures for 1500 ms, ERPs were only analyzed in the first 750 ms; thus, later modulations (i.e., the LPP) were not examined. In the present study, we sought to address limitations in the current literature by applying temporal-spatial PCA to ERP data recorded during a passive picture viewing task in a large sample ($N = 82$) using a relatively long stimulus duration (2 s). A passive viewing paradigm was used so that factors known to influence the P300 (e.g., decision making, probability) would not contaminate emotion-related ERP modulations. In this way, the present study is in a unique position to identify those underlying neural components that provide the best and most parsimonious representation of emotional processing.

Method

Participants

Eighty-nine undergraduate students (48 male, 41 female) participated in the current study. A total of 7 participants were excluded from analysis due to poor quality recordings, leaving 82 participants (43 male, 39 female) for the final sample. No participants discontinued their participation in the experiment once the procedures had begun. Five participants in the final sample received monetary compensation, and the remaining 78 received course credit for their participation.

Stimulus Materials

A total of 120 pictures were selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1999); of these, 40 depicted pleasant scenes (e.g., smiling faces, babies), 40 depicted neutral scenes (e.g., neutral faces, household objects), and 40 depicted unpleasant scenes (e.g., sad faces, violence images).[1] The three categories differed on normative ratings of valence, based on a 9-point scale with 1 being *maximally unpleasant* and 9 being *maximally pleasant* ($M = 2.42$, $SD = 1.58$ for unpleasant pictures; $M = 4.99$, $SD = 1.24$ for neutral pictures; and $M = 7.04$, $SD = 1.68$ for pleasant pictures); additionally, the emotional pictures were reliably higher on normative arousal ratings ($M = 6.18$, $SD = 2.21$ for unpleasant pictures; $M = 5.42$, $SD = 2.23$ for pleasant pictures; and $M = 2.80$, $SD = 1.90$ for neutral pictures).

The task was administered on a Pentium D class computer, using Presentation software (Neurobehavioral Systems, Inc., Albany, CA) to control the presentation and timing of all stimuli. Prior to each picture, a white fixation cross was presented on a black screen for 500 ms. Each picture was then displayed in color for 2000 ms and occupied the entirety of a 19-in. (48.26 cm) monitor. At a viewing distance of approximately 24 in. (60.96 cm), each picture occupied approximately 40° of visual angle horizontally and vertically.

Procedure

After a brief description of the experiment, electroencephalograph (EEG) sensors were attached and the participant was given more detailed task instructions. Participants were told that they would be viewing pictures depicting a wide range of scenes, some being pleasant, some being neutral, and others being unpleasant to look at. Participants were asked to focus on the screen and simply watch all of the pictures as they were displayed. All participants initially viewed a series of 10 practice pictures to accommodate them to the task. After the practice trials, participants performed 120 trials, with breaks after every 20 trials. At the beginning of each block, an instruction reading "SIMPLY VIEW THESE PICTURES" was displayed on the screen for 1000 ms. The order of the trials was randomly determined for each participant.

Psychophysiological Recording and Data Reduction

The continuous EEG was recorded using the ActiveTwo BioSemi system (BioSemi, Amsterdam, Netherlands). Recordings were taken from 64 scalp electrodes based on the 10/20 system, as well as 2 electrodes placed on the left and right mastoids. The electrooculogram (EOG) generated from blinks and eye movements was recorded from four facial electrodes: two approximately 1 cm above and below the participant's right eye, one approximately 1 cm to the left of the left eye, and one approximately 1 cm to the right of the right eye. As per BioSemi's design, the ground electrode during acquisition was formed by the Common Mode Sense active electrode and the Driven Right Leg passive electrode.

All bioelectric signals were digitized on a laboratory microcomputer using ActiView software (BioSemi). The EEG was sampled at 512 Hz. Off-line analysis was performed using Brain

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[1] The IAPS pictures used were pleasant (1050, 1200, 1300, 2730, 2800, 3010, 3160, 3170, 3230, 3261, 3300, 3350, 6200, 6210, 6230, 6244, 6250, 6312, 6313, 6370, 6550, 6560, 6571, 6821, 9040, 9042, 9050, 9253, 9300, 9400, 9405, 9410, 9433, 9520, 9600, 9611, 9810, 9910, 9920, 9921), neutral (2190, 2320, 2570, 2840, 2880, 5390, 5532, 5534, 5731, 5740, 5800, 5900, 7000, 7002, 7004, 7006, 7009, 7010, 7025, 7034, 7035, 7040, 7041, 7060, 7080, 7090, 7100, 7130, 7140, 7150, 7175, 7190, 7217, 7224, 7233, 7235, 7491, 7550, 7595, 7950), and unpleasant (1463, 1601, 1710, 1811, 2000, 2070, 2080, 2091, 2092, 2165, 2340, 2345, 4002, 4290, 4532, 4572, 4608, 4658, 4659, 4660, 4664, 4810, 5470, 5621, 5626, 5628, 7325, 8021, 8032, 8080, 8200, 8210, 8280, 8320, 8370, 8400, 8461, 8465, 8490, 8540).

