

The Late Positive Potential Predicts Subsequent Interference with Target Processing

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Abstract

■ The current study investigated the association between neural engagement with task-irrelevant images and subsequent interference with target processing using the Emotional Inter-rupt paradigm [Mitchell, D., Richell, R., Leonard, A., & Blair, R. Emotion at the expense of cognition: Psychopathic individuals outperform controls on an operant response task. *Journal of Abnormal Psychology*, 115, 559, 2006]. Consistent with previous studies, PCA-derived factors corresponding to the early posterior negativity, P300, and late positive potential (LPP) were enhanced for emotional (i.e., both unpleasant and pleasant) compared with neutral distracters, and the P300 elicited by targets was smaller following emotional compared with neutral pictures. In addition, RTs were increased to targets that followed emotional pictures.

Within-subject analyses demonstrated that slow trials were characterized by a smaller P300 and were preceded by pictures with a larger LPP. Additionally, between-subject analyses indicate that individuals with a larger LPP also demonstrated slower RTs to targets and reduced target-elicited P300s. All results were specific to the LPP and were not observed for either the early posterior negativity or the P300 elicited by task-irrelevant pictures. By relating the LPP to subsequent behavioral and ERP interference in both within- and between-subject analyses, the current study provides direct support for the notion that LPP indexes attentional engagement with visual stimuli that is uniquely associated with subsequent interference in terms of both RT slowing and P300 reduction to targets. ■

INTRODUCTION

The *biased competition* model of visual attention (Desimone & Duncan, 1995) suggests that stimuli can win competition for attention in several ways: attention can be preferentially allocated based on either bottom-up stimulus properties that are visually arresting (e.g., colorful or moving stimuli) or top-down control processes (e.g., stimuli relevant to current or ongoing behaviors and goals). A large corpus of research indicates that stimulus content pertaining to survival is inherently motivationally salient and automatically directs and captures visual attention (e.g., Bradley, Codispoti, Cuthbert, & Lang, 2001; Lang, Bradley, & Cuthbert, 1997). Compared with neutral stimuli, emotional cues are detected more easily (Tipples, Atkinson, & Young, 2002; Öhman, Flykt, & Esteves, 2001; Fox et al., 2000), more effectively capture and hold attention (Schupp et al., 2007; Vuilleumier, 2005; Armony & Dolan, 2002; Öhman et al., 2001; Lang et al., 1997; Mogg, Bradley, De Bono, & Painter, 1997), and are viewed for longer (Lang et al., 1997; Lang, Greenwald, Bradley, & Hamm, 1993).

Increased attention to emotional stimuli likely has a functional value, insofar as faster detection and increased processing of emotional stimuli could confer a strong evolutionary advantage (LeDoux, 1998). However, there is also increasing evidence indicating that visual attention is a limited resource and that attended visual stimuli are

preferentially processed at the expense of unattended stimuli (e.g., Driver, 2001; Desimone & Duncan, 1995; Bundesen, 1990; Broadbent, 1958). Thus, if attentional resources are limited (e.g., Kahneman, 1973; Broadbent, 1958), the prioritized processing of emotional stimuli can come at a cost. Indeed, task-irrelevant emotional stimuli can interfere with goal-directed behavior, slowing RTs to target stimuli or decreasing accuracy (MacNamara & Hajcak, 2009, 2010; Van Damme, Crombez, & Notebaert, 2008; Blair et al., 2007; Mitchell, Richell, Leonard, & Blair, 2006; Buodo, Sarlo, & Palomba, 2002; Hartikainen, Ogawa, & Knight, 2000; Vuilleumier, Armony, Driver, & Dolan, 2001).

Evidence from rapid serial visual presentation paradigms, in which images and targets are presented sequentially and for very short latencies (e.g., 100 msec), further suggests that emotional distracters can interfere with processing of target stimuli to such an extent that the awareness of targets is diminished (Most & Jungé, 2008; Smith, Most, Newsome, & Zald, 2006; Keil & Ihssen, 2004). That is, emotional stimuli can cause an “attentional blink” (Most, Chun, Johnson, & Kiehl, 2006; Most, Chun, Widders, & Zald, 2005); this has been demonstrated for both pleasant and unpleasant distracters (Flaisch, Stockburger, & Schupp, 2008; Most, Smith, Cooter, Levy, & Zald, 2007), for affective words (Arnell, Killman, & Fijavz, 2007; Barnard, Ramponi, Battye, & Mackintosh, 2005; Keil & Ihssen, 2004) and images (Most & Jungé, 2008), for affectively conditioned distracters (Smith et al., 2006), and even when the emotional

distracter appears subsequent to the target (Most & Jungé, 2008). Additionally, there is evidence that continued processing of task-irrelevant emotional pictures may even interfere with the processing of subsequent *emotional* stimuli in rapid serial presentation paradigms (Flaisch, Junghöfer, Bradley, Schupp, & Lang, 2008; Flaisch, Stockburger, et al., 2008). Collectively, these data indicate that task-irrelevant motivationally salient emotional stimuli command a disproportionate share of limited attentional resources.

The Emotional Interrupt Task, a paradigm designed by Mitchell and colleagues (2006, 2008) has proven useful for examining the competition between emotional processing and goal-relevant behaviors. In the task, participants are asked to identify a rapidly presented shape on the screen (e.g., a circle or a square), which is both preceded by and followed by the same task-irrelevant picture—an image from the International Affective Pictures System (IAPS; Lang, Bradley, & Cuthbert, 2005). Using this paradigm, Mitchell et al. (2006, 2008) demonstrated increased RTs to targets following both pleasant and unpleasant compared with neutral stimuli, suggesting that emotional stimuli capture and retain attention preferentially, at a cost to top-down directives regarding task performance. A recent fMRI study (Mitchell et al., 2008) examined neural activity during the Emotional Interrupt Task and found that emotional distracters were associated with increased activity in the inferior frontal gyrus, right amygdala, and occipital gyri; moreover, functional connectivity analyses indicated that increased activity in the amygdala was associated with decreased activity in areas thought to be involved in processes of cognitive control (Cunningham, Raye, & Johnson, 2004; Lévesque et al., 2003; Beauguard, Levesque, & Bourgouin, 2001). Results of the study further indicate that increased limbic activity and perceptual processing in response to emotional distracters may drain limited attentional resources.

Given that attention to emotional stimuli is a dynamic process that changes over time, research utilizing electrocortical activity measured through ERP, which does not rely on the sluggish hemodynamic response, may be critical to our understanding. Increasingly, ERPs are being used to study processes of attentional deployment for emotional stimuli (e.g., Foti, Hajcak, & Dien, 2009; Olofsson, Nordin, Sequeira, & Polich, 2008; Codispoti, Ferrari, & Bradley, 2007). For example, the magnitude of the auditory P300 elicited by an acoustic startle probe indexes orienting and attention to the startling sound but is attenuated by concurrent engagement in attentionally demanding tasks (Picton, 1992; Donchin & Coles, 1988; Roth, Dorato, & Kopell, 1984). In line with the notion that emotional stimuli have an advantage in the competition for attention, the magnitude of P300 elicited by startle probes is reduced throughout the presentation of emotional compared with neutral pictures (Bradley, Codispoti, & Lang, 2006). This has been interpreted in terms of the reduced availability of attentional resources,

which are instead allocated to the foreground emotional stimuli.

