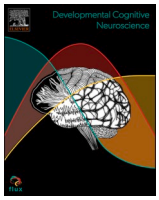
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Bidirectional associations between self-referential processing and depressive symptoms in early adolescents: A two-wave EEG study☆

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ABSTRACT

The transition into adolescence is a critical period that features rapid development of the self and elevated depressive symptoms. Maladaptive self-referential processing is an identified cognitive risk factor that predicts the development of depression; elevated depressive symptoms may also reinforce maladaptive patterns of self-referential processing. However, longitudinal data that speak to the directional associations between these two constructs are limited: extant research has focused on simple behavioral measures of self-referential processing, and no work has examined the directional relationships between the neural substrates of self-referential processing and depressive symptoms. In this study, 115 community-dwelling youths (66 girls; Mean age/SD =11.00/1.16 years) completed an EEG version of the Self-Referent Encoding Task (SRET) and reported their depressive symptoms at baseline and approximately a year later. A larger anterior late positive potential (LPP) elicited by negative self-referential processing at T1 predicted higher depressive symptoms a year later, with baseline symptoms controlled for. Further, depressive symptoms at T1 predicted higher drift rate during negative self-referential processing at T2, with baseline drift rate controlled for. We provided novel evidence concerning the bidirectional relationships between self-referential processing and depressive symptoms in early adolescence, with differential patterns observed in different indices of self-referential processing (neural or behavioral).

1. Introduction

Depression is a prevalent mental health condition that emerges as early as childhood (Birmaher et al., 2004). Although depressive psychopathology shows a more drastic increase during mid-to-late adolescence, depressive symptoms begin to elevate even during early adolescence, especially as youths hit puberty (e.g., Ge et al., 2001; Hamilton et al., 2016; Twenge and Nolen-Hoeksema, 2002). Indeed, the transition from childhood into adolescence features significant physical and psychosocial development in multiple domains, providing a useful time window to study the developmental processes associated with the emergence of depression. Exploring the early risk processes in younger adolescents will also directly inform similar investigations in older adolescents. Cognitive models of depression have identified a series of cognitive processes as risk factors for the development of depression, including self-referential processing (Beck, 2008; Gotlib and Joormann, 2010). Self-referential processing is a cognitive construct that guides the processing of positive and negative information about oneself (Derry and Kuiper, 1981; Kuiper and Derry, 1982; Northoff et al., 2006). Typically developing youths tend to show a positivity bias in self-referential processing, i.e., deeper processing of positive, and shallower processing of negative, self-referential information (e.g., Goldstein et al., 2015; Hudson et al., 2021). On the other hand, a diminished positivity bias – deeper processing of negative, or shallower processing of positive, self-referential information – is considered maladaptive and may confer risks for the development of depression in youths and adults (Allison et al., 2021; Auerbach et al., 2015; Derry and Kuiper, 1981; Dobson and Shaw, 1987; Kuiper and Derry, 1982; Liu et al., 2020a, 2020b, 2021; Prieto et al., 1992; Speed et al., 2016).

While maladaptive cognitive processes have been conceptualized as early precursors of depression risk, elevated depressive symptoms may also predict subsequent maladaptive cognitive processing, which, in turn, may reinforce later depressive symptoms. In other words, the relationships between self-referential processing and depressive symptoms may be bidirectional. However, longitudinal data that speak to the directional associations between these two constructs are scarce,

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hindering our mechanistic knowledge of the development of depression in youths. The limited number of extant longitudinal studies have focused on simple behavioral measures of self-referential processing, and no work has examined the directional relationships between the neural substrates of self-referential processing and depressive symptoms. This study aimed to address this gap by two waves of EEG data of self-referential processing and depressive symptoms from a group of community-dwelling early adolescents.

Early work on self-referential processing and its relationship with depression in adults established the Self-Referent Encoding Task (SRET; Derry and Kuiper, 1981; Kuiper and Derry, 1982), which has since been widely adopted in different populations, including children and adolescent. In this paradigm, participants are presented with a series of positive and negative personal trait words and decide whether each word is self-descriptive by a "yes" or "no" response. This endorsement task is often followed by an incidental memory task, when participants are asked to recall or recognize as many of the presented words as possible. An array of behavioral metrics has been extracted from the SRET to index self-referential processing, including the number/percentage of endorsed words, the number/percentage of remembered words (recalled or recognized), the number/percentage of words both endorsed *and* remembered, and response time (RT) of endorsement.