Vision Analyzer software (Brain Products). All data were rereferenced to the average of all scalp electrodes and band-pass filtered with cutoffs of 0.1 and 30 Hz. The EEG was segmented for each trial, beginning 500 ms before each picture onset and continuing for 2500 ms. The EEG for each trial was corrected for blinks and eye movements using the method developed by Gratton, Coles, and Donchin (1983). Specific trials for individual channels were rejected using a semiautomated procedure, with physiological artifacts identified by the following criteria: a voltage step of more than 50.0 μV between sample points, a voltage difference of 300.0 μV within a trial, and a maximum voltage difference of less than 0.50 μV within 100-ms intervals. An average of 28 artifacts was identified per participant. ERPs were constructed by separately averaging trials for the three picture types (pleasant, neutral, and unpleasant). In each case, the average activity in the 200-ms window prior to picture onset served as the baseline.

Statistical Analysis

Temporal and spatial regions of interest were chosen quantitatively using temporospatial principal components analysis (PCA; Dien, Beal, & Berg, 2005; Dien & Frischkoff, 2005; Spencer, Dien, & Donchin, 1999; Spencer et al., 2001). Temporospatial PCA is a method that extracts linear combinations of all data points that meet certain criteria that tend to distinguish between consistent patterns of electrocortical activity. Based on simulation results (Dien, Khoe, & Mangun, 2007), Promax was used to rotate to simple structure in the temporal domain followed by Infomax to rotate to independence in the spatial domain. Using the Matlab ERP PCA Toolbox (version 1.093), a temporal PCA was performed on the data first in order to capture variance across time and to maximize the initial separation of ERP components (Dien & Frischkoff, 2005). This PCA used all time points as variables and considered all subjects, picture types, and recording sites as observations, thereby yielding linear combinations of time points (referred to as temporal factors) and reducing the 1,126 temporal dimensions of the original data set. Based on the resulting Scree plot (Cattell, 1966; Cattell & Jaspers, 1967), 12 temporal factors were extracted for rotation. As per Dien, Beal, and Berg's (2005) suggestions, the covariance matrix and Kaiser normalization were used for this PCA. Each temporal factor may be considered to be a *virtual epoch* and can be described both by its *factor loading* (which describes the time course of that factor) and *factor scores* (which give that factor's value for each combination of subject, picture type, and recording site). Importantly, spatial information is preserved by temporal PCA; scalp topographies can be reconstructed for any time point, subject, and condition by multiplying the corresponding electrode scores by the factor loading and standard deviation (Dien, 1998a).

To reduce the spatial dimensions of the data set, a spatial PCA was then performed. Here, recording sites were used as variables and all subjects, picture types, and temporal factor scores were used as observations. A separate spatial PCA was performed for each temporal factor, although the resulting Scree plots were averaged across all temporal factors such that the same number of spatial factors was extracted in each case. The covariance matrix was used, and four spatial factors were extracted from each temporal factor for Infomax rotation. By representing a linear combination of recording sites, each spatial factor may be considered to be a *virtual electrode*. The factor loadings describe the scalp topography of each factor, and the factor scores describe the activity of each spatial factor across time, subjects, and picture types (*virtual ERPs*). To facilitate interpretation of the PCA results, the portion of the original data set represented by each temporospatial factor combination can be reconstructed (i.e., in microvolts) by multiplying factor scores by their corresponding loadings and standard deviations; in this way, both the time course and scalp topography of the electrocortical activity captured by that temporospatial factor combination can be directly assessed.

The temporospatial PCA yielded a total of 48 factor combinations (4 spatial factors extracted for each of 12 temporal factors), and it is the scores from these factors that were submitted for statistical analysis using a three-level repeated measures ANOVA (across pleasant, neutral, and unpleasant pictures). Statistical analysis was conducted using SPSS (Version 14.0) General Linear Model software, with Greenhouse–Geisser correction applied to *p* values associated with multiple-*df*, repeated measures comparisons. For multiple comparisons, *p* values were also adjusted with the Bonferroni correction.

