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Developmental trajectory of the late positive potential: Using temporal-spatial PCA to characterize within-subject developmental changes in emotional processing

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Abstract

The late positive potential (LPP) is characterized by temporal and spatial changes across development—though existing work has primarily relied on visual or statistical comparisons of relatively few electrodes and averaged activity over time. The current study used an empirically based approach to characterize temporal and spatial changes in ERPs over time. Data were utilized from a large longitudinal study ($N = 380$) in which the LPP was recorded to pleasant, neutral, and unpleasant pictures around age 9 and again around age 12. Age 9 ERPs were subtracted from age 12 ERPs for all three image types; the resulting ERPs for each subject at each electrode site were then submitted to a temporospatial principal component analysis (PCA). A PCA factor was greater in amplitude for emotional pictures compared to neutral pictures between ages 9 and 12, evident as an occipital negativity and frontocentral positivity that peaked approximately 850 ms following picture presentation. Furthermore, the factor scores to emotional pictures for this component increased as a function of age 12 pubertal development, consistent with the notion that the LPP shifts from occipital to more frontocentral sites in relation to developmental changes from childhood to adolescence. A similar factor was observed when PCA was applied to all ERPs from both ages 9 and 12. Using temporospatial PCA on ERPs collected from the same subjects over time—especially within-subject subtraction-based ERPs—provides a concise way of characterizing and quantifying within-subject developmental changes in both the timing and scalp distribution of ERPs.

KEYWORDS

development, difference scores, emotion, ERPs, late positive potential, temporospatial PCA

1 | INTRODUCTION

Psychophysiological measures are increasingly employed in studies of emotion and emotional development across the life span. ERPs are especially useful for examining emotional information processing across development due to their temporal precision for capturing neural response to emotional stimuli and the fact that EEG is noninvasive and relatively simple to acquire in studies with child and adolescent populations. The vast majority of studies of emotion utilizing ERPs have focused on the late positive potential (LPP), an ERP component thought to index sustained attention toward, and elaborative processing of, motivationally salient stimuli (Cuthbert, Schupp, Bradley, Birbaumer, & Lang, 2000; Hajcak, Weinberg, MacNamara, & Foti, 2011). Generally, the LPP is evident within 200 ms following the onset of a stimulus and continues through the presentation of the stimulus and beyond stimulus offset (Hajcak & Olvet, 2008; Kujawa,

Klein, & Hajcak, 2012). Critically, the LPP is potentiated for emotional (i.e., positively or negatively valenced) stimuli compared to neutral stimuli.

Increasingly, studies have utilized variability in the LPP as an index of affective reactivity. For instance, studies in adult and child samples have revealed that LPP to unpleasant pictures can be intentionally modulated with the use of cognitive reappraisal strategies, such that the LPP can be reduced to unpleasant images that were paired with the use of cognitive reappraisal, as compared to the LPP to unpleasant images without reappraisal (DeCicco, O'Toole, & Dennis, 2014; Dennis & Hajcak, 2009; Hajcak & Nieuwenhuis, 2006; Moser, Hajcak, Bukay, & Simons, 2006). Additionally, research on individual differences in the LPP has found that depressed adults and children as well as children at risk for depression exhibit a reduced LPP to emotional stimuli (Foti, Olvet, Klein, & Hajcak, 2010; Kujawa, Hajcak, Torpey, Kim, & Klein, 2012; Proudfit, Bress, Foti, Kujawa, & Klein, 2015; Weinberg, Perlman, Kotov, & Hajcak, 2016; Whalen et al., in press). Additionally, enhanced LPPs to unpleasant and fearful stimuli have been implicated in specific phobias (Leutgeb, Schäfer, Köchel, Scharmüller, & Schienle, 2010) and social anxiety (Moser, Huppert, Duval, & Simons, 2008), and the LPP prospectively predicts increase in psychiatric symptoms in youth following exposure to a natural disaster (Kujawa et al., 2016). Such associations between variability in the LPP and psychopathology underscore the importance of understanding the typical development of the LPP response from childhood into adulthood. It may be particularly important to understand developmental changes in the LPP in early adolescence, as epidemiological studies have reported that incidence of major depression exhibits a steep incline after the age of 10 and that increases in depression have been linked to pubertal development (Beesdo, Pine, Lieb, & Wittchen, 2010).

Indeed, the LPP appears to be characterized by significant developmental changes during the transition from childhood to adolescence and adulthood (Hajcak & Dennis, 2009; Kujawa, Klein, et al., 2012). Previous studies that have identified the LPP in children as young as 5 have found an occipital distribution of the LPP (Hajcak & Dennis, 2009). Separate studies note that the LPP to emotional pictures appears to shift from more occipital to more parietal sites in early adolescence (Kujawa, Klein, et al., 2012) and to more central-parietal sites by early adulthood (Foti, Hajcak, & Dien, 2009). While the developmental processes underlying these changes remain uncertain, the "frontalization" of the spatial distribution of the LPP aligns with previous work that links the LPP to functional connectivity of prefrontal and occipitoparietal cortex (Moratti, Saugar, & Strange, 2011) as well as research that indicates emotional processing relies less on subcortical regions and more on prefrontal cortex across development (Monk, 2008).

Largely, previous work has identified patterns of developmental changes in the LPP by comparing the LPP across samples that vary in age (Bunford, Kujawa, Fitzgerald, Monk, & Phan, 2018). Thus, apparent developmental changes in the LPP are based on between-subjects comparisons; other studies have based developmental claims on visual or statistical comparison of ERPs at relatively few electrodes. For instance, Kujawa, Klein, et al. (2012) examined differences in the spatial distribution of the LPP in 8- to 13-year-old youth at two assessments occurring 2 years apart by focusing solely on observed activity at occipital and parietal poolings of three electrodes each (i.e., O1, O2, and Oz for occipital sites, and P3, P4, and Pz for parietal sites) and averaging activity across large time windows to calculate LPP scores.

