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ORIGINAL ARTICLE

Neurophysiological responses to emotional faces predict dynamic fluctuations in affect in adolescents

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Abstract

The ability to accurately identify and interpret others' emotions is critical for social and emotional functioning during adolescence. Indeed, previous research has identified that laboratory-based indices of facial emotion recognition and engagement with emotional faces predict adolescent mood states. Whether socioemotional information processing relates to real-world affective dynamics using an ecologically sensitive approach, however, has rarely been assessed. In the present study, adolescents ($N = 62$; ages 13–18) completed a Facial Recognition Task, including happy, angry, and sad stimuli, while EEG data were acquired. Participants also provided ecological momentary assessment (EMA) data probing their current level of happiness, anger, and sadness for 1-week, resulting in indices of emotion (mean-level, inertia, instability). Analyses focused on relations between (1) accuracy for and (2) prolonged engagement with (LPP) emotional faces and EMA-reported emotions. Greater prolonged engagement with happy faces was related to less resistance to changes in happiness (i.e., less happiness inertia), whereas greater prolonged engagement with angry faces associated with more resistance to changes in anger (i.e., greater anger inertia). Results suggest that socioemotional processes captured by laboratory measures have real-world implications for adolescent affective states and highlight potentially actionable

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targets for novel treatment approaches (e.g., just-in-time interventions). Future studies should continue to assess relations among socioemotional informational processes and dynamic fluctuations in adolescent affective states.

KEYWORDS
adolescents, EMA, emotion, ERPs, LPP

1 | INTRODUCTION

Social interactions are a fundamental part of humans' lives, and the ability to effectively navigate these interactions is critical for optimal functioning throughout the lifespan. In adolescence, several foundational social–emotional developmental changes occur, including: (a) the self is increasingly defined in relation to others, (b) the capacity to take on the perspective of others advances, and (c) peer relationships play a more central role in adolescents' lives (Crone & Fuligni, 2020). Accordingly, adolescence represents an important period when changes in the social brain occur that support the navigation of increasingly complex and changing social structures and dynamics (Blakemore, 2012).

As social interactions and peer relationships take on an increasingly central role in adolescents' lives, risk for psychopathology and related behaviors also increases, including depression, certain anxiety disorders (e.g., panic disorder, posttraumatic stress disorder), substance use, and suicide (Blakemore, 2019; Kessler et al., 2007; Thapar et al., 2012). Not merely emerging in parallel, social processes directly influence mental health risk and outcomes (Rapee et al., 2019). Processes that are key for successful social interactions include the ability to recognize and respond to others' emotions (Crick & Dodge, 1994), which are critical aspects of socioemotional information processing that are purported to contribute to psychopathology in youth (Luebbe et al., 2010; Quiggle et al., 1992). Difficulties correctly identifying others' emotions and/or prolonged engagement with others' emotional states have been proposed to contribute to psychopathology via vulnerability to and maintenance of mood states (e.g., onset and maintenance of negative mood; MacLeod et al., 2002), and through the disruption of peer support/relationships (Luebbe et al., 2010). Relations between socioemotional information processing impairments and adolescent psychopathology are well-established, including inaccurate facial expression recognition (Auerbach et al., 2015; Jarros et al., 2012; Jenness et al., 2015; Joormann et al., 2010; Seymour et al., 2016) and atypical cognitive engagement with emotional facial expressions in depression and anxiety (Grunewald et al., 2019; Kujawa et al., 2015; McLean et al., 2020).

Although previous research has identified relations between aspects of socioemotional information processing using laboratory tasks and clinical measures (e.g., major depressive disorder, social anxiety disorder), relations between laboratory tasks and *real-world* affect have rarely been tested. Clarifying relations among laboratory measures of socioemotional information processing and real-world affect is an important step in identifying pathways through which aberrant social information processing deficits may contribute to adolescent psychopathology. This work can also help identify whether specific aspects of socioemotional information processing predict emotion processes that occur over time, outside of the lab. It may be the case, for example, that difficulty recognizing and/or reduced engagement with others' happy facial expressions may specifically relate to fewer changes in positive emotion in daily life (e.g., less mood brightening; Heininga & Kuppens, 2021), such as following social interactions with peers. This information could be critical for identifying when and for whom to deploy targeted treatment approaches (e.g., just-in-time interventions).

This gap in the literature has led to calls to link laboratory-based assessments with ambulatory assessments, such as ecological momentary assessment (EMA) methods (MacNamara et al., 2022; Reichert et al., 2021). Although EMA is not a new research tool (for reviews, see Ebner-Priemer & Trull, 2009; Shiffman et al., 2008; Wilhelm & Grossman, 2010), advances in and greater availability of technology have increased the capacity for EMA research, including studies aimed at identifying relations among laboratory-based and EMA measures. There are several advantages of using EMA in affective research, including its: (1) use of real-time responses, which reduces the potential impact of recall bias (Schuler et al., 2021), and (2) ability to measure dynamic emotional processes that emerge over time (e.g., changes that occur over days or weeks). Notably, emotions are increasingly being considered through the lens of dynamical systems theory (Salvi et al., 2021), with the recognition that the ways that emotions change and fluctuate over time are clinically meaningful (Schoevers et al., 2021; Trull et al., 2015). Furthermore, several studies have found that affective dynamics predict clinical outcomes above and beyond mean-level affect

(Funkhouser et al., 2021; Koval et al., 2016; Kuppens et al., 2012; Sperry & Kwapil, 2020).