Results

The original grand average waveforms for each picture type, prior to PCA, are presented in Figure 1. The N1 is evident at centroparietal sites at 130 ms and is enhanced for emotional relative to neutral pictures, as has been shown in previous work (Keil et al., 2001). A second relative negativity for emotional pictures is evident at occipital and temporal recording sites and is maximal at approximately 230 ms, consistent with previous reports on the EPN (Schupp, Flaisch, et al., 2006; Schupp et al., 2003a, 2003b; Schupp, Junghofer, et al., 2004; Schupp, Stockburger, et al., 2006). This peak is followed by a sustained negativity to emotional pictures, representing the inverted form of the LPP at these recording sites. The enhancement of the LPP at posterior-superior sites for emotional relative to neutral pictures can be seen as early as 300 ms following picture onset, which is also consistent with previous studies (Cuthbert et al., 2000; Hajcak et al., 2006; Hajcak & Nieuwenhuis, 2006; Moser et al., 2006; Schupp et al., 2000; Schupp, Junghofer, et al., 2004). In addition, unpleasant pictures appear to be associated with an enhanced LPP relative to pleasant pictures, which is consistent with the "negativity bias" that has been reported elsewhere (Carretie, Mercado, Tapia, & Hinojosa, 2001; Ito, Larsen, Smith, & Cacioppo, 1998; Northoff et al., 2000).

Given the exploratory nature of the study, each of the 48 temporospatial factor combinations that accounted for at least 1% of the variance were subjected to a three-level (Picture Type: pleasant, neutral, unpleasant), repeated measures ANOVA across the three picture types. Twenty-one factor combinations met this criteria, and a Bonferroni correction ($p < .0024$) resulted in 8 factor combinations that were sensitive to Picture Type (Table 1).

The factor combinations can be grouped into two broad categories. Two of the factor combinations (TF7/SF2 and TF10/SF1) represent an early negativity (< 300 ms) to emotional relative to neutral pictures at parietal and occipital recording sites, consistent with previous work on the N1 (Keil et al., 2001) and the EPN (Schupp et al., 2003a, 2003b; Schupp, Junghofer, et al., 2004; Schupp, Ohman, et al., 2004), respectively. Spatial topographies and waveforms for these are presented in Figure 2. The three possible pairwise comparisons across picture type were