By focusing on single sites or small poolings as well as averaging activity across relatively large windows of time, previous approaches have not fully characterized within-subject developmental changes in the timing and scalp distribution of emotional processing reflected in ERPs. For instance, the Kujawa, Hajcak, et al. (2012) article did not examine whether there were corresponding frontal increases in emotional modulation of the LPP. We propose that temporospatial principal component analysis (PCA) can be leveraged to more fully investigate developmental changes in the timing and scalp distribution of ERPs. Temporospatial PCA is a factor analytic approach used to parse the ERP waveform into underlying constituent components (Dien, 2010a). PCA examines variance across time points and electrode sites, thereby using all the data to discern latent components that underlie traditional ERP averages.

PCA might be used specifically to extract temporospatial factors that characterize within-subject changes in emotional processing over time. To examine factors that underlie within-subject changes in ERPs between two time points, PCA can be applied to subtraction-based ERP waveforms (i.e., ERPs from Time 1 are subtracted from ERPs at Time 2 for each subject, for each electrode site). The PCA would include this subtraction-based ERP separately for each picture type (i.e., pleasant, neutral, unpleasant). As the PCA uses all data points in a factor analytic approach, the factors that result from this PCA would provide a holistic representation of the temporal and spatial factors that underlie the observed ERP differences between the two assessments. The spatial and temporal distributions of resulting factors can be easily visualized, and individual PCA-derived LPP difference scores for each subject can be extracted, providing a metric of individual differences in the developmental changes in the ERP. Thus, this method characterizes within-subject developmental change in the ERP component such that resulting factor scores from the PCA incorporate spatial and temporal characteristics of developmental change. Although resulting PCA factors could reflect overall developmental changes evident across all ERPs, PCA factors that vary by picture type

would effectively reflect Age × Picture Type interactions that would characterize developmental changes in emotional processing more specifically.

In the present study, we examined the utility of temporospatial PCA for characterizing developmental changes in the LPP in early adolescence, a developmental period that has been characterized in terms of frontal spatial shifts in the LPP by one previous study using a separate sample (Kujawa, Klein, et al., 2012). With data from a large sample ($n = 380$) in which the LPP was recorded in response to pleasant, neutral, and unpleasant images from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 1997) at two time points, once around age 9 and again around age 12, we subtracted age 9 ERPs from age 12 ERPs to pleasant, neutral, and unpleasant stimuli; the resulting ERPs for each subject at each electrode site were then submitted to a temporospatial PCA. This yielded PCA factors that provided an empirically derived characterization of the temporal and spatial changes in the LPP from age 9 to 12. We sought to determine whether a PCA factor derived from these within-subject differences mapped onto both typical developmental changes and task effects (e.g., enhanced amplitude to emotional pictures vs. neutral pictures) evident in previous work on the LPP. Next, individual scores for the PCA-derived LPP difference were extracted for each subject, providing a measure of individual differences in developmental changes in the LPP. Furthermore, we examined correlations between the individual PCA-derived LPP difference scores and scores on the Pubertal Development Scale (PDS; Petersen, Crockett, Richards, & Boxer, 1988) to determine whether PCA-derived difference scores were indeed enhanced as a function of a critical age-appropriate indicator of development. Finally, we compared developmental differences in the PCA factor to developmental changes in the traditionally scored LPP to further examine the utility of our PCA approach and examined internal consistency reliability of the PCA-derived LPP difference score.

2 | METHOD

2.1 | Participants

Participants were a subsample of 380 children from a large-scale longitudinal study investigating temperament and psychopathology at Stony Brook University. Subjects were recruited from Stony Brook, NY, and the surrounding area using a commercial mailing list. Inclusion criteria were living with an English-speaking biological parent within 20 contiguous miles of Stony Brook University and no significant developmental disability or medical condition. Of the sample of 380 children reported here, 19.7% was ethnic minorities (i.e., nonwhite and/or Hispanic) and 43.4% was female. Assessments were completed at two time points, once around 9 years of age ($M = 9.17$, $SD = .38$) and again at around 12 years of age ($M = 12.62$, $SD = .42$). Informed consent was obtained prior to participation, and the research protocol was approved by the Institutional Review Board at Stony Brook University.

2.2 | Measures

2.2.1 | Pubertal development scale

The PDS is a self- and parent-report measure of physical development for youth under the age of 16 (Petersen et al., 1988). Male and female versions of the PDS were used, which ask respondents to report on their level of development on indices such as body hair, facial hair, skin change, breast development, and growth spurt. Responses are coded on a 4-point scale ranging from "*no development*" to "*completed development*." For both genders, ratings are averaged to create an overall score of pubertal development. The scale has been shown to have good reliability and validity and is correlated with measures of pubertal development derived from physical examination (Petersen et al., 1988). The PDS was completed by both the participant and mother of the participant, and mother- and self-reported PDS scores at age 12 were found to be highly correlated in the present study, $r(356) = .71$, $p < .001$. Thus, for analysis, a composite age-12 PDS score was made by z-scoring the mother- and self-reported PDS scores and averaging them together.