In the current study, we employed a version of the Emotional Interrupt Task to examine whether and how neural response to task-irrelevant visual stimuli relates to subsequent behavioral (i.e., RT) and neural (e.g., P300 to targets) measures of interference. Moreover, we examined the time course of this relationship by quantifying multiple ERP responses to the distracting stimuli. We focus on three components elicited by motivationally engaging stimuli, the early posterior negativity (EPN), P300, and late positive potential (LPP; for a review, see Schupp, Flaisch, Stockburger, & Junghöfer, 2006), as well as P300 elicited by the subsequently presented target.

The EPN is an occipital negativity observed between 200 and 300 msec after stimulus onset and has been linked to increased visual processing of emotional compared with neutral stimuli (Foti et al., 2009; Schupp et al., 2006; Schupp, Junghöfer, Weike, & Hamm, 2003b). Functionally, the EPN appears sensitive to perceptual aspects of stimuli, including emotional content, that relate to increased selective attention (Bradley, Hamby, Löw, & Lang, 2007; Schupp et al., 2006). There is also evidence that the EPN is sensitive to sequence-based interference effects (Flaisch, Junghöfer, et al., 2008; Flaisch, Stockburger, et al., 2008), such that the magnitude of the EPN elicited by emotional images is reduced when preceded by emotional pictures, suggesting that inherently salient images may interfere even with the processing of subsequent emotional stimuli.

Following the EPN, the parietally maximal P300 peaks between 300 and 400 msec after stimulus onset and appears sensitive to the motivational significance of stimuli. The P300 is enhanced for target stimuli (Delplanque, Silvert, Hot, Rigoulot, & Sequeira, 2006; Delplanque, Silvert, Hot, & Sequeira, 2005; Delplanque, Lavoie, Hot, Silvert, & Sequeira, 2004) as well as emotional compared with neutral images (Olofsson et al., 2008; Keil et al., 2002). Thus, the P300 appears larger for stimuli that are more motivationally salient, regardless of whether salience is defined in terms of task demands or stimulus content (Hajcak, MacNamara, & Olvet, 2010; Weinberg & Hajcak, 2010; Olofsson et al., 2008).

Other recent studies on emotion have focused on the LPP—a protracted P300-like modulation of the ERP with a central-parietal scalp distribution that begins as early as 200–300 msec following stimulus onset but which may be sustained for the duration of stimulus presentation (Foti et al., 2009; Codispoti, Ferrari, & Bradley, 2006; Schupp et al., 2000, 2004) and for as much as 1000 msec after stimulus offset (Hajcak et al., 2010; Hajcak & Olvet, 2008). The LPP is sensitive to the emotional content of images, increasing in amplitude to both positively and negatively valenced stimuli compared with neutral stimuli (Hajcak et al., 2010; Weinberg & Hajcak, 2010; Briggs & Martin, 2009; Schupp et al., 2000, 2004).

Although emotional stimuli elicit similar increases in EPN, P300, and LPP, there has been some question as to

whether these components index similar or distinct aspects of attention to emotion and emotional processing. For instance, some works suggest that early (e.g., <300 msec) components index relatively automatic increases in selective attention, whereas later components (e.g., >300 msec) may be associated with more sustained and elaborative processes following the presentation of emotional stimuli (Hajcak, Weinberg, MacNamara, & Foti, 2011; Foti et al., 2009; Hajcak & Olvet, 2008; Olofsson et al., 2008; Azizian & Polich, 2007; Codispoti et al., 2007; Olofsson & Polich, 2007; Mecklinger & Pfeifer, 1996).

Consistent with this possibility, early components such as the EPN appear to index relatively gross discrimination between affective and nonaffective stimuli (Weinberg & Hajcak, 2010), whereas the LPP indexes more fine-grained distinctions among specific picture contents within the broad affective categories of pleasant, neutral, and unpleasant (Weinberg & Hajcak, 2010; Briggs & Martin, 2009; Schupp et al., 2004). Likewise, although the onset of the P300 and LPP is similar, the shorter duration of the P300 as well as its sensitivity to nonemotional manipulations has led some to argue that the P300 indexes initial allocation of attention to motivationally salient stimuli, whereas the later LPP reflects more elaborated processing related to stimulus significance (Schupp et al., 2006). And indeed, the later LPP, unlike earlier components, has been uniquely linked to memory encoding and storage (Koenig & Mecklinger, 2008; Dolcos & Cabeza, 2002), reinterpretation of stimulus meaning (MacNamara, Foti, & Hajcak, 2009; Foti & Hajcak, 2008; Hajcak & Nieuwenhuis, 2006), and attentional biases as measured by RT (Gable & Harmon-Jones, 2010). Finally, unlike earlier components, later portions of the LPP may also be uniquely related to individual differences (Horan, Wynn, Kring, Simons, & Green, 2010). Functionally, we have suggested that later slow wave activity reflected in the LPP is a dynamic measure of the sustained allocation of attentional resources to visual stimuli (Hajcak et al., 2010; Weinberg & Hajcak, 2010; Hajcak et al., 2011).

The current study examined whether response times and P300 amplitude to targets in the Emotional Interrupt Task are predicted by neural activity in response to preceding, task-irrelevant pictures. If the EPN, P300, and LPP similarly index increased visual attention to salient stimuli, variation in these components should predict greater subsequent behavioral interference and reduction in the target-elicited P300. However, it is also possible that specific aspects of emotional processing (i.e., elaborative processes reflected in the LPP) might predict behavioral responses better than others (i.e., early obligatory ERP components such as the EPN). Because the later LPP component is thought to be associated with ongoing elaborative processing and sustained attention, it was hypothesized that reduced processing of targets reflected in the magnitude of the target-locked P300 as well as increased RT to targets would specifically be associated with

the LPP. This hypothesis was examined in both a within- and between-subject approach.

METHODS

Participants

A total of 82 Stony Brook University undergraduates (40 women) participated in the study for course credit. The mean age of participants was 21.03 years ($SD = 4.96$ years); 43.9% were white, 14.6% were Hispanic, 19.5% were Asian, 6% were black, 12.1% chose to define themselves as "other," and 3.7% did not indicate any race.