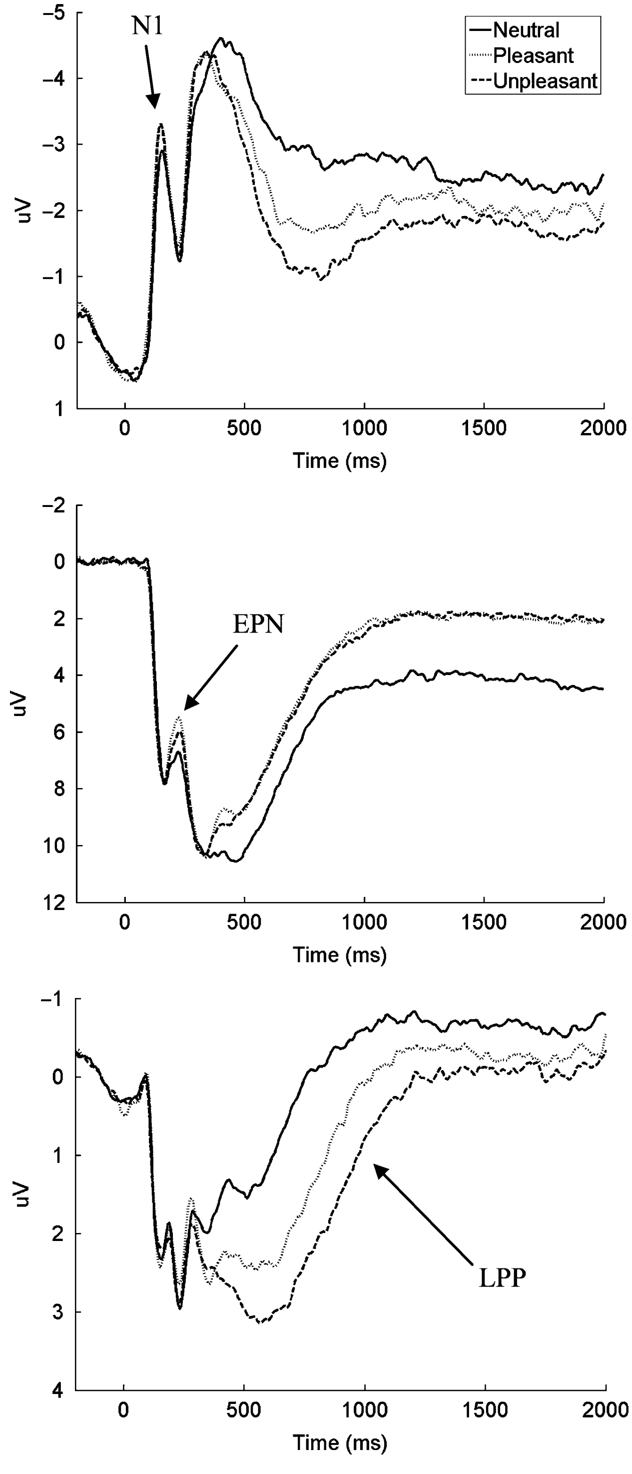

Figure 1. Grand average ERPs (prior to PCA analysis) presented for the three picture types (pleasant, neutral, and unpleasant). The following sites were used for each average: N1 (top), Cz and CPz; EPN (middle), Iz and P9/10; and LPP (bottom), CP1/2, CP3/4, P1/2, P3/4, and PO3/4.

performed, using a significance cutoff of $p < .017$ (Bonferroni correction for three follow-up contrasts). As expected, both factor combinations showed an enhanced negativity for both pleasant and unpleasant pictures relative to neutral pictures, but pleasant and unpleasant pictures did not differ from one another (Table 1).

The remaining six factor combinations (TF2/SF1, TF2/SF2, TF4/SF1, TF4/SF2, TF4/SF4, and TF1/SF4),[2] conversely, represent a later positivity (>300 ms) to emotional relative to neutral pictures at posterior and superior recording sites, consistent with previous work on the LPP (Cuthbert et al., 2000; Foti & Hajcak, 2008; Hajcak et al., 2006; Hajcak & Nieuwenhuis, 2006; Krompinger et al., 2008; Moser et al., 2006; Schupp et al., 2000; Schupp, Junghofer, et al., 2004). Due to the fact that temporal PCA models ERP components as having fixed time courses, it is possible that these six factor combinations actually represent latency differences of a smaller set of components across subjects and picture types. That is, if the LPP develops earlier in some individuals than others (or for one picture type compared to another), temporal PCA will generate at least two different temporal factors, one for each latency. One way to resolve this is to compare the spatial topographies of different temporal factors (cf., Dien, Spencer, & Donchin, 2004). In doing so, it is apparent that these six factor combinations can be more parsimoniously organized as representing three components: relative positivities at occipital (TF2/SF1, TF4/SF1; Figure 3), parietal (TF2/SF2, TF4/SF2; Figure 4), and central (TF1/SF4, TF4/SF4; Figure 5) recording sites. The parietal positivity is of particular interest, as this is maximal as early as 353 ms (TF2/SF2) and is consistent with previous reports of both the LPP and the P3. Pairwise comparisons were once again performed across picture type for these six factor combinations, using a significance cutoff of $p < .017$. For each factor combination, pleasant and unpleasant pictures were both associated with enhanced positivities relative to neutral pictures; however, three of the factor combinations (TF2/SF1, TF4/SF1, and TF4/SF2) showed an additional effect of valence, with unpleasant pictures associated with a significantly enhanced positivity compared to pleasant pictures (Table 1).

It should be noted that some of the factor waveforms presented reverse polarity across conditions. For example, it can be seen that TF7/SF2 (Figure 2) represents an absolute positivity for neutral pictures and an absolute negativity for emotional pictures. One possible explanation for this is that the PCA misestimated the zero voltage line of the scores for that factor. Because the waveforms presented represent the product of the factor scores and loadings, the only time points to be affected would be those containing that specific ERP component (i.e., those time points with nonzero loadings). Alternatively, it may be possible that the PCA did not manage to fully separate a P1 and an N1, resulting in there being more N1 in one condition (emotional images) and more P1 in the other condition (neutral pictures). It is for these reasons that the factor combinations have been interpreted in terms of the *relative differences* between picture types, and not the absolute values for each.

Discussion

The results of the current study provide support for the broad distinction that has previously been made between early pro-

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[2] TF1/SF4 is maximal at the end of the epoch, a pattern that commonly occurs during temporal PCA due to the fact that the standard deviation of the ERP increases over time. These late temporal factors often accounts for a large amount of the variance, although it is not necessarily meaningful (Kayser & Tenke, 2003). In the current study, we chose to retain TF1/SF4 due to the fact that it significantly varies across picture type, indicating that it contains systematic variance relevant to our effect of interest.