2.3 | Procedure and task

Participants completed an identical EEG task at two time points, once at the age 9 assessment and once at the age 12 assessment. All participants first provided written informed consent/assent and subsequently completed self-report questionnaires, including the PDS. Next, after EEG setup, participants completed a total of five tasks. The current study focuses only on data from the picture-viewing task, and the results of other tasks administered during the same experimental sessions are presented elsewhere (Kujawa, Kessel, Carroll, Arfer, & Klein, 2017; Kujawa, Proudfit, Laptook, & Klein, 2015; Meyer, Hajcak, Glenn, Kujawa, & Klein, 2017; Meyer, Hajcak, Torpey-Newman, Kujawa, & Klein, 2015). Task order was counterbalanced across all participants. For the picture-viewing task, a total of 60 developmentally appropriate images were selected from the IAPS (Lang et al., 1997). Of these, 20 images were pleasant, 20 images were neutral, and 20 images were unpleasant. Images utilized in the task were identical across age 9 and age 12 assessments. Each image was randomly presented once in each of two blocks, making for 120 trials total. Each trial began with a fixation cross (+) presented for 800 ms, then an image was presented for 1,000 ms followed by a target (< or >) presented for 150 ms,

and the same picture presented for another 400 ms. The target was an arrow pointed to the left or right, and participants were required to press the left or right button on the mouse to indicate the direction of the arrow. The LPP was measured in response to the first presentation of images. The intertrial interval varied randomly between 1,500 and 2,000 ms. Prior to the start of the task, participants completed 10 practice trials.

2.4 | EEG recording, processing, and data reduction

Continuous EEG was recorded using an elastic cap with 34 electrode sites placed according to the 10–20 system (32-channel cap with the addition of Iz and FCz). Electrooculogram (EOG) was recorded using four additional facial electrodes: two placed approximately 1 cm outside of the right and left eyes and two placed approximately 1 cm above and below the right eye. All electrodes were sintered Ag/AgCl electrodes. Data were recorded using the ActiveTwo BioSemi system (BioSemi, Amsterdam, Netherlands). The EEG was digitized with a sampling rate of 1,024 Hz using a low-pass fifth order sinc filter with a half-power cutoff of 204.8 Hz. A common mode sense active electrode producing a monopolar (i.e., nondifferential) channel was used as recording reference. EEG data were analyzed using BrainVision Analyzer (Brain Products, Gilching, Germany). Data were referenced offline to the average of left and right mastoids and band-pass filtered (0.1 to 30 Hz, with a 24 dB/oct roll-off).

Picture-locked epochs were extracted with a duration of 1,200 ms, including a 200-ms prestimulus and 1,000-ms poststimulus interval relative to the first presentation of IAPS images; these segments were then corrected for eye movement artifacts using a regression-based approach (Gratton, Coles, & Donchin, 1983). Epochs containing a voltage greater than 50 μV between sample points, a voltage difference of 300 μV within a segment, or a maximum voltage difference of less than 0.50 μV within 100-ms intervals were automatically rejected. The 200-ms prestimulus interval was used as the baseline. Picture-locked ERPs were averaged separately for pleasant, neutral, and unpleasant IAPS. ERP waveforms at Fz and Oz, for both time points and the difference between time points, are depicted in Figure 1.

2.5 | Data analysis

First, the more traditional LPP was exported as the mean amplitude from 400 to 1,000 ms following picture presentation at the Oz electrode site for pleasant, unpleasant, and neutral conditions. Next, we computed separate traditional LPP age-related difference scores for each condition (i.e., pleasant, unpleasant, neutral) by subtracting the age 9 averaged LPP from the age 12 averaged LPP. We examined the effect of picture type on traditional LPP age-related difference scores to pleasant, neutral, and unpleasant IAPS using a repeated measures analysis of variance (ANOVA) and follow-up paired samples *t* tests.