Visual Stimuli

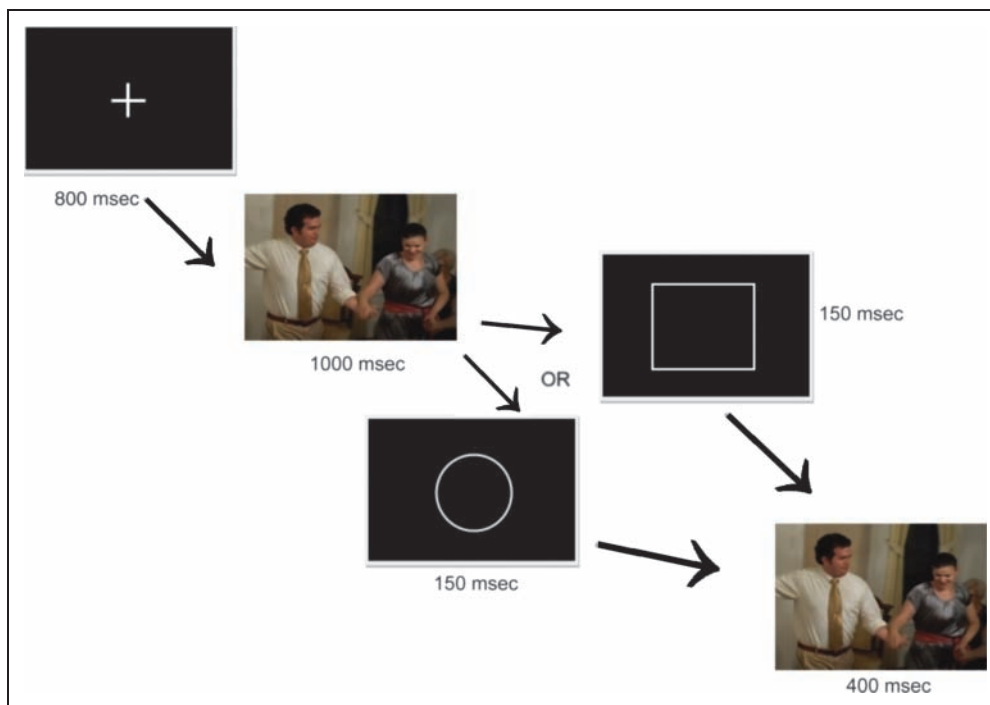
Sixty images were selected from the IAPS (Lang et al., 2005); of these, 20 were pleasant, 20 were neutral, and 20 were unpleasant (see Appendix A for specific images selected, including 10 practice images). Normative ratings indicated that the unpleasant pictures were less pleasant (valence $M = 2.40$, $SD = 0.45$) than the neutral pictures ($M = 5.04$, $SD = 0.39$), which were less pleasant than the pleasant pictures ($M = 7.01$, $SD = 0.63$; larger numbers indicate more pleasant ratings). Unpleasant ($M = 6.16$, $SD = 0.59$) and pleasant ($M = 5.59$, $SD = 1.14$) images were more emotionally arousing than neutral images ($M = 2.73$, $SD = 0.50$; larger numbers indicate higher arousal).

All visual stimuli were presented on a Pentium D computer, using Presentation software (Neurobehavioral Systems, Inc., Albany, CA). Before each trial, participants viewed a white fixation cross on a black background. Each picture was displayed in color at the full size of the monitor (48.26 cm). Participants were seated approximately 70 cm from the screen, and the images occupied about 40° of visual angle horizontally and vertically.

Procedure

Subsequent to verbal instructions indicating that they would be engaging in a speeded response task while also viewing pictures of varying emotional quality, participants were seated and electroencephalograph sensors were attached. We adapted the Emotional Interrupt Task based on previous reports (Mitchell et al., 2006, 2008). Each trial consisted of a fixation point (800 msec), followed by an image drawn from the IAPS for 1000 msec, followed by either a circle or a square (i.e., the target; 150 msec), followed by the same IAPS image that had preceded the target (400 msec). Between each trial was an intertrial interval that ranged from 1500 to 2000 msec; during the intertrial interval, the screen was blank. Figure 1 depicts the sequence of events during a trial of the task. In the present study, there were 180 trials presented in a random order for each participant, with 60 trials for each of the valence conditions: pleasant, unpleasant, or neutral.

Figure 1. A sample trial from the task: A fixation cross-directed participants' attention. Next, an IAPS image was presented, followed rapidly by one of two targets (circle or square), followed by the same IAPS image. Participants were instructed to identify the shape of the target as quickly as possible.



Participants were instructed to respond as quickly as possible to targets by clicking the left mouse button. Per Mitchell et al. (2006), trials for which the participants' RTs were less than 150 msec or greater than 1500 msec were excluded from the analysis.¹

Electroencephalographic Recording and Data Processing

Continuous EEG recordings were collected using an elastic cap and the ActiveTwo BioSemi system (BioSemi, Amsterdam, the Netherlands). Sixty-four electrode sites were used based on the 10/20 system as well as two electrodes on the right and left mastoids. EOG generated from eye movements and eye blinks was recorded using four facial electrodes: horizontal eye movements were measured via two electrodes located approximately 1 cm outside the outer edge of the right and left eyes. Vertical eye movements and blinks were measured via two electrodes placed approximately 1 cm above and below the right eye. The EEG signal was preamplified at the electrode to improve the signal-to-noise ratio and amplified with a gain of 1× by a BioSemi ActiveTwo system (BioSemi, Amsterdam, the Netherlands). The data were digitized at a 24-bit resolution with a sampling rate of 512 Hz using a low-pass fifth order sinc filter with a half-power cutoff of 102.4 Hz. Each active electrode was measured on-line with respect to a common mode sense active electrode producing a monopolar (non-differential) channel. Off-line, all data was re-referenced to the average of the left and right mastoids and band-pass filtered with low and high cutoffs of 0.1 and 30 Hz, respectively; eye blink and ocular corrections were conducted as per Gratton, Coles, and Donchin (1983).

A semiautomatic procedure was employed to detect and reject artifacts. The criteria applied were 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-msec intervals. These intervals were rejected from individual channels in each trial. Visual inspection of the data was then conducted to detect and reject remaining artifacts.

Only ERP data associated with *correct* responses were included in averages; therefore, 4688 pleasant trials were included ($M = 57.21$, $SD = 3.70$), as were 4710 neutral trials ($M = 57.62$, $SD = 3.74$) and 4661 unpleasant trials ($M = 56.96$, $SD = 3.46$). The EEG was segmented for each trial beginning 200 msec before the *pretarget* picture and continuing for 1200 msec (i.e., the entire duration of the pretarget picture presentation). In addition, ERP response to correctly identified *targets* was examined; here, the EEG was segmented 200 msec before the target onset and continuing for 1200 msec. The baseline for all ERPs was the 200 msec before picture onset. Traditional component-scoring techniques were used in an initial examination of the target-locked responses, as the target-locked P300 is a well-defined component (see, e.g., Polich, 2007, for a review). The P300 to targets was scored as the average activity at five sites (CP1, CP2, CPz, Cz, and Pz) between 300 and 600 msec after target onset. Nine averages were created for each subject: Three were the average of all responses to targets following pleasant, neutral, and unpleasant images. Because we also wished to examine whether, for each subject, speed of response was associated with the magnitude of the P300 to targets and if this varied by the preceding picture type, median RTs were calculated for each individual subject for each picture type. Grand averages

for each subject were then constructed by separately averaging ERPs to targets that preceded correct RTs falling below *that individual's* median score (i.e., fast RTs) and above each individual's median score (i.e., slow RTs) for targets following each picture type. Thus, six new ERP averages were created for each subject: pleasant fast, pleasant slow, neutral fast, neutral slow, unpleasant fast, and unpleasant slow.

Because there is substantial temporal and spatial overlap between the EPN, P300, and LPP (Foti et al., 2009) and because area and peak measurements may not be sensitive to this overlap (Donchin & Heffley, 1979), the present study also utilized temporospatial PCA to distinguish latent components of the pretarget stimulus-locked ERPs to the task-irrelevant pictures; this approach does not average over temporal or spatial data points a priori. Factor combinations derived from PCA have both spatial and temporal loadings, analogous to typical temporal and spatial characteristics of ERPs. In traditional ERP analyses, a frequently used method for scoring ERP components is to consider the average activity in specific time window at a subset of electrode sites where the ERP is maximal. For instance, the P300 might be scored as the average difference between target and standard trials between 300 and 600 msec at a representative cluster of parietal recording sites. This approach essentially weights certain sites and time points by multiplying by 1 and multiplies all other time points and sites by 0. Rather than weighting electrode sites and time points in a binary fashion, the PCA-based approach derives continuous weights for both electrodes and time points, thus using all the data. The factor loadings derived from the two-step PCA then convey these continuous weightings. However, there is also evidence to suggest that mean activity derived from component-scoring techniques can be highly correlated with scores on the corresponding PCA-derived temporal-spatial factor ($r = .81$; Hajcak et al., 2011).