Affective dynamics that are commonly examined using EMA include: (a) emotional inertia, which refers to affect that is resistant to change, and (b) emotional instability, characterizing sudden large shifts in affect over time (Trull et al., 2015). In adolescents with or at risk for depression, there is evidence of greater emotional inertia for positive and negative emotions (Funkhouser et al., 2021; Kuppens et al., 2010, 2012), as well as instability of emotions in adolescents who engage in non-suicidal self-injury (Santangelo et al., 2017) and who exhibit dysregulated patterns of eating (Egbert et al., 2022). A few studies have examined links between laboratory measures and affective dynamics using EMA (Bylsma et al., 2022; Funkhouser et al., 2021; Sequeira et al., 2021; Tan et al., 2022). For example, heightened neural responses during the Flanker Task were found to predict greater EMA-reported negative emotional reactivity following stressors and greater mean-level anxiety (i.e., worry; Tan et al., 2022), blunted neural responses to rewards were found to predict greater negative affect inertia (Funkhouser et al., 2021), and increased neural response to threat (an index of threat reactivity) predicted greater negative emotional reactivity in daily life (Sequeira et al., 2021). However, only a subset of these studies included adolescents, only one focused on socio-emotional information processing, and none focused on facial expression recognition or engagement. Furthermore, the majority of studies focused on EMA-measured reactivity. In contrast with inertia and instability, reactivity is typically operationalized as total within-person variance and does not capture temporal (successive) changes in emotion (Ebner-Priemer & Trull, 2009; Jahng et al., 2008).

Building on previous research, we assessed relations between laboratory indices of recognition of and engagement with facial emotional expressions, and several real-world measures of emotion including mean levels of emotion, as well as affective dynamics (inertia and instability) in adolescents. To assess recognition and engagement with facial expressions (i.e., happy, angry, and sad), we used the Facial Recognition Task (FRT), an established laboratory measure of adolescents' ability to accurately recognize emotional faces (Auerbach et al., 2015). In addition to behavioral data EEG data were collected during the FRT to measure the late positive potential (LPP), which is an event-related potential (ERP) that is frequently used to assess prolonged engagement with information (particularly emotional/motivationally salient information; Olofsson et al., 2008).

In youth, an enhanced LPP response to unpleasant stimuli relates to familial risk for and prospectively predicts internalizing psychopathology, particularly for fear and anxiety-related symptoms (McLean et al., 2020; Nelson et al., 2015). By contrast, blunted LPP response to pleasant stimuli and faces relates to depressive and distress-related symptoms (Grunewald et al., 2019; Nelson et al., 2015; Seidman et al., 2020). In addition to symptom dimension associations, the LPP exhibits development-related changes from childhood to adulthood. For example, adolescents exhibit a smaller LPP response to emotional faces than younger children (MacNamara et al., 2016) and a larger LPP response to subtle changes in ambiguous peer facial expressions (Sandre et al., 2022). These changes are purported to have greater salience for peer social cues in adolescence, along with development in emotion regulation ability (Bylsma et al., 2022). Overall, the LPP is a sensitive measure of engagement with emotion that relates to mental health symptoms and risk in adolescents and can index developmentally relevant changes in information processing.

To assess emotion in daily life, participants provided 1-week of intensive EMA of emotion ratings on their personal smartphone four times per day. Notably, the emotions probed via EMA, which included happiness, anger, and sadness, paralleled the facial expressions presented in the FRT when EEG data were recorded. It was hypothesized that recognition of and engagement with emotional faces would predict mean levels of emotion and affective dynamics in daily life and, furthermore, that these effects would exhibit emotion specificity (e.g., greater accuracy for and engagement with happy faces would relate to higher mean levels of happiness during the EMA). Whereas better recognition and more engagement were expected to predict greater mean-level emotion, the direction of the inertia and instability effects were not specified.

2 | METHOD

2.1 | Participants

Adolescents ($N=74$) aged 13-18 years old were enrolled across two recruitment sites (New York, NY and Chicago, IL) from August 2020 to January 2022 as part of an ongoing NIMH-funded study. Equivalent study procedures and equipment were used at both sites. Informed assent was obtained from adolescents younger than 18 years old, as well as informed consent from their parents. Informed consent was obtained from adolescents who were 18 years old. All study procedures were approved by the Institutional Review Boards for each site and all procedures were followed in accordance with the ethical standards of the responsible committee on human experimentation and with the Helsinki Declaration of 1975, as revised in 2000.

Inclusion criteria included: (1) owning a personal smartphone (Android or iOS), (2) fluency in English, (3) Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II) score > 85 (Wechsler, 2011), (4) self-reported right-handedness, (5) Tanner Stage ≥ 3 (to reduce neuroendocrine variability). Exclusion criteria were: (1) lifetime history of seizure or neurological disorder (e.g., head injury, loss of consciousness > 5 min), (2) lifetime history of bipolar or psychotic disorders, oppositional defiant disorder, conduct disorder, organic mental disorder, developmental disorder (e.g., autism), and (3) use of psychotropics, other than antidepressants or ADHD-related medications. Exclusionary criteria were selected to reduce puberty-related heterogeneity in cognitive and neural processing and to rule out potential effects of medication, brain injury, global intellectual impairments, and learning disabilities on outcomes. Adolescents who did not participate in the EMA protocol or complete the FRT task were excluded from all analyses ($n=6$), and participants ($n=6$) with an insufficient number of ERP trials per emotion (less than 8 trials across all intensities on correct trials) were excluded. The final sample included 62 participants, and the participant demographics are summarized in Table 1.

2.2 | Assessments and measures

2.2.1 | Facial recognition task

Participants completed a modified version of the Facial Recognition Task (FRT; Auerbach et al., 2015), which probes emotion processing biases during the presentation of emotional faces. Three emotional expressions (happy, angry, sad) were presented in three different intensity gradients: 30% (low intensity), 60% (moderate intensity), and 90% (high intensity). Standardized face images came from the National Institute of Mental Health Child Emotional Faces Picture Set (NIMH-ChEFS; Egger et al., 2011) and

TABLE 1 Participant characteristics.