Table 1. *Descriptions and Statistical Results for the Eight Temporospatial Factor Combinations Found to Be Sensitive to Emotion*

Temporospatial factor combination	Temporal loading peak (ms)	Spatial distribution of emotional enhancement	Main effect of picture type, *F*(2,162)	Pleasant vs. neutral, *t*(81)	Unpleasant vs. neutral, *t*(81)	Unpleasant vs. pleasant, *t*(81)
TF7/SF2	136	Parietal negativity	36.44**	6.85**	8.80**	n.s.
TF10/SF1	241	Occipital negativity	77.55**	10.31**	9.58**	n.s.
TF2/SF1	353	Occipital positivity	16.46**	3.42*	5.18**	2.53*
TF4/SF1	841	Occipital positivity	26.41**	3.05*	5.82**	5.45**
TF2/SF2	353	Parietal positivity	45.20**	7.20**	9.60**	n.s.
TF4/SF2	841	Parietal positivity	12.33**	2.84*	3.82**	3.38*
TF4/SF4	841	Central positivity	44.67**	7.80**	7.53**	n.s.
TF1/SF4	1595	Central positivity	25.84**	7.01**	5.55**	n.s.

*$p < .017$, **$p < .0024$.

cesses (<300 ms) that reflect initial attentional capture by emotional stimuli and later processes (>300 ms) that reflect continued processing and encoding of these stimuli (Codispoti et al., 2007; Olofsson & Polich, 2007). After performing a PCA across both time and space, eight separate temporospatial factor combinations were found to be enhanced for emotional relative to neutral pictures in the present sample; of these, two corresponded to an early negativity (N1, EPN) and the remaining six corresponded to later positivities (P3, LPP). Although some studies have found modulation of the P1 and P2 by emotional stimuli (Carretie et al., 2007; Delplanque et al., 2004; Rigoulot et al., 2008), these studies have used either categorization or oddball tasks; in the context of the present results obtained during passive viewing, variation in the P1 and P2 may depend on interactions between emotional and task-related factors.

The current study builds on the existing literature on the emotional modulation of ERP components in several ways. First, it provides evidence that the emotional modulation of the N1, EPN, and LPP do, in fact, represent effects of distinct electrocortical components. A parietal negativity peaking at 136 ms following picture presentation was the earliest factor combination found to be sensitive to emotion and is most similar to previous work on the N1 (Keil et al., 2001). This was followed by a more occipital negativity peaking at 241 ms, which corresponds with previous studies of the EPN (Schupp, Flaisch, et al., 2006; Schupp et al., 2003a, 2003b; Schupp, Junghofer, et al., 2004; Schupp, Ohman, et al., 2004; Schupp, Stockburger, et al., 2006).

Importantly, these negativities were found to occur independently of three later positivities at occipital, parietal, and central recording sites, all of which were larger for emotional relative to neutral pictures. These positivities were represented by six temporospatial factors with peaks ranging from 353 to 1595 ms, which is consistent with the sustained LPP to emotional pictures that has repeatedly been observed elsewhere (Cuthbert et al., 2000; Foti & Hajcak, 2008; Hajcak & Nieuwenhuis, 2006; Hajcak et al., 2006, 2007; Krompinger et al., 2008; Moser et al., 2006; Schupp et al., 2000; Schupp, Junghofer, et al., 2004).