Two temporospatial PCAs (Dien, 2010; Foti et al., 2009; Dien, Beal, & Berg, 2005; Dien & Frishkoff, 2005) were conducted on the present data. To determine if, for each individual, longer response times to targets were also associated with greater electrocortical activity to task-irrelevant IAPS images preceding targets, median RTs were again calculated for each individual subject for each picture type, as above. This resulted in six new ERP averages for the pretarget IAPS images for each subject: pleasant fast, pleasant slow, neutral fast, neutral slow, unpleasant fast, and unpleasant slow. These six conditions were then entered into the data matrix for each subject in the first PCA.

Following this, we wished to examine whether individuals with greater electrocortical activity to task-irrelevant pictures were also characterized by longer response times to targets. Therefore, for the second PCA, we collapsed across slow and fast trials to derive a single measure for each picture type for each subject to examine between-subject correlations between ERP and behavioral data.

For each subject, the overall average ERP responses to pleasant, neutral, and unpleasant images that preceded targets were created. These three conditions were then entered into the data matrix.

For within-subject (i.e., separating fast versus slow trials for each subject) and between-subject (i.e., collapsing across fast and slow trials) analyses, the same steps were used for deriving PCA factors. PCA extracts linear combinations of data that distinguish patterns of electrocortical activity across all time points and recording sites. Using the Matlab ERP PCA Toolbox (version 1.093), a temporal PCA was performed first to capture variance across time and to maximize the initial separation of ERP components (Dien & Frishkoff, 2005). Simulation studies suggest that Promax rotations are most effective for temporal analyses (Dien, 2010; Dien, Khoe, & Mangun, 2007); therefore, Promax rotation was used to rotate to simple structure in the temporal domain. The temporal PCA used all time points as variables and considered all 82 subjects, conditions (six or three, in the within- and between-subject analyses, respectively), and 64 recording sites as observations, thereby yielding linear combinations of time points (referred to as temporal factors) and reducing the 614 temporal dimensions of the original data set (512 samples per second multiplied by a total trial-plus-baseline length of 1200 msec).

On the basis of the resulting Scree plots (Cattell, 1966), seven temporal factors were extracted for rotation for both the within- and between-subject analyses. Covariance matrix and Kaiser normalization were used for these PCAs (Dien et al., 2005). 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 topography can be reconstructed for any time point, subject, and condition by multiplying the corresponding electrode scores by the factor loading and standard deviation (Dien, 1998).

Following the temporal PCA, a spatial PCA was then performed to reduce the spatial dimensions of the data sets. Simulation studies suggest that Infomax rotations are most effective for spatial analyses (Dien, 2010; Dien et al., 2007); therefore, Infomax was used to rotate to independence in the spatial domain. In the spatial PCA, recording sites were used as variables, and all subjects, conditions, and temporal factor scores were used as observations. Five spatial factors were extracted from each temporal factor for Infomax rotation, yielding a total of 35 temporospatial factor combinations for both the within- and between-subject PCAs. In each PCA, nine factors accounted for more than 1% of the variance each and were subjected to a one-way repeated measures ANOVA examining the impact of picture type (unpleasant, neutral, pleasant). A Bonferroni correction (.05/9; $p < .006$) resulted in three factor combinations for each PCA that were sensitive to picture type (Tables 1

Table 1. Description and Analysis of Variance Results for Each Temporospatial Factor for Between-Subject Analyses

Temporospatial Factor Combination	Temporal Peak Loading (msec)	Spatial Distribution of Emotional Enhancement	Main Effect of Picture Type $F(2, 162)$	Greenhouse–Geisser ϵ	Unpleasant vs. Neutral, $t(81)$	Pleasant vs. Neutral, $t(81)$	Unpleasant vs. Pleasant, $t(81)$
TF3SF1 (EPN)	288	Occipital	62.59** [†]	.82	10.04**	9.64**	1.19
TF1SF2 (P300)	358	Parietal	88.33**	.99	12.69**	10.29**	1.51
TF2SF2 (LPP)	977	Parietal	102.10**	.95	11.95**	11.76**	1.92

** $p < .006$.

[†]Corrected $p < .001$, corrected df (1.65, 133.34).

and 2) and which were temporally and spatially similar to those observed in previous works on emotional processing (e.g., Foti et al., 2009). The resulting factors were an early occipital negativity peaking at 257 msec, an early parietal positivity peaking around 374 msec, and a later parietal positivity peaking at 979 msec. To directly assess timing and spatial voltage distributions, we then translated the factors back into voltages.

Mahalanobis distances were calculated to screen out multivariate outliers. None were detected; therefore, all subjects were entered into subsequent analyses. Accuracy was evaluated as a function of the preceding picture type using a one-way repeated measures ANOVA. A median split was conducted on RTs to compare fast with slow responses and was entered into a 2 (Reaction Time: fast, slow) \times 3 (Picture Type: unpleasant, neutral, pleasant) repeated measures ANOVA to evaluate RTs as a function of the preceding picture type as well as possible interactions between speed of response and picture type. Similarly, two 2 (Reaction Time: fast, slow) \times 3 (Picture Type: unpleasant, neutral, pleasant) repeated measures ANOVAs were conducted on PCA factors related to pretarget pictures and the P300 elicited by targets, with Greenhouse–Geisser correction applied to p values associated with multiple- df , repeated measures comparisons when necessitated by violation of the assumption of sphericity. Paired-samples t tests were utilized for all post hoc comparisons; p values were adjusted when necessary with the Bonferroni correction for multiple post hoc comparisons. For between-subject analyses that collapsed across fast and

slow trials for each subject, Spearman’s correlations were utilized to examine the relationship between RT and ERP data.

RESULTS

Behavioral Data

Mean accuracy following each picture type was calculated as a percentage of correct responses. Accuracy varied according to picture type ($F(2,160) = 4.16, p < .05$; Greenhouse–Geisser $\epsilon = 0.96$). Post hoc comparisons indicated that performance was worse following unpleasant ($M = 94.55, SD = 5.30$) compared with neutral trials ($M = 95.69, SD = 5.46; t(80) = 3.30, p < .001$). Performance differences following neutral and pleasant images did not reach significance ($M = 94.90, SD = 6.02; t(80) = 1.73, p = .09$). In addition, accuracy was comparable following pleasant and unpleasant images ($t(80) = .86, p = .40$; critical p value = .02 for three contrasts).

Mean correct RTs were calculated for each picture type (e.g., pleasant, neutral, and unpleasant). As expected, RTs varied according to picture type ($F(2,160) = 14.67, p < .001$; Greenhouse–Geisser $\epsilon = 0.93$). Additionally, there was a main effect of response speed (e.g., fast vs. slow responders; $F(1,79) = 46.17, p < .001$), and this did not vary according to picture type ($F(2,160) = 1.88, p = .16$; Greenhouse–Geisser $\epsilon = 0.93$). Post hoc comparisons indicated that correct RTs following pleasant ($M = 488.99, SD = 134.28$) and unpleasant ($M = 485.65, SD = 136.06$)

Table 2. Description and Analysis of Variance Results for Each Temporospatial Factor for the Within-Subject Analyses

Temporospatial Factor	Peak Loading (msec)	Spatial Distribution	Main Effect of Picture Type $F(2, 162)$	Greenhouse–Geisser ϵ	Main Effect of Response Time $F(1, 81)$	Greenhouse–Geisser ϵ	Picture Type \times Response Time $F(2, 162)$
TF3SF1 (EPN)	257	Occipital	62.59** [†]	.79	<1	1.00	<1
TF1SF2 (P300)	374	Parietal	68.12**	.96	<1	1.00	1.87
TF2SF2 (LPP)	979	Parietal	81.57**	.92	35.81**	1.00	<1

** $p < .001$.

[†]Corrected $p < .001$, corrected df (1.57, 127.29).

images were significantly longer than correct RTs following neutral images ($M = 474$, $SD = 134.19$; $t(80) = 4.98$, $p < .001$ and $t(80) = 3.66$, $p < .001$, respectively). Correct RTs following pleasant and unpleasant images were not significantly different from one another ($t(80) = 1.35$, $p = .18$; critical p value = .02 for three contrasts).