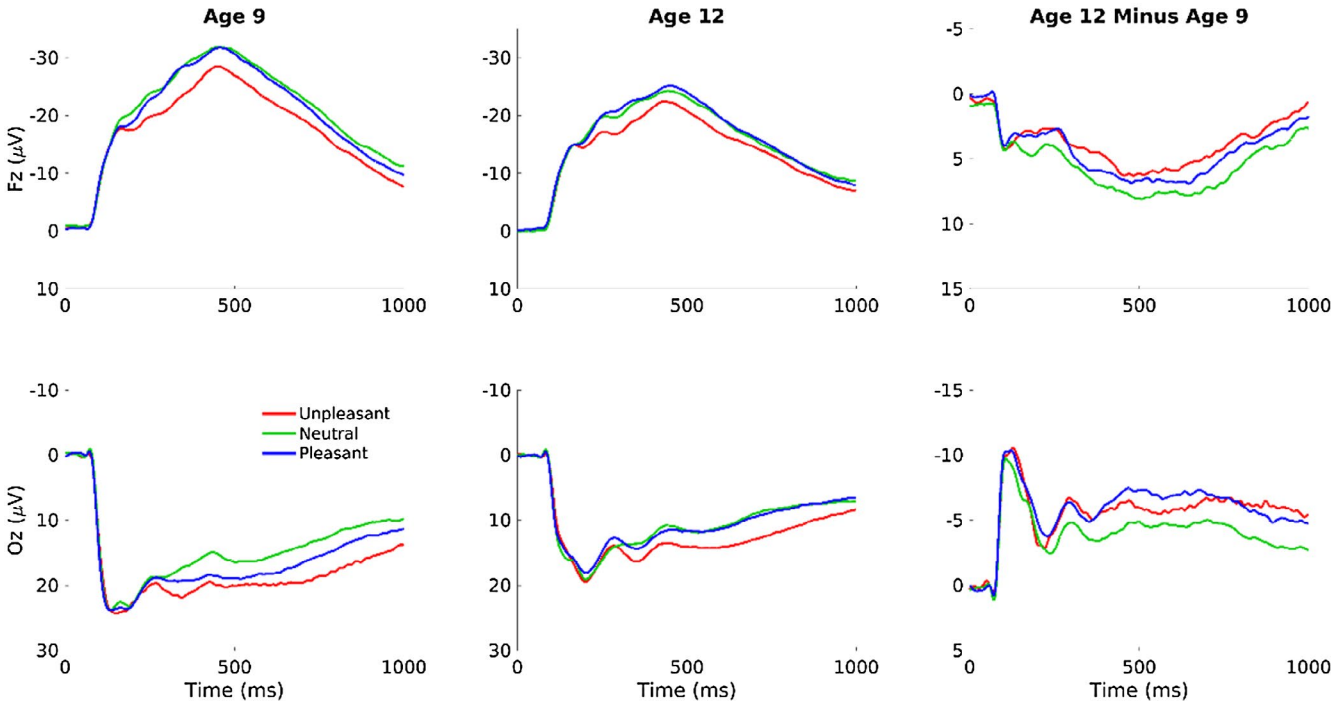

FIGURE 1 Picture-locked ERPs to pleasant, unpleasant, and neutral pictures at Fz (top) and Oz (bottom) sites. Activity is shown for age 9 (left) and age 12 (middle) assessments, as well as the difference in activity between assessments (right). Activity at Fz was more positive at age 12 as compared to age 9, and activity at Oz was more negative at age 12 as compared to age 9

Next, averaged ERP activity at age 9 was subtracted from ERP activity at age 12 for each condition, at each electrode site, to create within-subject ERP difference waveforms, and the resulting difference waveforms were submitted to a temporospatial PCA using ERP PCA Toolkit, version 2.54 (Dien, 2010a). Consistent with previous research utilizing PCA for computing evoked potentials (Dien, 2010b; Foti et al., 2009), promax rotation was used in the temporal domain. Based on the resulting scree plot, 28 temporal factors were extracted. Covariance matrix and Kaiser normalization were used for the PCA (Dien, Beal, & Berg, 2005). Consistent with previous research suggesting that the combination of temporal promax rotation and spatial infomax rotation yielded the lowest Type I and Type II error rates in ANOVAs of experimental effects (Dien, 2010b), the spatial distributions of these temporal factors were then analyzed with a spatial PCA using infomax rotation. Based on the averaged scree plot for all temporal factors, four spatial factors were extracted, yielding 112 factor combinations. Nineteen factors accounted for more than .5% of the variance and were retained for further inspection (Dien, 2012). Finally, our procedure was to identify the factor representing the LPP based on a priori characteristics and to examine only this factor in subsequent analyses. A repeated measures ANOVA and follow-up paired samples *t* tests were utilized to examine the effects of picture type on the PCA-derived LPP difference scores.

Next, to examine whether changes in the LPP across assessments were related to pubertal maturation, correlations were utilized to examine whether PCA-derived LPP difference scores and traditional LPP scores were related to pubertal development, as indexed by composite age-12 PDS scores. Finally, to examine the internal consistency reliability of the developmental difference scores yielded by the PCA approach, we computed within-subject ERP difference waveforms for odd and even trials separately and submitted these waveforms to separate (i.e., odd and even) PCAs. LPP difference scores from these PCAs were exported, and Spearman-Brown-corrected correlations were computed.

3 | RESULTS

3.1 | Traditional ERPs

A repeated measures ANOVA was conducted to compare the effect of image type on the traditional LPP difference score (i.e., age 12 minus age 9). There was a significant effect of image type on this age-related LPP difference score, $F(1, 379) = 11.91$, $p < .001$, $\eta_p^2 = .03$. Three paired samples *t* tests were used to make post hoc comparisons between conditions. The *t* tests indicated that the traditional LPP difference scores were significantly reduced to unpleasant ($M = -5.73$, $SD = 10.03$) pictures as compared to neutral ($M = -2.88$, $SD = 13.04$) pictures, $t(379) = -4.43$, $p < .001$, and were also significantly reduced to pleasant ($M = -5.20$, $SD = 11.58$) pictures as compared to neutral pictures, $t(379) = -3.57$, $p < .001$. LPP difference scores did not differentiate between unpleasant and pleasant pictures, $t(379) = .94$, $p = .35$. Thus, traditional LPP scoring at Oz suggested that emotional modulation of the LPP was reduced at age 12 in comparison to age 9.

3.2 | Temporospatial PCA results

One factor, TF1SF2 (temporal factor 1, spatial factor 2), which accounted for 6.12% of the variance, was temporally analogous to the LPP, peaking around 850 ms, and was enhanced at age 12 as compared to age 9 for both pleasant and unpleasant pictures as compared to neutral pictures. Spatially, this factor was evident as an occipital negativity and a frontocentral positivity, consistent with the notion that the emotional modulation of the LPP shifts from occipital to more frontocentral sites as a function of development from childhood to early adolescence. The spatial and temporal characteristics of the TF1SF2 factor are depicted in Figure 2. Based on these characteristics, the TF1SF2 LPP difference scores were selected for subsequent analyses. The TF1SF2 factor was scored at the site of the numerical maximum, O2, and exported for each condition within each subject.[1]