	Across sites $N=62$	**New York site $n=38$**	**Chicago site $n=24$**	***t*/chi-square test**	***p*-value**
Age	16.5 (1.5)	16.5 (1.6)	16.4 (1.4)	$t(60)=0.15$	$p=.886$
Biological sex (% female)	73%	74%	71%	$\chi^2(1)=0.06$	$p=.806$
Gender					
Female	68%	68%	67%	$\chi^2(3)=0.79$	$p=.852$
Male	27%	26%	29%		
Gender non-conforming	3%	3%	5%		
Other	2%	3%	0%		
Race					
White	48%	40%	63%	$\chi^2(5)=6.93$	$p=.226$
Black/African American	10%	10%	8%		
Asian	16%	13%	21%		
More than one race	11%	16%	4%		
Native American	2%	3%	0%		
Prefer not to answer	13%	18%	4%		
Hispanic ethnicity	27%	34%	18%	$\chi^2(1)=2.28$	$p=.131$
Accuracy					
Happy	82% (11%)	80% (12%)	85% (7%)	$t(60)=-1.52$	$p=.133$
Angry	64% (14%)	65% (13%)	64% (14%)	$t(60)=0.17$	$p=.863$
Sad	62% (13%)	61% (13%)	64% (12%)	$t(60)=-1.03$	$p=.306$
Late positive potential (amplitude on correct trials)					
Happy	8.7 (4.6)	8.7 (5.0)	8.8 (4.0)	$t(60)=-0.09$	$p=.929$
Angry	10.5 (4.8)	10.3 (4.6)	10.9 (5.2)	$t(60)=-0.46$	$p=.647$
Sad	9.8 (4.5)	9.6 (4.5)	10.1 (4.5)	$t(60)=-0.43$	$p=.670$
(# of correct trial segments)					
Happy	46.4 8.6)	46.0 (8.2)	47.0 (9.5)	$t(60)=0.65$	$p=.520$
Angry	36.7 (9.7)	37.2 (9.2)	36.0 (10.7)	$t(60)=0.62$	$p=.540$
Sad	34.8 (9.1)	34.3 (9.1)	35.6 (9.3)	$t(60)=0.58$	$p=.565$

Note: Accuracy = across all trials.

were presented with an equivalent number of trials for each intensity (20 trials) for each emotion (60 total trials per emotion).[1] During the task, participants were asked to identify, as quickly as possible, the emotion of the face by pressing the key labeled with the corresponding emotion (i.e., happy, angry, sad, neutral). Each trial started with a jittered fixation cross that was presented for 300–500 ms. Following this, a facial stimulus was presented (in pseudorandom order) and displayed for 500 ms. The facial stimulus was followed by an intertrial interval (ITI) fixation cross that was presented for 2500 ms. Participants could respond to the facial stimulus offset until the offset of the ITI. Accuracy was the primary behavioral outcome measure used for this task.

2.2.2 | Electrophysiological recordings and data reduction

Continuous EEG data were recorded during the FRT using the 32-channel ActiCHamp from Brain Products (Brain Products, Munich, Germany), digitized at a 500 Hz sampling rate, and referenced online to FCz. Vertical and horizontal EOG data were recorded, and electrode impedances were maintained below 20 Kohms. EEG data were processed offline using the EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes in MATLAB (2019). Independent component analysis (ICA) was used to identify and correct for ocular artifacts prior to artifact rejection. Data were re-referenced offline using an average mastoid reference. A notch filter (60 Hz) and a second-order digital Butterworth filter with a bandpass from 0.1 to 30 Hz were applied. Channels were baseline-adjusted by subtracting the average amplitude for 200 ms prior to the stimulus onset.

Stimulus-locked ERPs were averaged separately for each facial emotion. ERPs during correct responses were averaged across the different intensities. Based on the maximal LPP across participants, topographical maps, and previous research (e.g., Kujawa et al., 2012; Sandre et al., 2022), amplitudes were averaged between 400 to 1200 ms post-stimulus onset at the Pz electrode, on correct trials, separately for happy, angry, and sad faces (see Figure 1 for grand-average waveforms and topographical maps). Notably, results for an early (400–800 ms) and late LPP (800–1200 ms) were consistent with our overall results using a 400–1200 ms window (see Supplement). In line with prior research regarding LPP reliability (Moran et al., 2013), participants with fewer than eight usable ERP segments for each face emotion on correct trials (pooling across intensity) following preprocessing procedures were excluded from all analyses ($n = 6$). This resulted in an average of 46.4 ($SD = 8.6$), 36.7 ($SD = 9.7$), and 34.8 ($SD = 9.1$) usable segments for happy, angry, and sad faces, respectively, which did not significantly differ by site (see Table 1).

2.2.3 | Ecological momentary assessment (EMA)

Following the baseline assessment, the Effortless Assessment Research System (EARS) was installed on participant smartphones to obtain EMA data. EARS is a HIPAA-compliant software application that can be used to collect active and passive response data and has been shown to have high user acceptability (Lind et al., 2018). Over the course of seven consecutive days, participants received a prompt on their phone four times per day (morning [6:30–10:30 a.m.], afternoon [3:00–5:00 p.m.], evening [5:00–7:00 p.m.], night [7:00–9:00 p.m.])[2] and were asked to rate their current level of emotion (happiness, anger, and sadness) on a scale of 0 (*not at all*) to 100 (*extremely*).