ERP Response to Pretarget IAPS Images

ERP factor combinations. In the present study, the factor combinations can be grouped into three broad categories. The first is an early negativity (Temporal Factor 3/Spatial Factor 1; TF3/SF1) to emotional compared with neutral images, which peaks at 288 msec at occipital recording sites, consistent with previous works on EPN (Weinberg & Hajcak, 2010; Foti et al., 2009; Flaisch, Junghöfer, et al., 2008; Schupp et al., 2006; Schupp, Junghöfer, Weike, & Hamm, 2003a). Spatial topographies and waveforms for this factor combination are presented in Figure 2 (top). The three possible pairwise comparisons across picture type were performed using a significance cutoff of $p < .017$ for three contrasts (.05/3). As previously demonstrated, this factor combination showed an enhanced negativity for both pleasant and unpleasant compared with neutral pictures, but pleasant and unpleasant pictures did not differ from one another (Table 1).

A second combination is an increased positivity (Temporal Factor 1/Spatial Factor 2; TF1/SF2) to emotional compared with neutral images, which peaks at 358 msec at parietal recording sites, consistent with previous works on P300 (e.g., Foti et al., 2009). Spatial topographies and waveforms for this factor combination are presented in Figure 2 (middle). The three pairwise comparisons across picture type were again performed using a significance cutoff of $p < .017$ for three contrasts (.05/3). As previously demonstrated, this factor combination showed an enhanced positivity for both pleasant and unpleasant compared with neutral pictures, but pleasant and unpleasant pictures did not differ from one another (Table 1).

Finally, the third combination represents a later positivity (Temporal Factor 2, Spatial Factor 2; TF2/SF2) to emotional compared with neutral images, which peaks at 979 msec at parietal recording sites, consistent with previous works on the later and more sustained LPP (e.g., Foti et al., 2009). Spatial topographies and waveforms for this factor combination are presented in Figure 2 (bottom). The three pairwise comparisons across picture type were again performed, using a significance cutoff of $p < .017$ for three contrasts (.05/3). As previously demonstrated, this factor combination, too, showed an enhanced positivity for both pleasant and unpleasant compared with neutral pictures, but pleasant and unpleasant pictures did not differ from one another (Table 1).

Relationship between neural response to emotional images and behavioral measures: Within-subject effects. To determine whether any of these factor combinations

were related to delays in response time, we utilized the six conditions (unpleasant fast, unpleasant slow, neutral fast, neutral slow, pleasant fast, and pleasant slow) from the within-subject PCA to examine the within-subject relationship between ERP factor scores and response speed. As indicated above, each factor combination varied as a function of picture type, but only TF2/SF2 (LPP) also varied as a function of RT (Table 2). Spatial topographies and waveforms associated with fast and slow responses for this factor combination are presented in Figure 2. As suggested by the figure, trials associated with long RTs were preceded by an enhanced positivity compared with trials that followed short RTs. Thus, emotional compared with neutral images elicited an increased EPN, P300, and LPP, consistent with previous works; these trials were also associated with slower RTs. Importantly, only the LPP factor was also larger for slower RTs, suggesting a specific relationship between variability in RT and this later positivity (Figure 3).

Relationship between neural response to emotional images and behavioral measures: Between-subject effects.

Because RTs were significantly kurtotic for unpleasant ($k = 9.38$), neutral ($k = 9.58$), and pleasant ($k = 8.65$) images, Spearman's correlations were used to examine the relationship between behavioral interference and the factor loadings for TF3/SF1 (EPN), TF1/SF2 (P300), and TF2/SF2 (LPP) for each of the three picture types (Unpleasant, Table 3; Neutral, Table 4; and Pleasant, Table 5). Neural response to each of the three picture types was highly correlated *within* each factor (r s ranged from .61 to .89). Additionally, although RT differed significantly by picture type (as indicated above), RTs were also highly correlated across the three picture types (r s ranged from .94 to .97). However, across all three picture types, only TF2/SF2 (LPP) was significantly correlated with RTs to subsequent targets, such that larger LPP factor scores correlated with slower RT (Table 5).

ERP Response to Targets

Because there was no effect of target type, (i.e., circle compared with square; $F(1,81) < 1$), correctly identified circles and squares were collapsed into a single category. Table 6 presents the means and standard deviations of P300 elicited by correctly identified targets following each picture type; target-locked ERPs and scalp distribution of the P300 are displayed in Figure 4 (top). As indicated by Figure 4, the magnitude of the P300 varied according to picture type ($F(2,162) = 36.69$, $p < .001$), such that targets following emotional images (both pleasant and unpleasant) elicited a significantly smaller P300 than targets following neutral images; however, there was no difference between targets following pleasant and unpleasant images (Table 6). Spatial topographies and waveforms associated with fast and slow responses to targets are also presented in Figure 4 (bottom). As suggested by the figure, trials associated with