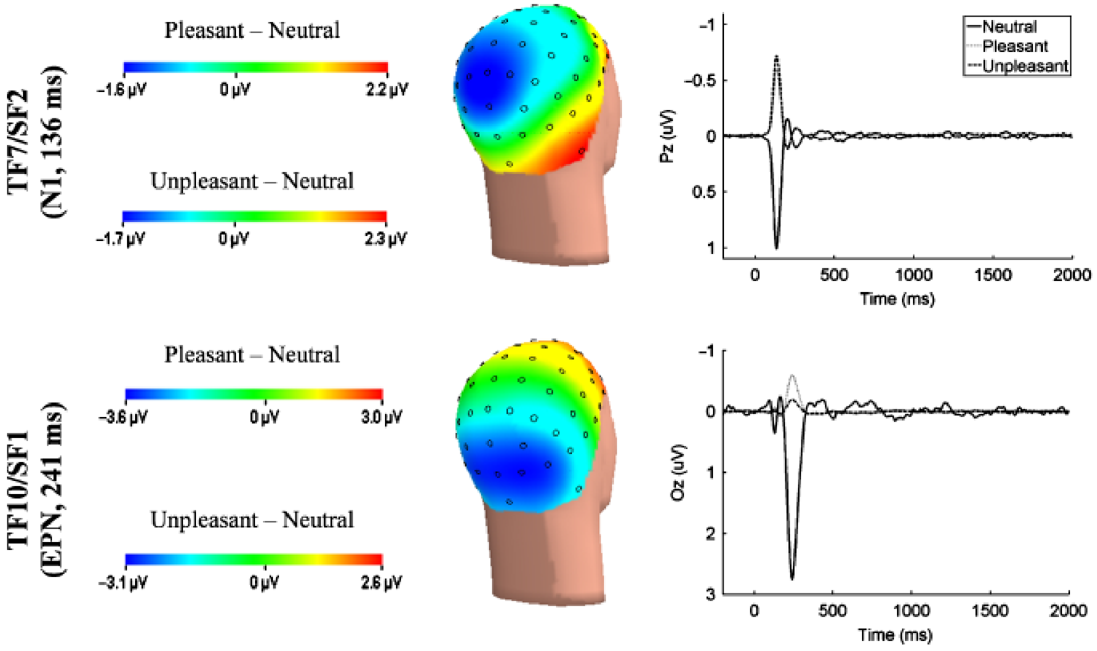

Figure 2. Topographic maps and waveforms for those temporospatial factors that are associated with the N1 and the EPN. In each case, the scales presented give the microvolt range at the time of the maximum difference between picture types.

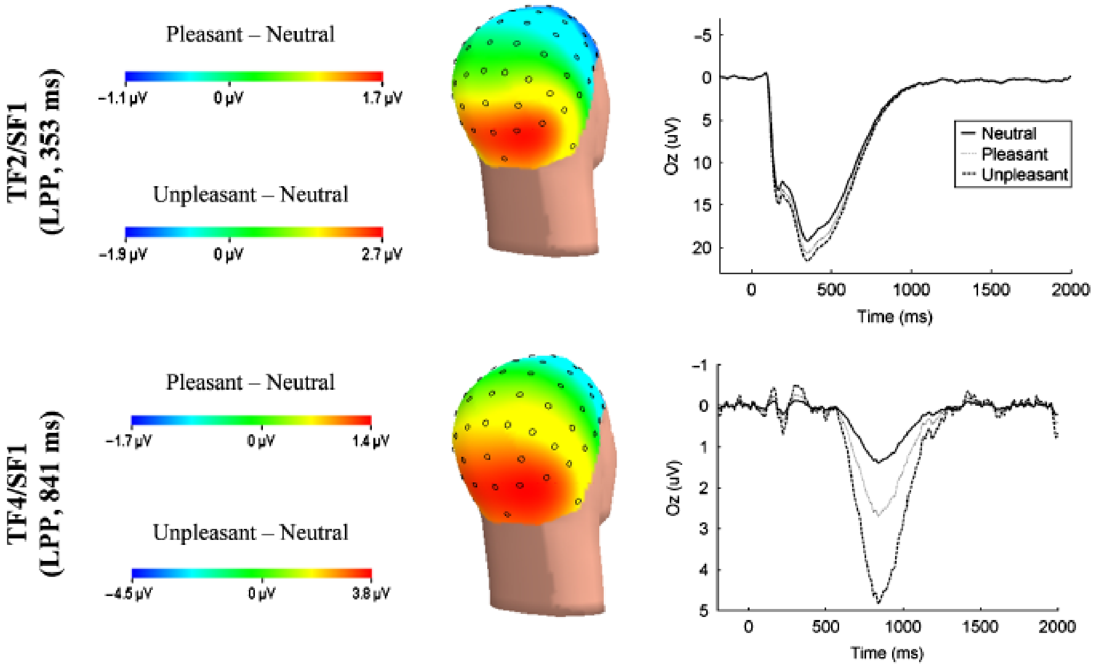

Figure 3. Topographic maps and waveforms for those temporospatial factors that are associated with the LPP (occipital positivities).

Interestingly, no evidence for a negativity bias was found in the present study for the early factor combinations; that is, those factor combinations associated with the N1 and EPN did not significantly differ between unpleasant and pleasant stimuli, despite the fact that the unpleasant pictures used had somewhat higher normative ratings on emotional arousal. This is at odds with previous reports of a negativity bias for early visual ERP components (Carretie et al., 2006; Carretie, Martin-Loeches, et al., 2001; Delplanque et al., 2004; Smith et al., 2003), but is actually consistent with previous reports of a *positivity* bias of the EPN (Schupp, Junghofer, et al., 2004; Schupp, Stockburger, et al., 2006). That is, given that relatively less arousing pleasant pictures did not elicit significantly reduced peaks compared to more arousing unpleasant pictures, it is possible that the early emotional modulation of ERPs is especially pronounced for pleasant stimuli when equating for arousal. Another possibility is that valence biases are influenced by sample idiosyncrasies or individual differences in psychological variables such as anxiety.