Participants completed up to 28 total possible prompts, and on average, participants completed 15.37 of 28 prompts [response rate: 54.9%; the number of prompts completed did not vary by site, $t(60) = -0.51$, $p = .615$; average ratings for happiness: 54.0 (19.2), anger: 12.6 (14.1), and sadness: 19.9 (18.4)]. Participants had an average of 7.76 ($SD = 5.38$) pairs of successive surveys for the inertia analyses and 8.34 ($SD = 5.19$) pairs of surveys for the instability analyses. Sites did not differ in the number of pairs of consecutive surveys completed per person for the inertia or instability analyses ($t(60) = -0.38$, $p = .708$ and $t(60) = -0.04$, $p = .966$, respectively). At the daily level, participants had an average of 1.11 pairs of successive surveys ($SD = 0.77$) per day for the inertia analyses, and 1.19 pairs ($SD = 0.74$) per day for the instability analyses (note: all of the numbers excluded overnight lags; see

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[1] Neutral trials ($n = 40$) were also included in the FRT task; however, given the primary aim of examining specific relations between EMA-reported happiness, anger, and sadness and responses to happy, angry, and sad faces, neutral was not included in the primary analyses. Neutral was included, however, in sensitivity analyses.

[2] The morning prompt was sent at 6:30 a.m. and the survey was available until 10:30 a.m. The afternoon, evening, and night prompts had a randomized delivery, and the surveys were available until the end of the time window. The time windows were based on the participants' time zone. Windows were not spaced evenly throughout the day so adolescents would not be prompted during school hours when their phones might be unavailable, following common EMA research practices with youth (Heron et al., 2017).

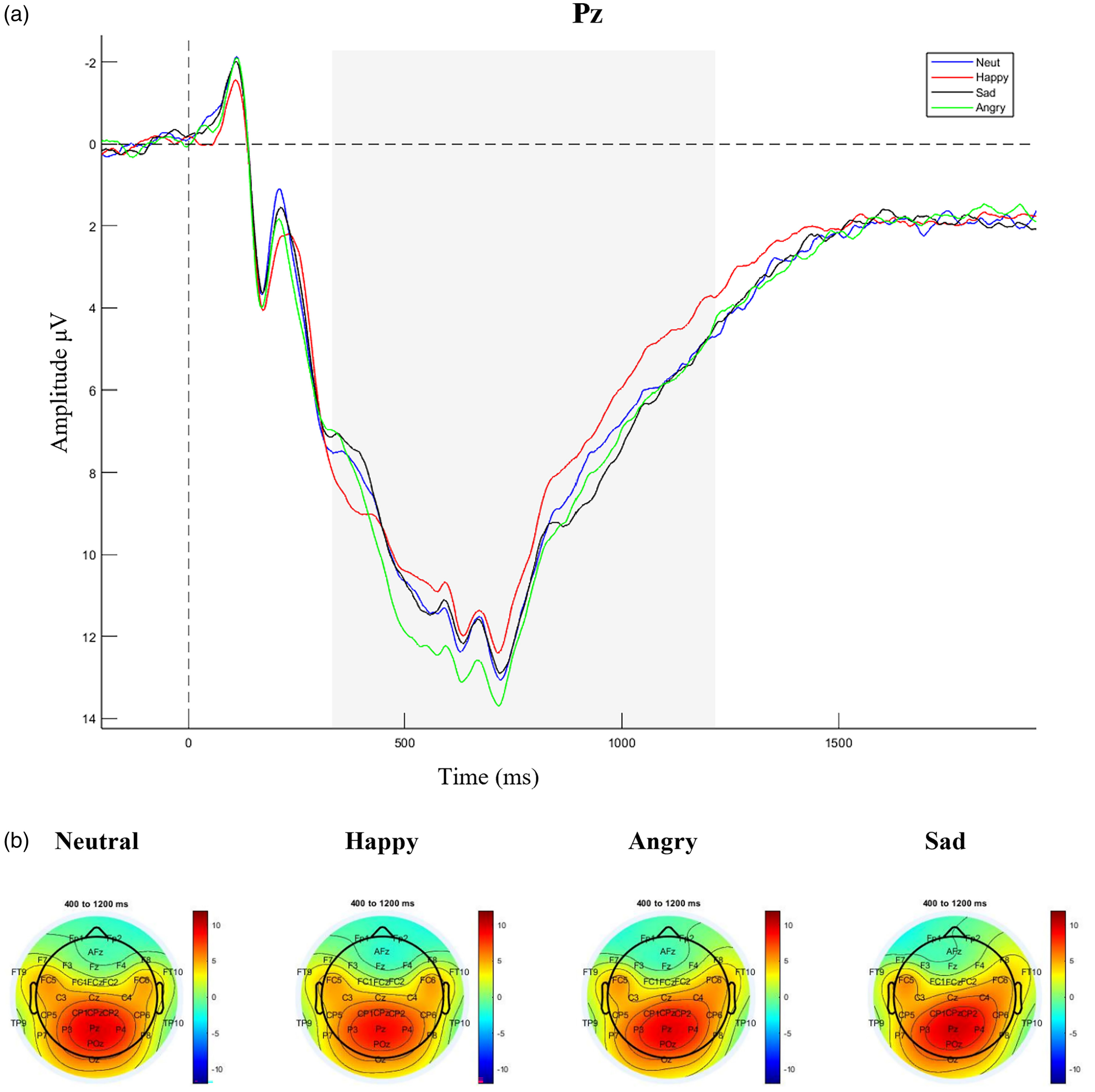

FIGURE 1 (a) Grand-average waveforms for correct trials at the Pz electrode. Time course is depicted on the *x* axis and the gray rectangle indicates the scoring interval for the late positive potential (LPP) (400–1200 msec; note: negative amplitude is plotted upward). (b) Topographies illustrating areas of maximal voltage for the LPP for facial stimuli on correct trials. Neutral is shown for reference.

Supplement for additional details regarding survey completion rates by site).

2.3 | Data analysis

Linear mixed effects models were used to test FRT (accuracy, LPP) main effects, as well as effects for different emotion faces (happy, angry, sad). We also explored whether there were effects for Intensity of facial expressions (30%, 60%, 90%), or Emotion x Intensity interactions, and these results are provided in the Supplement. All models included a random (participant-specific) intercept, which allowed mean levels of accuracy or LPP to vary across individuals.