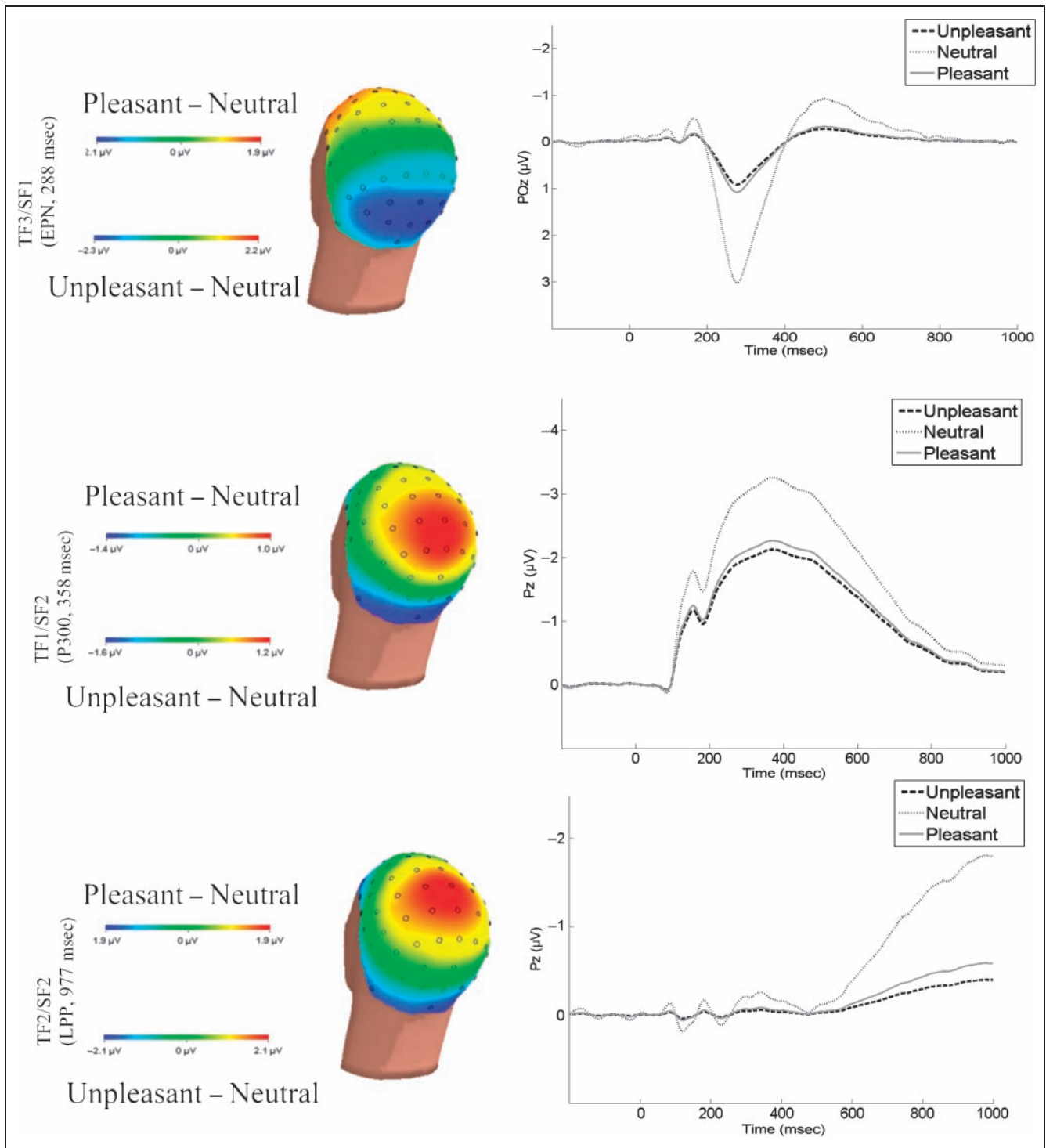


Figure 2. Topographic maps and waveforms for temporospatial factors TF3SF1 (EPN; top), TF1SF2 (P300; middle), and TF2SF2 (LPP; bottom). Each topographic map is accompanied by two scales—one representing pleasant minus neutral and one representing unpleasant minus neutral. The distribution for each condition is identical by necessity, although the scaling of the difference between conditions may differ.

long RTs were preceded by a smaller P300 compared with trials associated with short RTs (Table 6).

Tables 3–5 present the relationship for each picture type between behavioral indices (response time), electrocortical response to targets, and factor loadings for the three PCA-derived factors as measured by Spearman's r .

Neural response to targets following each of the three picture types was highly correlated ($r_s > .79$), as were the RTs across the three picture types ($r_s > .94$). Nonetheless, negative relationships were demonstrated between the magnitude of P300 and RTs across picture types, such that smaller P300s to targets were associated with longer RTs.

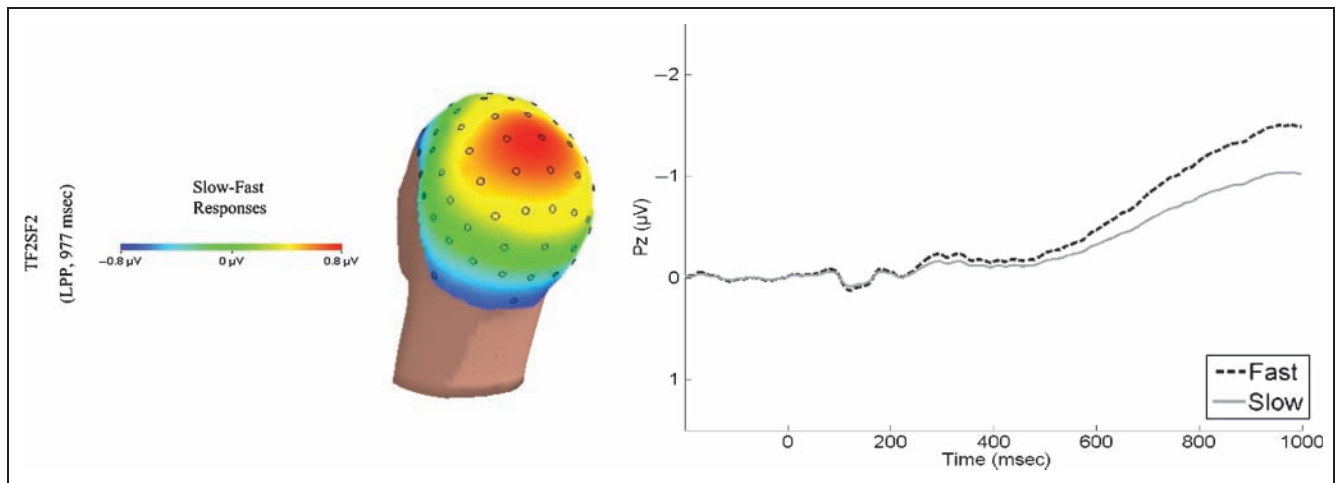


Figure 3. Topographic maps and waveforms for temporospatial combination TF2/SF2 (LPP) displaying fast compared with slow responses.

Additionally, the magnitude of the P300 to targets was associated negatively with the LPP elicited by preceding pictures, such that a larger LPP was associated with a smaller subsequent P300 response to targets.

Following this, three multiple regressions were conducted within each picture type (pleasant, neutral, and unpleasant) to predict RT from both factor loadings for TF2SF2/LPP to preceding pictures and the P300 to targets, which were simultaneously entered predictor variables. For pleasant pictures, the overall model significantly predicted RT ($R^2 = .25$; $F(2, 80) = 13.16$, $p < .001$), and the association with both predictors remained significant (TF2SF2/LPP pleasant: $\beta = .35$, $t(80) = 3.44$, $p < .001$; P300 to targets following pleasant pictures: $\beta = .28$, $t(80) = 2.75$, $p < .01$). For neutral pictures, the overall model was also significant ($R^2 = .16$; $F(2, 80) = 7.54$, $p < .001$); however, when entered simultaneously, only TF2SF2/LPP neutral significantly predicted RT (TF2SF2/LPP neutral: $\beta = .27$, $t(80) = 2.42$, $p < .05$; P300 to targets following neutral pictures: $\beta = .22$, $t(80) = 1.92$, $p = .06$). Finally, as above, the overall model was significant for unpleasant pictures ($R^2 = .15$; $F(2, 80) = 7.07$, $p < .01$). But, as demonstrated with neutral pictures, only TF2SF2/LPP unpleasant significantly predicted RT (TF2SF2/LPP un-

pleasant: $\beta = .30$, $t(80) = 2.77$, $p < .01$; P300 to targets following unpleasant pictures: $\beta = .19$, $t(80) = 1.76$, $p = .08$).

DISCUSSION

The results of the present study replicate previous findings regarding increased RT following emotional compared with neutral images in the Emotional Interrupt Task (Mitchell et al., 2006, 2008). Moreover, the current study also found that task-irrelevant and distracting emotional stimuli elicited an increased EPN, P300, and LPP-latent factors that were derived empirically using temporospatial PCA. In addition, the present study examined the association between the magnitude of these ERP factors and the degree of subsequent behavioral interference from distracting pictures. Importantly, the magnitude of the LPP evoked by pictures presented before a target was uniquely associated with an increase in RT: the larger the LPP, the slower the RT to subsequent targets. This effect was found in both within- and between-subject analyses and did not generalize to either the earlier EPN or P300.