3.3 | PCA-derived LPP difference scores

A repeated measures ANOVA was conducted to compare the effect of image type on the PCA-derived LPP difference score. There was a significant effect of image type on the PCA-derived LPP difference score, $F(1, 379) = 6.43$, $p = .002$, $\eta_p^2 = .02$. Three paired samples *t* tests were used to make post hoc comparisons between conditions. The *t* tests indicated that the PCA-derived LPP difference was significantly reduced to unpleasant ($M = -7.37$, $SD = 8.20$) pictures as compared to neutral ($M = -5.86$, $SD = 8.44$) pictures, $t(379) = -3.40$, $p = .001$, and was also significantly reduced to pleasant ($M = -7.02$, $SD = 9.08$) pictures as compared to neutral pictures, $t(379) = -2.50$, $p = .01$. The PCA-derived

[1]We also examined whether a similar PCA component would be identified if we submitted data from both assessments to a temporospatial PCA rather than the within-subject difference waveforms. In this PCA, 15 temporal factors and 4 spatial factors were extracted, yielding 60 factor combinations. Twelve factors accounted for more than .5% of the variance and were retained for further inspection. Indeed, we identified a factor resembling the LPP as well as the previous factor examined in the difference waveform PCA. This factor, TF2SF2 (temporal factor 2, spatial factor 2) accounted for 7.9% of the variance and was temporally analogous to the LPP, peaking around 851 ms. Spatially, this factor was evident as an occipital negativity and a frontocentral positivity, virtually identical to the TF1SF2 component in the difference wave PCA.

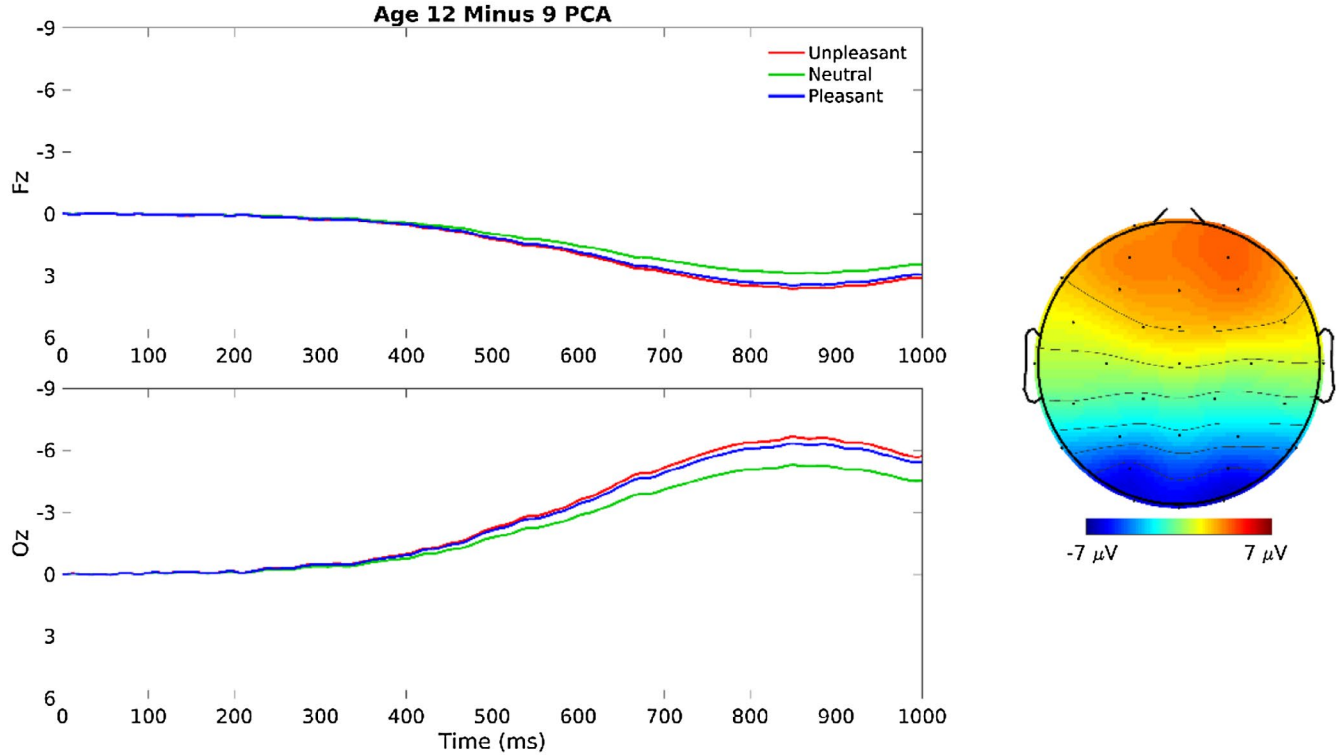

FIGURE 2 Waveforms associated with factor TF1SF2 to pleasant, unpleasant, and neutral pictures at Fz (top) and Oz (bottom) sites. The PCA factor represents the difference in activity between age 9 and age 12 assessments. Activity at Fz was more positive at age 12 as compared to age 9, and activity at Oz was more negative at age 12 as compared to age 9

LPP difference score did not differentiate between unpleasant and pleasant pictures, $t(379) = -.85$, $p = .40$.[2]

3.4 | Associations with pubertal development

Table 1 depicts correlations between composite age-12 PDS score, and PCA-derived LPP difference scores and traditional LPP difference scores at Oz. Greater pubertal development as indexed by the composite PDS score at age 12 was associated with attenuated PCA-derived LPP difference scores to pleasant, $r(358) = -.12$, $p = .03$, and unpleasant, $r(358) = -.15$, $p < .01$, pictures but were unrelated to PCA-derived LPP difference scores to neutral pictures, $r(358) = -.07$, $p = .22$. Thus, attenuated activity in occipital regions and increased activity in frontal regions to pleasant and unpleasant images as indexed by the PCA-derived LPP difference scores was associated with greater mother- and self-reported pubertal development.