We then tested whether FRT accuracy and/or LPP were associated with the following indices of emotion derived from EMA ratings: (1) mean level (i.e., each participant's mean), (2) inertia (i.e., random autoregressive slope), and (3) instability (i.e., mean square of successive differences

[MSSD]). Each FRT predictor (accuracy, LPP) and EMA-related emotion outcome (mean-level, inertia, and instability) was examined separately for each EMA emotion of interest (happiness, anger, and sadness). Multiple regression was used to identify unique effects of responses to emotional faces and EMA outcomes (i.e., IVs for the three emotional faces were included in each model).

The following analyses were used to test FRT-emotion relationships. First, to test effects for mean levels of emotion, the average rating for each emotion (happiness, anger, sadness) across the 7-day EMA period was included as the EMA outcome variable of interest. Second, for inertia, multilevel autoregressive models were used (for additional details, see Funkhouser et al., 2021) in which each emotion at time t (within-person centered) predicted emotion at time $t+1$, modeled as a random slope. This random autoregressive slope reflected individual differences in inertia, and associations between FRT predictors and inertia were modeled as cross-level interactions. Inertia analyses covaried for the linear effect of time and were estimated using maximum likelihood. Last, for emotional instability, we calculated the MSSD separately for each EMA emotion (happiness, anger, sadness; Von Neumann, 1941). This approach captures variability and temporal dependency, the combination of which characterizes affective instability (for a review, see Trull et al., 2015). Instability analyses included mean (person)-level affect as a covariate to identify effects of instability beyond average levels of emotion, which is important because mean-level affect and instability are often highly correlated (Dejonckheere et al., 2019). Overnight lags were excluded in all inertia and instability analyses. Analyses were performed in R using the lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017), and psych (Revelle, 2022) packages.

Of primary interest was the *homotypic* associations between the lab-based measures and EMA outcomes for specific emotions (e.g., LPP to sad faces predicting EMA ratings of sadness), rather than *heterotypic* associations (e.g., LPP to sad faces predicting EMA ratings of happiness). However, heterotypic associations were also explored and did not require additional models, since the lab indices for each emotion were included as simultaneous predictors of EMA outcomes using multiple regression models (i.e., FRT responses to happy, angry, and sad faces were entered together). As mean levels of emotion and two affective dynamics (inertia and instability) were separately assessed for three emotion outcomes (happiness, anger, and sadness), Bonferroni correction was applied for the nine analyses that were implemented for each lab-based measure ($\alpha = .05/9$), resulting in a revised significance threshold of $p = .006$.

Additionally, follow-up sensitivity analyses were conducted to examine: (1) whether the results changed after including responses to neutral faces as an additional predictor in the multiple regression models and (2) following an approach that was used in Funkhouser et al., 2021, we re-estimated the instability model adjusting for time intervals between successive prompts. First, time lags that were greater than 1.5 *SD* above the sample mean were excluded, which resulted in an average within-day lag of 228.36 min between successive EMA surveys (*SD* = 165.18; range = 36.63–567.63). Second, the adjusted squares of successive differences were calculated separately for happy, angry, and sad EMA responses following Jahng et al. (2008).

3 | RESULTS

3.1 | Sample demographics

The average age for participants was 16.45 years old (*SD* = 1.50), and the majority were female (73%, $\chi^2(1) = 12.65$, $p < .001$). Most participants identified as White (48%) and as non-Hispanic (73%). Sites did not differ on age, biological sex, self-identified gender, race, or Hispanic ethnicity (see Table 1). Zero-order correlations among FRT accuracy and LPP are provided in Table 2.

TABLE 2 Zero-order correlations between facial recognition task measures (accuracy and LPP amplitude).

	Happy accuracy	Angry accuracy	Sad accuracy	Happy LPP	Angry LPP	Sad LPP
Happy accuracy	–	33*	0.18	−0.14	−0.07	−0.19
Angry accuracy	–	–	0.54**	−0.12	−0.09	−0.22
Sad accuracy	–	–	–	−0.06	−0.13	−0.10
Happy LPP	–	–	–	–	0.75**	0.68**
Angry LPP	–	–	–	–	–	0.77**
Sad LPP	–	–	–	–	–	–

Abbreviation: LPP, late positive potential.

*$p < .01$, **$p < .001$.

3.2 | FRT accuracy

As shown in Figure 2, there was a significant main effect of Emotion, $F(2,122)=74.83$, $p<.001$, partial $\eta^2=.551$. This was characterized by greater accuracy for happy versus sad ($p<.001$, partial $\eta^2=.612$), and happy versus angry faces ($p<.001$, partial $\eta^2=.641$). Accuracy for angry and sad faces did not significantly differ ($p=.227$, partial $\eta^2=.024$; see Supplement for accuracy as a function of intensity). A similar pattern of results emerged across study sites (see Figure S2a).

3.3 | FRT accuracy predicting EMA mean, inertia, and instability

None of the effects were significant for inertia ($ps>.077$), instability ($ps>.040$), or mean-level affect ($ps>.030$). Additionally, after covarying for time intervals, accuracy ($ps>.009$) remained non-significant predictors of happiness, anger, and sadness instability (Bonferroni corrected). For full results, see Table 3.

3.4 | FRT task effects for the late positive potential

There was a significant main effect of Emotion, $F(2,122)=8.81$, $p<.001$, partial $\eta^2=.126$. As shown in Figure 3, the main effect of Emotion was characterized by higher LPP responses for angry than happy faces ($p<.001$, partial $\eta^2=.188$), but not for angry relative to sad faces ($p=.089$, partial $\eta^2=.047$). Additionally, LPP was higher for sad than happy faces ($p=.009$, partial $\eta^2=.106$). A similar pattern of results emerged across study sites (see Figure S2b,a).