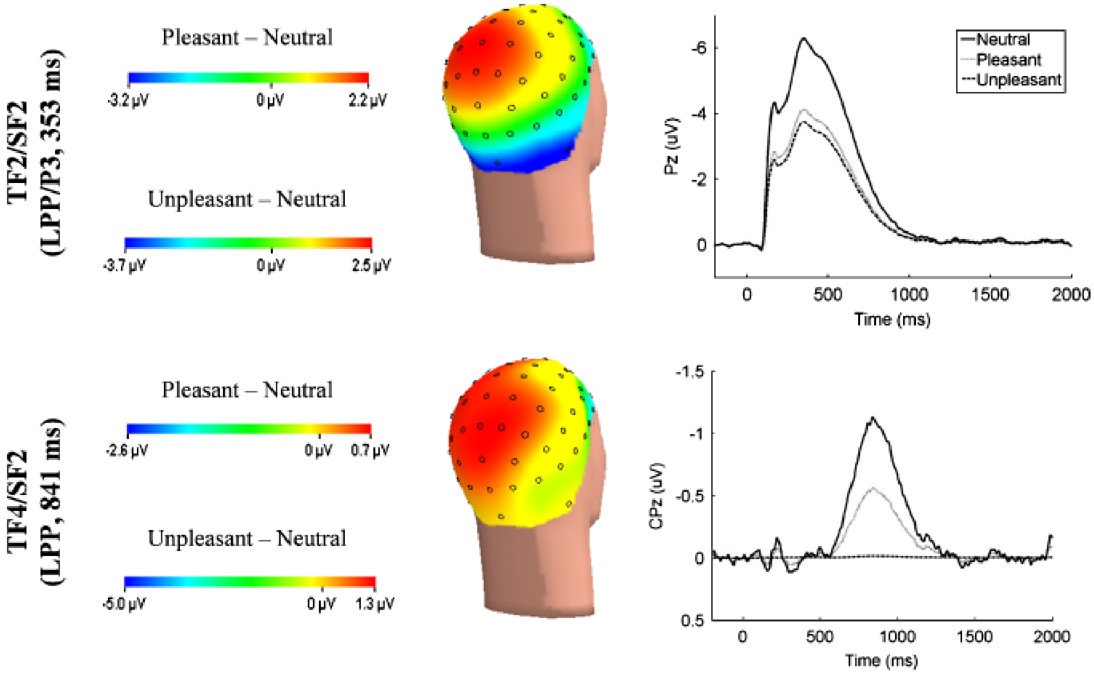

Figure 4. Topographic maps and waveforms for those temporospatial factors that are associated with the LPP and P3 (parietal positivities).