A similar pattern of findings occurred between PCA-derived LPP difference scores and traditional LPP difference scores at Oz, such that greater pubertal development was associated with greater reductions in occipital activity to unpleasant pictures between time points in both the PCA and non-PCA difference scores. Also, across both the traditional LPP difference score and the PCA-derived LPP difference score, there was no association between occipital activity to neutral pictures and pubertal development. Whereas the PCA-derived LPP difference scores to pleasant images also showed a negative association with pubertal development, the traditional LPP difference score to pleasant images did not relate to pubertal development.[3]

[2]A repeated measures ANOVA on the factor score derived from the PCA that was conducted on data from both assessments revealed a similar pattern of findings: a significant interaction emerged between age and image type. Similar to the difference waveform PCA, the factor score here was significantly reduced at occipital sites and increased at frontal sites at the age 12 assessment as compared to the age 9 assessment, and the emotional modulation of this factor score (i.e., the difference between emotional stimuli and neutral stimuli) was reduced at occipital sites and increased at frontal sites at age 12 in comparison to age 9.

[3]We also examined correlations between pubertal development and change in the factor scores between assessments for each condition using the factor scores derived from the PCA that was conducted on data from both assessments. First, difference scores were computed by subtracting factor scores at age 9 from factors scores at age 12 for pleasant, unpleasant, and neutral conditions. Next, correlations between these difference scores and PDS scores at age 12 were examined. PDS scores were correlated with these difference scores for unpleasant, $r(378) = -.12$, $p = .02$, and pleasant, $r(378) = -.12$, $p = .03$, trials. However, PDS scores were unrelated to the PCA-derived LPP difference scores for neutral trials, $r(378) = -.06$, $p = .22$. Thus, these results mirrored results from the PCA conducted on the difference waveforms, such that attenuated activity in occipital regions and increased activity in frontal regions to pleasant and unpleasant images, but not neutral images, as indexed by the PCA-derived factor scores, was associated with greater mother- and self-reported pubertal development.

TABLE 1 Correlations between pubertal development and PCA-derived and traditional LPP difference scores

	Pubertal development scale score		
	Pleasant	**Unpleasant**	**Neutral**
TF1SF2	−.12*	−.15*	−.07
LPP at Oz	−.06	−.13*	−.01

Note: TF1SF2 represents the PCA-derived LPP difference score to pleasant, unpleasant, and neutral images. LPP at Oz represents the traditional windowed LPP difference score to pleasant, unpleasant, and neutral images.
*$p < .05$.

3.5 | Internal consistency reliability

To examine reliability of this approach, we submitted odd and even trials separately to a PCA. A factor structure similar to the original factor structure emerged from both of the analyses, such that TF1SF2 from both the odd and even PCAs resembled the original factor of interest (i.e., an occipital negativity and frontal positivity; see Figure 3). TF1SF2 LPP difference scores were exported for odd and even trials separately, and Spearman-Brown-corrected correlations were computed. Reliability coefficients suggested moderate reliability for pleasant, $r(380) = .61$, $p < .001$, unpleasant, $r(380) = .53$, $p < .001$, and neutral, $r(380) = .43$, $p < .001$, conditions.

4 | DISCUSSION

The present study was a proof-of-concept demonstration that PCA can be utilized to both characterize and quantify developmental changes in the spatial and temporal characteristics of ERPs across time as a function of trial type. To demonstrate the utility of this approach, we examined whether the temporospatial PCA method could be used to characterize within-subject developmental changes in the LPP during early adolescence. To this end, we conducted a temporospatial PCA on within-subject ERP difference waveforms (i.e., age 12 minus age 9) to examine the factor structure of developmental changes in the emotional modulation of the LPP—and to provide concise characterizations of the changes in terms of temporospatial PCA-derived difference scores. Note that if ERPs were identical at age 9 and 12 for each participant and condition, there would not have been any resulting difference waveforms; the resulting PCA waveforms reflect the structure of developmental changes in the ERPs from age 9 to 12.

A factor analogous to the LPP was identified based on its spatial and temporal characteristics: temporally, the factor peaked approximately 850 ms after picture onset and was enhanced for emotional pictures as compared to neutral pictures; spatially, this factor was evident as an occipital negativity and a frontocentral positivity. The scalp distribution of this factor (i.e., relative frontal positivity and occipital negativity) is consistent with previous studies that have observed a shift in the LPP from occipital to more frontocentral sites as a function of development from childhood to adolescence (Hajcak & Dennis, 2009; Kujawa, Klein, et al., 2012; Kujawa, Klein, & Proudfit, 2013). Visual inspection of traditional ERP waveforms depicted in Figure 1 and the results of the repeated measures ANOVA examining traditional LPP difference scores at Oz corroborate this pattern. Activity at Fz was more positive at age 12 as compared to age 9, and activity at Oz was more negative at age 12 as compared to age 9. Moreover, the age-related change in the occipital negativity was greater for emotional compared to neutral trials. Thus, the PCA-based factor appeared to simultaneously capture within-subject increases in the frontal positivity and occipital negativity in response to emotional pictures. Because this factor varied by picture type, it is important to note that this factor did not simply reflect overall developmental changes in all ERPs.