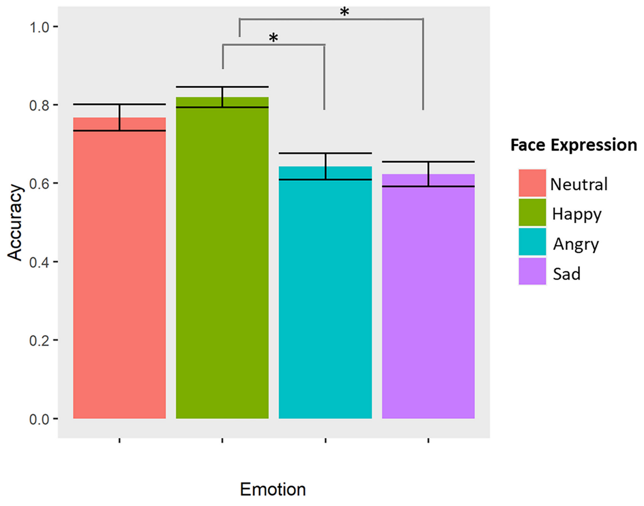

FIGURE 2 Facial recognition task accuracy results (*$p<.05$; error bars represent 95% CIs). Neutral is shown for reference.

3.5 | FRT late positive potential predicting EMA mean, inertia, and instability

3.5.1 | Mean-level

No significant homotypic or heterotypic results emerged for happiness, anger, or sadness ($ps>.030$). For full results, see Table 3.

3.5.2 | Inertia

Regarding homotypic associations, as shown in Figure 4a, greater LPP amplitudes following happy faces predicted weaker happiness inertia, $t(128.76)=-3.92$, $\beta=-.23$, $p<.001$, covarying for LPP following angry and sad faces. As shown in Figure 4b, greater LPP amplitudes following angry faces were significantly associated with greater anger inertia, $t(56.43)=4.87$, $\beta=.26$, $p=.002$. However, the LPP following sad faces was not associated with inertia of sadness ($ps>.069$). There also were no heterotypic associations for inertia. For full results, see Table 3. A similar pattern of results emerged across study sites (see Figure S3a,b). Additionally, sensitivity analyses were conducted to account for neutral faces. Homotypic effects for inertia remained significant and were in the same direction: happiness, $t(133.87)=-3.60$, $\beta=-.23$, $p<.001$, and anger, $t(56.14)=4.65$, $\beta=.25$, $p=.003$.

3.5.3 | Instability

No homotypic or heterotypic associations for instability of affect reached significance, after adjusting for multiple comparisons ($ps>.035$). Effects for the LPP remained null after covarying for time intervals ($ps>.032$), adjusting for multiple comparisons. For full results, see Table 3 and the Supplement.

4 | DISCUSSION

In the present study, adolescents' socioemotional processes were assessed using a laboratory task while EEG data were recorded and then, related to mean levels of emotion and affective dynamics probed over a subsequent 1-week period. Interesting homotypic results emerged for the neurophysiological measure indexing prolonged

TABLE 3 Facial recognition task accuracy and the late positive potential in relation to affect.

(a) Accuracy									
	Independent variables								
	Happy accuracy			**Angry accuracy**			**Sad accuracy**		
	***t*-value**	**Standardized beta (*β*)**	***p*-value**	***t*-value**	**Standardized beta (*β*)**	***p*-value**	***t*-value**	**Standardized beta (*β*)**	***p*-value**
I. Mean-level									
1. Happiness	*t*(920) = 0.87	.08	.386	*t*(920) = −1.41	−.14	.160	*t*(920) = 1.77	.18	.077
2. Anger	*t*(759) = −0.12	−.01	.902	*t*(759) = −0.29	−.03	.770	*t*(759) = −1.24	−.12	.214
3. Sadness	*t*(797) = −0.23	−.02	.817	*t*(797) = 0.74	.08	.461	*t*(797) = −1.37	−.15	.170
II. Inertia									
1. Happiness	*t*(29.01) = −1.01	−.04	.319	*t*(52.80) = 0.96	.05	.343	*t*(27.71) = 2.06	.09	.049
2. Anger	*t*(17.73) = 1.83	−.12	.084	*t*(37.50) = 0.78	.06	.442	*t*(22.17) = 2.19	.12	.040
3. Sadness	*t*(162.47) = −1.59	−.06	.113	*t*(210.48) = −0.02	.00	.984	*t*(180.85) = 1.93	.07	.056
III. Instability									
1. Happiness	*t*(57) = −0.74	−.10	.463	*t*(57) = 0.68	.10	.497	*t*(57) = −1.62	−.23	.110
2. Anger	*t*(54) = −1.15	−.15	.254	*t*(54) = 0.09	.01	.931	*t*(54) = −2.23	−.31	.030
3. Sadness	*t*(56) = −0.93	−.10	.358	*t*(56) = 0.46	.05	.649	*t*(56) = −2.05	−.24	.046

(b) Late positive potential									
	Independent variables								
	Happy LPP			**Angry LPP**			**Sad LPP**		
	***t*-value**	**Standardized beta (*β*)**	***p*-value**	***t*-value**	**Standardized beta (*β*)**	***p*-value**	***t*-value**	**Standardized beta (*β*)**	***p*-value**
I. Mean-Level									
1. Happiness	*t*(797) = 1.03	.14	.305	*t*(797) = −2.18	−.30	.030	*t*(797) = 0.06	.01	.951
2. Anger	*t*(645) = −0.16	−.02	.874	*t*(645) = 1.67	.22	.095	*t*(645) = −0.31	−.05	.757
3. Sadness	*t*(681) = 1.65	−.26	.100	*t*(681) = 1.00	.15	.320	*t*(681) = 0.87	.15	.387
II. Inertia									
1. Happiness	***t*(128.76) = −3.92**	**−.23**	**<.001***	*t*(118.05) = 0.80	.04	.423	*t*(156.57) = 1.63	.11	.105
2. Anger	*t*(17.29) = −1.22	−.10	.240	***t*(56.43) = 4.87**	**.26**	**.002***	*t*(5.73) = 0.00	.00	1.00
3. Sadness	*t*(229.81) = −1.27	−.08	.206	*t*(212.98) = 1.82	.09	.069	*t*(167.29) = 0.97	.05	.333
III. Instability									
1. Happiness	*t*(50) = 2.17	.44	.035	*t*(50) = −1.43	−.30	.158	*t*(50) = 0.73	.16	.467
2. Anger	*t*(47) = −0.45	−.10	.653	*t*(47) = 0.23	.05	.816	*t*(47) = 0.09	.02	.931
3. Sadness	*t*(47) = −1.21	−.23	.232	*t*(49) = −1.21	−.23	.232	*t*(49) = 1.51	.27	.138