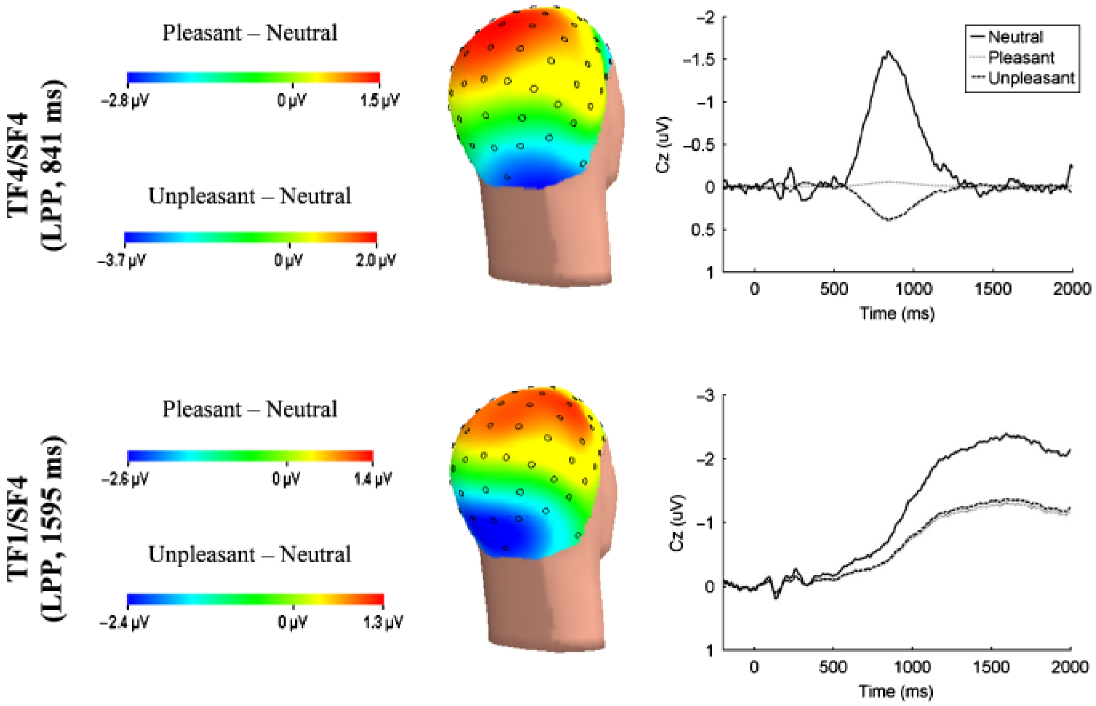

Figure 5. Topographic maps and waveforms for those temporospatial factors that are associated with the LPP (central positivites).

Indeed, the role of individual differences in emotional processing has been largely neglected in ERP studies (Olofsson et al., 2008), and it will be important for future work to look for interactions between sample demographics, psychological variables, and the emotional modulation of ERP components.

The present study also offers further insight into how best to conceptualize the LPP. Three positivities with distinct spatial topographies were identified, suggesting that it may be overly simplistic to view the LPP as simply a sustained positivity. Furthermore, although one of these was highly consistent with the P3 (a parietal positivity peaking as early as 353 ms), the fact that relative occipital and central positivities with varying time courses also emerged indicates that the LPP and the P3 should not be considered to be identical components. Instead, it appears that the initial portion of the LPP (300–600 ms) is consistent with the P3, and the later portion of the LPP (> 600 ms) may reflect one or more additional processes relevant for emotional processing. Moreover, these results highlight the importance of analyzing relatively sustained ERP activity elicited by emotional stimuli (cf., Hot et al., 2006).

In particular, it is worth noting that the central positivity occurred the latest of the three and was broadly distributed across superior recording sites. This finding is consistent with the observation made in our own laboratory that the LPP appears to shift in topography over time, extending from parietal sites to nearly all superior recording sites in the 1000–2000-ms time range (Foti & Hajcak, 2008; Hajcak et al., 2007). The results of the PCA not only replicate our earlier observation, but also offer stronger evidence that this shift in topography is indicative of the modulation of independent neural activity. By splitting the LPP into subcomponents in this way, it may be possible in future studies to gain further insight into specific cognitive processes that are relevant to discrete stages of emotional processing.

To our knowledge, the current study represents the application of temporospatial PCA to the emotional modulation of ERP components in the largest sample to date, and the results of this analysis both support and extend previous studies of affective picture processing. The present findings, though, are qualified by several limitations. First, the set of pleasant and unpleasant pictures used were not perfectly balanced in terms of valence and emotional arousal, making it difficult to draw strong conclusions about the negativity bias. The lack of an evident negativity bias in the early temporospatial factors is informative due to the fact that the pictures used should have favored a slight enhancement for unpleasant relative to pleasant pictures; however, the finding that three of the later temporospatial factors were sensitive to both emotional arousal and valence is difficult to interpret because this effect could be due to either a true negativity bias or to the higher normative ratings of emotional arousal for unpleasant pictures. Second, although the temporospatial factors observed in the present study suggest that the LPP may represent a broad set of positivities that includes a component resembling the P3, a more direct test of this would be to incorporate a nonaffective P3 within the current paradigm. If the same P3-like factor is found to be sensitive to both emotion and to target versus nontarget stimuli, this would provide strong evidence not only for the emotional sensitivity of the P3 but also for the notion that the LPP also reflects the presence of additional and separate processes. We are currently investigating this topic to further clarify the relationship between the LPP and the P3.

In conclusion, the current study found that a wide range of ERP components are sensitive to emotion, beginning as early as 136 ms after stimulus onset and persisting throughout stimulus presentation. Support was also found for the broad distinction between the modulation of early components (< 300 ms), which seem to be represented by a parietal-occipital negativity and may be related to initial attention capture, and later components (> 300 ms), which seem to be represented by a posterior-superior positivity and may be related to elaborative processing and encoding. These results suggest that the EPN and the LPP may, in fact, be indexing separate portions of emotional processing, and that much of the apparent LPP also reflects emotionally relevant processing that is separate from the P3. As basic research on emotions continues to play an important role across multiple domains of psychology, including recent conceptualizations of psychopathology (Drevets, 2001; Johnson, Hurley, Benkelfat, Herpertz, & Taber, 2003; Kring & Bachorowski, 1999; Lang, Bradley, & Cuthbert, 1998; Southam-Gerow & Kendall, 2002; Weems & Silverman, 2006), it will be important for future studies in this areas to integrate ERP findings in order to maximize our ability to both quantify and understand emotional processing.

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