Moreover, greater mother- and self-reported pubertal development was related to an enhanced PCA-derived LPP difference score (i.e., reduced occipital activity and increased frontal activity) to emotional, but not neutral, images. This finding suggests that individuals with more advanced pubertal development at the second assessment were characterized by greater frontalization of the LPP response to emotional pictures. Of note, greater pubertal development similarly related to reduced activity in the traditional LPP difference score at Oz (representing the difference between ages 9 and 12) but only to unpleasant images. One possibility is that the temporospatial PCA better captures underlying processes in the ERP waveform related to emotional processing relative to traditional LPP difference scores. Additionally, the PCA-based approach also captures data from frontal sites in the PCA-derived factor score and thus does not rely solely on data from occipital leads. Thus, developmental changes in response to pleasant pictures may have been evident in the PCA-derived score but not traditional LPP scores.

Of note, similar results were found when we included ERP data from both assessments in a PCA (i.e., including age 9 and age 12 data, rather than the difference waveforms). Specifically, the emotional modulation of the LPP was reduced at occipital leads and increased at frontal leads from age 9 to age 12—and that changes in the LPP to emotional images from the age 9 to age 12 assessment were significantly correlated with pubertal development at age 12. Thus, while temporospatial PCA on within-subject subtraction-based ERPs may be a more efficient way of characterizing and quantifying developmental changes in both the timing and scalp distribution of ERPs, entering all data from both assessments into a PCA also yielded a similar factor structure—and

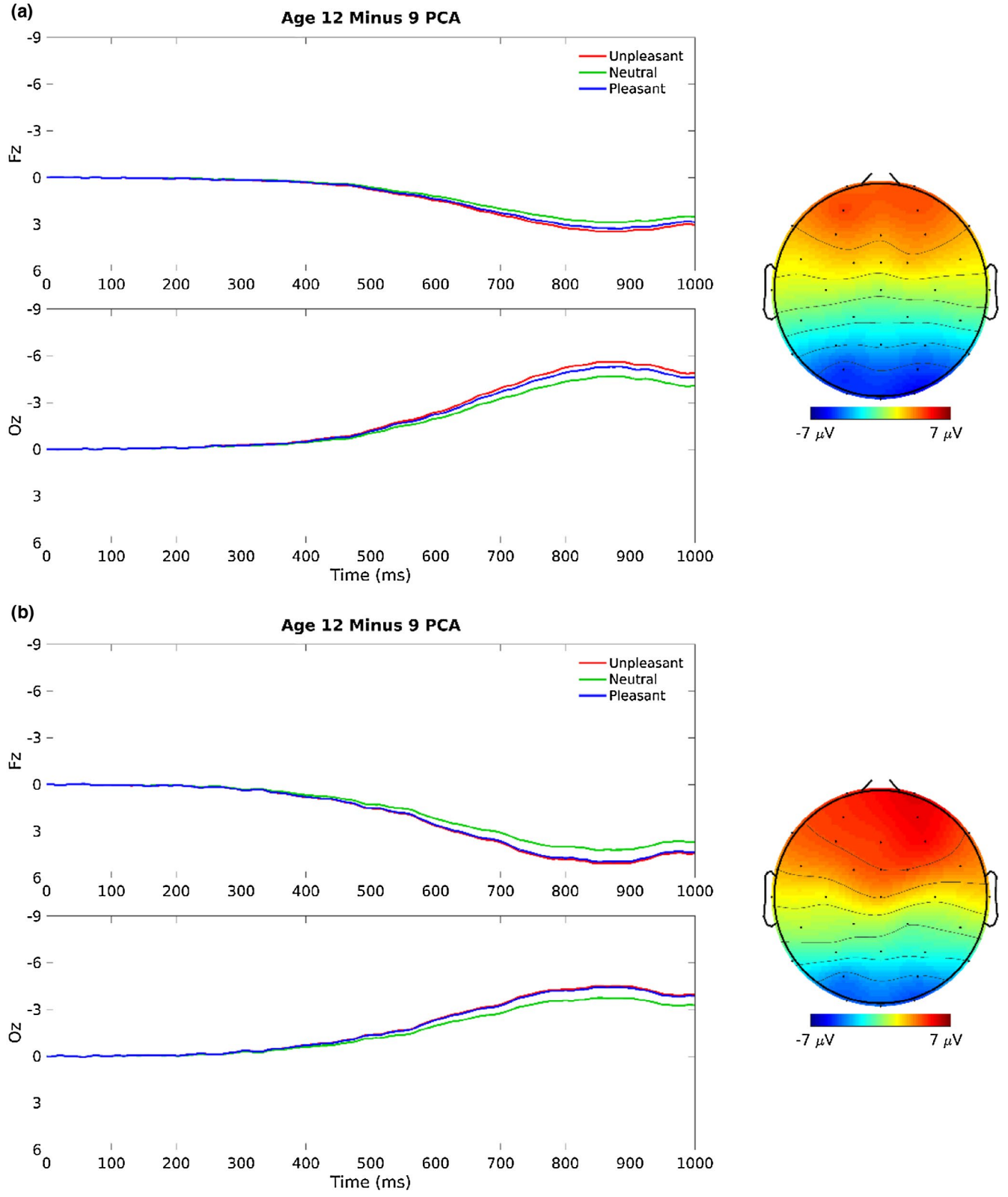

FIGURE 3 Waveforms associated with factor TF1SF2 to pleasant, unpleasant, and neutral pictures at Fz (top) and Oz (bottom) sites for (a) even, and (b) odd trials. The PCA factors represent the difference in activity between age 9 and age 12 assessments on odd and even trials. For odd and even trials, activity at Fz was more positive at age 12 as compared to age 9, and activity at Oz was more negative at age 12 as compared to age 9

appears to be a comparable way to leverage PCA to characterize within-person developmental changes in ERPs.