*Significance level = .006 ($\alpha = .05/9$).

encoding of emotional information (i.e., LPP). Specifically, increased engagement with happy faces predicted less resistance to changes in happiness (lower inertia), whereas increased engagement with angry faces predicted more resistance to changes in anger (greater inertia). Importantly, these findings controlled for LPPs to the other emotion conditions, highlighting the potential specificity of these effects. Taken together, findings indicate that adolescents' neural response to emotional facial expressions may have meaningful implications for how their emotions unfold in their daily life.

Previous studies found that greater emotional inertia (of both positive and negative emotions) relates to poorer outcomes (Kuppens et al., 2010, 2012). In our study, more engagement with happy faces predicted less happiness inertia, which is in line with prior LPP findings indicating that sustained engagement with happy faces is adaptive for mood. For example, the LPP is enhanced for positive stimuli in adolescents with higher levels of extraversion (Speed et al., 2015)—a personality dimension that is negatively related to depression and lifetime mental health diagnoses (Jylhä & Isometsä, 2006; Watson et al., 2015). Relatedly, savoring pleasant information is linked with larger LPP responses to positive stimuli and with changes (increases) in positive affect (Wilson & MacNamara, 2021). In adolescents with depression, the LPP is reduced for positive stimuli and happy faces (Benning & Ait Oumeziane, 2017; Grunewald et al., 2019; Klawohn et al., 2021). Increased engagement with others' happy expressions may reflect greater motivation for social engagement (Bublatzky et al., 2014), which could facilitate approaching others, leading to changes in one's own happiness (e.g., being able to identify opportunities to approach and engage with others who are expressing happiness could enhance one's own happiness). Of clinical relevance, lower levels of positive emotion and anhedonia are associated with depression risk and substance use in adolescence (Bennik et al., 2014; Leventhal et al., 2017).

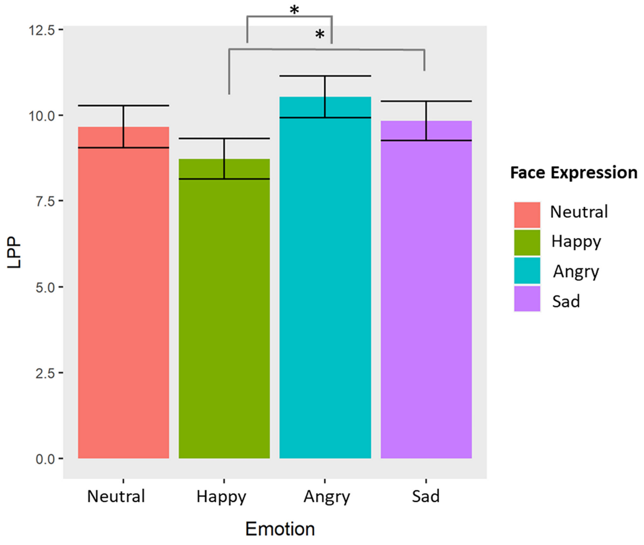

FIGURE 3 Facial recognition task late positive potential results (*$p < .05$; error bars represent 95% CIs). Neutral is shown for reference.

Whereas sustained engagement with happy faces predicted less happiness inertia (i.e., changes in happiness), prolonged engagement with angry faces was associated with a greater propensity for anger persistence. This suggests that there are opposing effects of prolonged engagement with different emotional faces on affective dynamics outside of the lab, which may be driven by specific effects of valence and/or arousal on mood (e.g., Wilson & MacNamara, 2021). It is also plausible that the opposing LPP effects reflect valence or arousal-related effects on emotion regulation and/or cognitive control (Bylsma et al., 2022; Cudo et al., 2018; Kuhbandner &

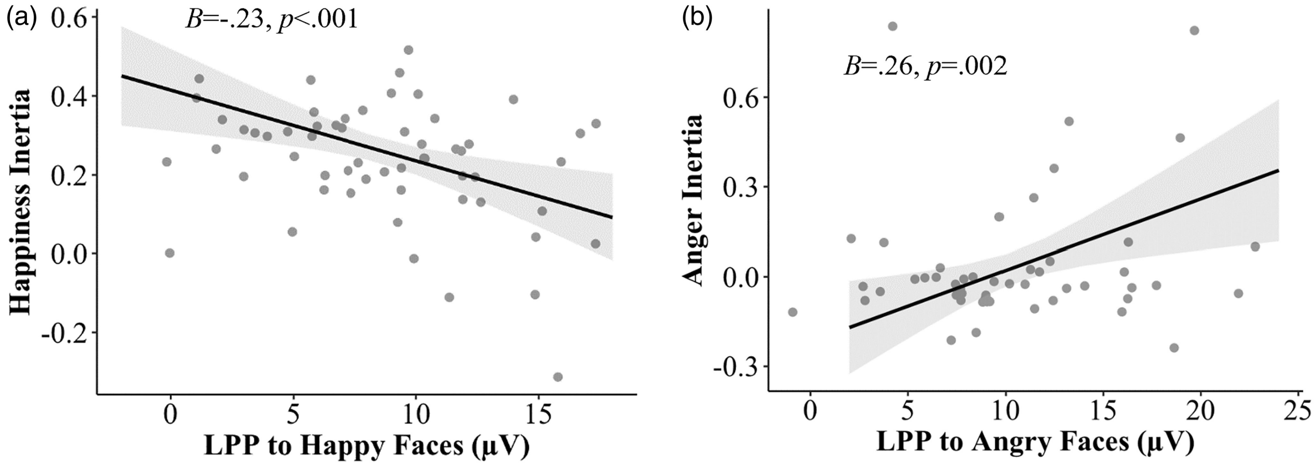

FIGURE 4 Late positive potential predicting ecological momentary assessment outcomes. (a) Happiness inertia. (b) Anger inertia.