Within subjects, both emotional pictures and pictures that preceded trials with RTs above the median (i.e., slow trials) were associated with larger LPPs. In addition,

Table 3. Spearman's Correlations for the Three PCA-Derived Components Elicited by Unpleasant Distracters, the P300 Elicited by Targets following Unpleasant Distracters, and RT following Unpleasant Distracters

	<i>TF1SF2 (P300) Unpleasant</i>	<i>TF2SF2 (LPP) Unpleasant</i>	<i>Target-Locked P300 Unpleasant</i>	<i>RT Unpleasant</i>
TF3SF1 (EPN) unpleasant	.04	.10	-.01	.11
TF1SF2 (P300) unpleasant	–	-.38**	.02	.03
TF2SF2 (LPP) unpleasant		–	-.24*	.42**
Target-locked P300 Unpleasant			–	-.28*

* $p < .05$.

** $p < .01$.

Table 4. Spearman's Correlations for the Three PCA-Derived Components Elicited by Neutral Distracters, the P300 Elicited by Targets following Neutral Distracters, and RT following Neutral Distracters

	<i>TF1SF2 (P300) Neutral</i>	<i>TF2SF2 (LPP) Neutral</i>	<i>Target-Locked P300 Neutral</i>	<i>RT Neutral</i>
TF3SF1 (EPN) Neutral	.02	-.02	-.01	.08
TF1SF2 (P300) Neutral	–	-.22**	.09	.004
TF2SF2 (LPP) Neutral		–	-.35**	.49**
Target-locked P300 Neutral			–	-.32**

** $p < .01$.

between-subject analyses suggested that those participants with greater LPP magnitudes were characterized by slower RTs. Together, these data confirm that trials associated with larger LPPs are associated with subsequently slower RTs to targets. Consistent with this, the P300 to targets was significantly smaller following a task-irrelevant emotional compared with neutral image, in keeping with previous works, suggesting that emotional stimuli may also interfere with relatively obligatory attentional allocation (Flaisch, Junghöfer, et al., 2008; Flaisch, Stockburger, et al., 2008; Bradley et al., 2006). Indeed, evidence from rapid serial visual presentation tasks suggests that task-irrelevant emotional stimuli may even interfere with processing of other emotional stimuli, such that the EPN and LPP elicited by emotional images following emotional images are attenuated (Flaisch, Junghöfer, et al., 2008; Flaisch, Stockburger, et al., 2008).

In the present study, the magnitude of the P300 to targets was also associated with behavioral interference, such that smaller P300s were associated with longer RTs, suggesting a plausible mechanism by which emotional images might interfere with targets. Specifically, emotional images demand greater sustained attentional processing, resulting in diminished cognitive resources for processing subsequent targets and delaying RTs. Furthermore, although the reduction in the P300 to targets was also associated with increased RTs, in most cases, the magnitude of the LPP predicted RTs even when controlling for the P300 response to targets.

The specificity of the relationship between the LPP and behavioral interference is particularly noteworthy. Previous research has suggested a distinction between early, relatively obligatory attentional capture by emotional images

(<300 msec) and, later, more elaborative processes (>300 msec), which may reflect continued processing and encoding (Hajcak et al., 2011; Foti et al., 2009; Hajcak & Olvet, 2008; Olofsson et al., 2008; Azizian & Polich, 2007; Codispoti et al., 2007; Olofsson & Polich, 2007; Mecklinger & Pfeifer, 1996). Although the factor combinations representing the EPN and P300 reliably differentiated emotional from neutral task-irrelevant pictures, it was only the later LPP factor combination that related to subsequently increased response time and attenuation of the target-locked P300. Thus, the results of the present study suggest that processes indexed by the EPN and P300 do not interfere with the subsequent processing of targets. Rather, it appears to be the continued elaboration and encoding indexed by the LPP that relates to subsequently slower response times and reduced P300s to targets. These data suggest a functional differentiation between the later LPP and the relatively earlier EPN and P300.

It should be noted that we have opted here to refer to TF1SF2 as the P300 and to TF2SF2 as the LPP on the basis of the timing of these components; however, it might be equally appropriate to refer to these components in terms of earlier and later portions of LPP, respectively. The scalp-recorded LPP is a broad and sustained positivity that begins 200–300 msec after picture presentation and persists throughout the full duration of the picture presentation (Weinberg & Hajcak, 2010; Hajcak & Olvet, 2008; Sabatinelli, Lang, Keil, & Bradley, 2007; Schupp et al., 2004) and even beyond stimulus offset (Hajcak, MacNamara, et al., 2010; Hajcak & Olvet, 2008). On the basis of prior PCA results, we have argued that this apparent positivity may reflect multiple overlapping positivities (e.g., Foti et al., 2009; MacNamara et al., 2009). In the current

Table 5. Spearman's Correlations for the Three PCA-Derived Components Elicited by Pleasant Distracters, the P300 Elicited by Targets following Pleasant Distracters, and RT following Pleasant Distracters

	<i>TF1SF2 (P300) Pleasant</i>	<i>TF2SF2 (LPP) Pleasant</i>	<i>Target-Locked P300 Pleasant</i>	<i>RT Pleasant</i>
TF3SF1 (EPN) Pleasant	.01	-.13	-.18	.02
TF1SF2 (P300) Pleasant	–	-.32**	-.01	-.08
TF2SF2 (LPP) Pleasant		–	-.24**	.43**
Target-locked P300 Pleasant			–	-.32**

** $p < .01$.

Table 6. Means, SDs, and ANOVA Results for the Target-Locked P300

Component	Mean Area in μV (SD) Unpleasant	Mean Area in μV (SD) Pleasant	Mean Area in μV (SD) Neutral	Unpleasant vs. Neutral, $t(81)$	Pleasant vs. Neutral, $t(81)$	Unpleasant vs. Pleasant, $t(81)$
Target-locked P300 (300–600 msec)	2.18 (1.93)	2.34 (1.80)	3.11 (2.13)	8.10**	5.81**	1.62
	Main Effect of Picture Type $F(2, 162)$	Greenhouse– Geisser ϵ	Main Effect of Response Time $F(1, 81)$	Greenhouse– Geisser ϵ	Picture Type \times Response Time $F(2, 162)$	Greenhouse– Geisser ϵ
Target-locked P300 (300–600 msec)	37.29**	.92	17.77**	1.00	2.97	.96

** $p < .006$.

study for instance, combining TF1SF2 and TF2SF2 would produce the apparent sustained positivity observed in the ERP averages. Previous research indicates that important information about the time course of emotional responding may be reflected in differences between early and later windows of the LPP (Weinberg & Hajcak, 2010, in press; Foti & Hajcak, 2008). The results discussed here further point to a functional difference between these two empirically identified components. Future studies may wish to further clarify the relationship between earlier-peaking component and the classic P300.

Also of note is the fact that, in the present study, the between-subject relation between the LPP and RT was not unique to emotional images: for example, neural response to unpleasant pictures is associated with RTs following not just unpleasant but also neutral and pleasant pictures. However, the correlations between RTs to different picture types were quite high (ranging from .94 to .97) as were the correlations within the TF2/SF2 (LPP) factor combination (ranging from .61 to .77). These data indicate that

individuals with slow RTs following one picture type tend to be slow following other picture types and that individuals with larger LPPs to one picture type tend to have large LPPs to other picture types. However, it is also the case that individuals with larger LPPs tend to be the ones who are slower.