Importantly, the present study serves as a replication of age-related effects on the spatial and temporal characteristics of the LPP that have been previously reported in a separate sample (Kujawa, Klein, et al.. 2012). Similar to the findings by Kujawa, Klein, et al. (2012), the current analyses suggest that the emotional modulation of the LPP shifts from occipital to more frontal sites over the course of early adolescence. The present findings extend this previous work by demonstrating that these developmental shifts in the LPP to emotional images are correlated with pubertal development, suggesting that these changes in emotional processing occur as a function of typical development during puberty.

We conducted internal consistency analyses of our PCA-based approach by analyzing odd and even trials separately (i.e., PCA on age 12 minus age 9 ERPs derived only from odd trials)—and this approach suggested moderate internal consistency reliability. Given that difference scores often suffer from limited reliability (Peter, Churchill, & Brown, 1993), these reliability scores are reasonable and encouraging. Future studies are necessary to determine the reliability of this approach for use with other ERPs and for use with ERPs in other developmental periods (e.g., adulthood and aging populations).

Given our findings, we propose that temporospatial PCA on within-subject subtraction-based ERPs, or on ERPs from two within-subject assessments, may be a succinct way of more fully characterizing and quantifying within-subject developmental changes in ERPs. Studies aiming to identify within-subject spatial and temporal changes in ERPs across two developmental time points could uniquely benefit from utilizing PCA methods, as it is an empirical way of discerning changes that occur in the ERP difference waveforms over time. This method not only informs one's understanding of broad developmental changes in ERPs but also can provide a succinct measure of individual differences in developmental changes (i.e., individual PCA-derived factor scores). In the current study, the PCA-derived LPP difference score for each participant represents a relatively specific developmental change in ERPs to each picture type; specifically, the PCA-derived difference score reflects the relative increase in frontal activity and decrease in parietal activity in the slow positive wave that is larger for emotional than neutral pictures (i.e., the LPP). These scores could be utilized as individual difference measures to better understand how variation in developmental changes in the LPP interface with, and possibly contribute to, social and personality development (Speed et al., 2015), development of emotion regulation (DeCicco et al., 2014; Dennis & Hajcak, 2009), and risk for psychopathology such as depression (Foti et al., 2010; Kujawa, Hajcak, et al., 2012; Proudfit et al., 2015; Weinberg et al., 2016), social anxiety (Moser et al., 2008), and specific phobias (Leutgeb et al., 2010).

The current PCA-based method provides value above and beyond more traditional ways of analyzing developmental changes in ERPs for several reasons. First, the resulting PCA factors characterize age-related changes in both the temporal and spatial domain—it provides a basis for thinking about the underlying factor structure of developmental changes. Along these lines, this approach could be used to parse developmental effects. That is, it could be used to examine whether two developmental changes tend to hang together or not. For example, if the frontal positivity and occipital negativity in the TF1SF2 component had instead emerged as two different factors, it would have suggested that those developmental changes were two different processes. However, in this case, the frontal positivity and occipital negativity emerged as a single factor, suggesting that changes in the frontal positivity and occipital negativity go together. Other studies could similarly use this approach to parse developmental changes in overlapping ERP components, such as the P300 and reward positivity. Second, the resulting factor score provides a holistic metric representing a linear combination of all time points and electrode sites—so the resulting factor scores are single-value metrics that integrate all of the data (not just the window of interest at a single site or two of interest). These factor scores, for instance, capture both the frontal and occipital contribution of the developmental change in emotional processing in the present sample. Finally, the PCA approach utilized in the present study may have improved utility for elucidating developmental effects on ERPs. In the present study, the PCA-derived LPP factor scores to pleasant stimuli were correlated with pubertal development scores, whereas traditional LPP difference scores to pleasant images were unrelated to pubertal development scores. Thus, the PCA-based factor scores were more sensitive to developmental changes in the LPP to pleasant images.

The PCA approach described here has several limitations that warrant consideration. The choice of which PCA factor to examine in subsequent analyses is, to some degree, at the discretion of the researcher. As such, this approach could be prone to bias. When deciding which PCA factors to examine, researchers should follow typical guidelines (Dien, 2012) and carefully consider the timing, scalp topography, and amount of variance that the temporospatial factors account for. Additionally, if used to understand developmental change, correlations between the individual PCA-derived factor scores and other indices of development, such as age or physical maturation, should be taken into consideration. Moreover, the application of this method to situations in which there are selective age-related changes in one condition may produce distinct temporal factors (i.e., Age × Condition interactions in ERPs would likely be captured in terms of a PCA factor). Future studies might test the current approach with ERPs that have more well defined and earlier latencies to further examine the current PCA approach to developmental changes in ERPs.

In conclusion, the methods reported here provide an empirically based approach to quantifying and illustrating changes in the spatial and temporal characteristics of ERPs across development. Our application of temporospatial PCA to within-subject subtraction-based ERPs from a large sample of youth in transition from childhood to adolescence yielded a factor combination that resembled the LPP and previously described developmental changes in the LPP—it was evident as a slow frontal positivity and occipital negativity that peaked around 850 ms after stimulus presentation and was enhanced for emotional (i.e., pleasant and unpleasant) compared to neutral pictures. This factor combination reflected a shift of the LPP response to emotional images from occipital to more frontal sites from age 9 to 12, consistent with the frontalization of the LPP response that has been reported in previous studies. Participants higher in pubertal development were characterized by enhanced PCA-derived factor scores for emotional, but not neutral, trials—further suggesting that this factor is associated with developmental processes in emotional processing specifically. The findings reported here provide evidence for spatial shifts in the LPP, a psychophysiological index of emotional reactivity, from childhood to adolescence, and support the utility of temporospatial PCA in characterizing within-subject developmental changes in ERPs more broadly.

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