Zehetleitner, 2011). For example, greater engagement with unpleasant/angry information may require greater emotion regulation/top-down control to change or regulate one's current emotions than attention to pleasant/happy information. With regard to anger specifically, previous studies have identified that enhanced attention toward negative or aversive faces, and angry faces more specifically, is evident in individuals with higher levels of trait anger (Van Honk et al., 2001) and youth with persistent irritability (Kessel et al., 2017). Engagement with others' angry expressions may reflect a more general tendency to elaborate or ruminate on anger-related information that results in the maintenance of anger over time. Importantly, anger and irritability are transdiagnostic symptoms for several internalizing and externalizing psychopathologies and related behavior in youth, including depression, generalized anxiety disorder, risk-taking, substance use, and suicide (Klein et al., 2021).

Overall, our results add to a growing body of research that highlights the importance of examining dynamic affective processes in relation to adolescent functioning. Whereas significant results emerged for emotional inertia and were in the expected direction for instability (but did not remain significant after our strict correction for multiple comparisons), there were no significant effects for simple mean-level affect. Several previous studies also found that affective dynamics relate to adolescent mental health outcomes (e.g., depression, depression risk), and in many cases these, effects were more consistent than and/or held above and beyond mean levels of emotion (Funkhouser et al., 2021; Koval et al., 2016; Kuppens et al., 2012). Also, in line with conceptual considerations and results of previous studies, accuracy and LPP amplitude were not significantly correlated (Kujawa et al., 2013; MacNamara et al., 2016) and were differentially related to EMA outcomes (i.e., no effects of accuracy reached significance, although this may have been due to the relatively high accuracy levels across all emotions). This provides further evidence that emotion recognition and prolonged engagement may reflect non-overlapping aspects of socioemotional information processing.

There are several limitations of the present study that should be noted. First, directionality cannot be concluded from our study. Although it may be the case that greater engagement with angry faces, for example, leads to greater anger inertia, alternatively, experiencing greater anger inertia may impact one's engagement with angry faces. Second, although we speculate that the emotion effects are related to socioemotional information processes, it may be that results reflect general emotional information processing (e.g., engagement with angry stimuli more broadly). Relatedly, it is unclear to what extent the affective dynamics captured via EMA in our study were the result of changes in emotions linked to social contexts or interpersonal processes. Whether the relations identified are specific to social processes should be considered in future studies. Third, at the daily level, fewer than half of the surveys were completed successively (on average), which may have affected our ability to detect inertia and instability-related effects. Fourth, although not a limitation per se, our sample was not large enough (i.e., sufficiently powered) to assess whether relations among socioemotional information processes and affective dynamics may change over time across adolescent development (for a discussion of age-related changes in emotional inertia and instability, see Bailen et al., 2019). Fifth, most participants completed the study during the height of the COVID-19 pandemic (i.e., a period of heightened stress and physical social isolation), which may reduce the ability of the results to generalize to less turbulent times. Last, similar to other studies with youth (Heron et al., 2017), we did not prompt EMA assessments during school hours. Although this minimizes potential disruption to teachers and students, it may prevent the assessment of emotions that occur during school.

Adolescent emotion research has typically used retrospective assessments that probe for mean levels of emotion. These approaches do not capture potentially important dynamic emotion processes, such as emotional inertia. Additionally, these approaches are not positioned to clarify how impairments identified in the laboratory translate to difficulties in daily life in an ecologically sensitive manner. It is important to continue to link laboratory and EMA measures, especially those that capture socioemotional information processing and related real-world affect in adolescence, given that this is a critical time for social development, is characterized by greater sensitivity to peer social cues (including faces; Sandre et al., 2022), and is a period of increased risk for psychopathology. This work may reveal prevention or intervention targets that could facilitate the development of approaches that improve adolescent well-being, such as personalized and adaptive just-in-time interventions.

AUTHOR CONTRIBUTIONS

Aishwarya Sritharan: Data curation; project administration; writing – review and editing. **Akina Umemoto:** Formal analysis; software; visualization; writing – review and editing. **Allison M. Letkiewicz:** Conceptualization; data curation; formal analysis; visualization; writing – original draft; writing – review and editing. **Carter J. Funkhouser:** Formal analysis; visualization; writing – original draft; writing – review and editing. **Emily Zhang:** Data curation; project administration; writing – review and editing. **Esha Trivedi:** Data curation; formal analysis; software; writing – review and editing.

Fiona Helgren: Data curation; project administration; writing – review and editing. **Grace O. Allison:** Project administration; writing – review and editing. **Jürgen Kayser:** Conceptualization; methodology; visualization; writing – review and editing. **Randy P. Auerbach:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – original draft; writing – review and editing. **Savannah N. Buchanan:** Project administration; writing – review and editing. **Stewart A. Shankman:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

Dr. Auerbach is an unpaid scientific advisor for Ksana Health, the developer of the EARS application software used in the present study, and a paid scientific advisor for Get Sonar, Inc. No other authors have conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1: Supporting Information

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