The amplitude of the LPP can be modulated by contextual factors (Dunning & Hajcak, 2009; MacNamara et al., 2009; Foti & Hajcak, 2008; Hajcak & Nieuwenhuis, 2006); even the magnitude of the LPP to neutral pictures can be increased or decreased by manipulating picture salience (MacNamara et al., 2009). In the current study, it stands to reason that those neutral images associated with prolonged RTs (i.e., the slow neutral trials in the within-subject analyses) may have been more interesting or engaging. Previous work examining amygdala response to images has likewise demonstrated increased activity to more interesting neutral stimuli compared with less interesting neutral stimuli (Hamman, Ely, Hoffman, & Kilts, 2002), a result mirrored by data suggesting that more motivationally salient neutral

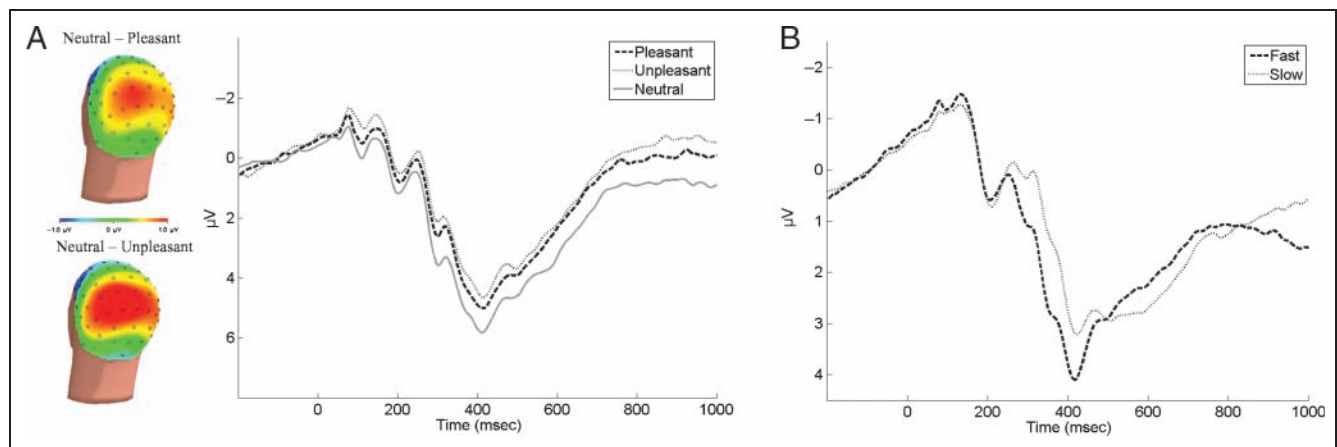


Figure 4. (A) Topographic maps (left) depicting voltage differences (in μV) for targets preceded by neutral images minus targets preceded by pleasant images (top) and targets preceded by neutral images minus targets preceded by unpleasant images (bottom) in the time range of P300 to targets (300–600 msec following target onset). Because targets preceded by neutral images elicited a *larger* P3, targets preceded by emotional images were subtracted from these averages; note that this is in contrast to Figure 2, in which the neutral average is subtracted from emotional averages. Also shown (right) are stimulus-locked ERPs averaged at CP1, CP2, CPz, Cz, and Pz for targets following pleasant, neutral, and unpleasant images. Target onset occurred at 0 msec. (B) Depicts stimulus-locked ERPs averaged at CP1, CP2, CPz, Cz, and Pz depicting P300s associated with fast and slow responses to targets.

images (e.g., scenes containing people) elicit a larger LPP than other neutral images (e.g., pictures of household objects; Weinberg & Hajcak, 2010).

There is also work to suggest that increased allocation of attentional resources to emotional stimuli occurs primarily when concurrent task difficulty is low (Flaisch, Junghöfer, et al., 2008; Pessoa, Padmala, & Morland, 2005; Pessoa, McKenna, Gutierrez, & Ungerleider, 2002). In the present study, task difficulty was low (i.e., identifying the shape of a target), and the emotional content was relatively high (i.e., IAPS images). Future studies might further examine the relationship between the LPP and behavioral interference in more cognitively demanding tasks (e.g., identifying the orientation of a target object as per Pessoa et al., 2005).

Previous research suggests that interference from emotional stimuli in the Emotional Interrupt Task is associated with increased limbic activity and decreased activity in areas thought to be involved in processes of cognitive control (Cunningham et al., 2004; Lévesque et al., 2003; Beauregard et al., 2001). Because of the broad spatial distribution and its sustained nature, accurate source localization of LPP is difficult, and the neural generators are not yet well understood. However, some have suggested the neural source of the LPP to be the occipital and posterior parietal cortex (Keil et al., 2002), and research from fMRI has demonstrated associations between variation in the magnitude of the LPP and the neural activity in occipital, parietal, and inferotemporal regions of the brain (Sabatinelli et al., 2007). A recent study utilizing a small clinical sample further indicates that stimulation of the DLPFC, an area implicated in cognitive control (Ochsner & Gross, 2007), may reduce the amplitude of the LPP (Hajcak et al., in press). Combined, these studies are consistent with the notion that the LPP indexes activity in parietal and occipital regions implicated in visual attention, which may be modulated by activity in more frontal regions. The results of the present study are therefore consistent with data from neuroimaging paradigms, suggesting that increased allocation of attentional resources toward emotional stimuli is associated with decreased resources for processing top-down directives. However, fully understanding the circuitry that supports emotional modulation of ERPs will require more research combining ERP and other neuroimaging techniques.

The present study supports previous works suggesting that the LPP indexes sustained attentional engagement with salient stimuli. In addition, it provides novel evidence that attentional engagement with both emotional and neutral stimuli as indexed by LPP is *uniquely* associated with subsequent RT slowing and reduction in the target-elicited P300. Although this represents a preliminary examination, the results of the present study support the utility of integrating affective ERP measures with behavioral paradigms, by which the functional significance of ERP components related to attention and emotion may be further clarified. Increasingly detailed examinations of the multiple processes that occur between early evaluative categorization

and later behavioral output, as well as the ways in which emotional content and stimulus salience interact with and influence attentional deployment, will be essential to our understanding of emotional experience.

APPENDIX A

Practice Images: 4605, 2620, 1450, 1600, 2110, 2050, 2206, 2320, 2753.

Pleasant Images: 2092, 2165, 1463, 2340, 4002, 4608, 4658, 4659, 4660, 4664, 5268, 7325, 8021, 8032, 8080, 8370, 8400, 8465, 8490, 8540.

Neutral Images: 5390, 7550, 7130, 5532, 5534, 7002, 7004, 7006, 7009, 7010, 2320, 7060, 7080, 7090, 7100, 7224, 7233, 7235, 7491, 7950.

Unpleasant Images: 2800, 3261, 3160, 9042, 3230, 6210, 9400, 6230, 6244, 6250, 6550, 6560, 9433, 6571, 6821, 9600, 9910, 3010, 9920, 9921.

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Note

1. Four incorrect trials from three subjects were excluded because they fell under 150 msec—three of these followed an unpleasant image and one followed a pleasant image. Three correct trials from three subjects were excluded because they fell above 1500 msec. Of these, one followed an unpleasant image, one followed a pleasant image, and one followed a neutral image.

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