More recently, researchers have applied the drift diffusion model to calculate the drift rate *(v)* based on the trial-level RT and endorsement responses of the SRET (Beevers et al., 2019; Castagna et al., 2023; Dainer-Best, Disner, et al., 2018; Dainer-Best, Lee, et al., 2018; Disner et al., 2017; Hsu et al., 2020). The drift diffusion model is a sequential sampling technique that gleans latent cognitive parameters underlying decision-making processes from the trial-to-trial distribution of RTs and binary responses (Ratcliff, 1978; Ratcliff and McKoon, 2008), with the assumption that on each trial, evidence is accumulated until one of two responses can be made (e.g., whether a given word is self-descriptive). In the context of the SRET, the drift rate indicates the relative ease of evidence accumulation in a given condition. In the positive SRET condition, a drift rate of a highly positive value indicates that it is easy for this individual to respond "yes" and endorse the positive words as self-descriptive (deeper, adaptive positive self-referential processing); a highly negative drift rate suggests that it is easy to respond "no" and reject the positive words (shallower, maladaptive positive self-referential processing). Likewise, in the negative condition, a highly positive drift rate reflects the ease of endorsing negative words (deeper, maladaptive negative self-referential processing), whereas a negative drift rate indicates the ease of rejecting negative words (shallower, adaptive negative self-referential processing). Compared to the more traditional behavioral indices, the drift rate is considered a more fine-grained measure as it captures the latent cognitive parameters underlying the dynamic processes of cognitive decision making (Ratcliff, 1978; Ratcliff and McKoon, 2008).

These different metrics of the SRET show consistent patterns in association with depression: heightened depressive symptoms are associated with deeper processing of negative self-referential information (e.g., a larger number/percentage of negative words endorsed/remembered or a higher drift rate in the negative condition) or shallower processing of positive self-referential information (e.g., a smaller number/percentage of positive words endorsed/remembered or a lower drift rate in the positive condition; Dainer-Best, Lee, et al., 2018). Further, among the different SRET metrics, the number (or percentage) of endorsed words and the drift rate appeared to show the most robust concurrent associations with depressive symptoms in large samples of adults and adolescents (Dainer-Best, Lee, et al., 2018).

However, the majority of this literature, as reviewed above, has relied on cross-sectional data to examine the concurrent relationships between self-referential processing and depressive symptoms. Does self-referential processing solely serve as a risk marker that predicts and precedes subsequent depressive symptoms, or is it also a "consequence" of elevated symptoms? Only a few studies have investigated the directionality of the relationships between these two constructs. These studies all relied on a single behavioral measure of self-referential processing (i.e., the proportion of positive or negative words endorsed *and* recalled) and generated inconsistent findings. One study found that in a community youth sample, positive self-referential processing at age seven predicted lower depressive symptoms at ages eight and nine with baseline symptoms controlled for; on the other hand, depressive symptoms at age seven predicted more negative self-referential processing at age nine (Hayden et al., 2013). In another community sample, positive self-referential processing at age six predicted lower depressive symptoms at age nine with baseline symptoms controlled for; however, depressive symptoms at age six did not predict self-referential processing at age nine (Goldstein et al., 2015). Thirteen- to 15-year-old adolescents did not show significant relationships between negative self-referential processing and depressive symptoms over a six-month period in either direction (Black and Pössel, 2013).

In addition to generating behavioral metrics, the SRET has also been combined with neuroscience techniques such as the event-related potentials (ERP) to tap the neural underpinnings of self-referential processing (Auerbach et al., 2015, 2016; Hudson et al., 2020; Ke et al., 2020; Liu et al., 2024; Liu and Tan, 2024a, 2023b, 2023a, 2024b; Shestyuk and Deldin, 2010; Speed et al., 2016). This literature, whether on youths or adults, has most consistently reported an anterior late positive potential (LPP) elicited during the SRET. The anterior LPP is a fronto-centrally located slow positive deflection starting around 400–600 ms after stimulus onset and lasting through the duration of stimulus. While the late positivity is generally considered a neural marker of in-depth, sustained processing of motivationally salient information, the literature has noted the functional differences between the anterior and posterior late positivity. Compared to the posteriorly located LPP elicited by non-referential paradigms (e.g., passive viewing of emotional stimuli; Cuthbert et al., 2000; Foti et al., 2009; Foti and Hajcak, 2008; Kujawa et al., 2013; MacNamara et al., 2009, 2019), the anterior LPP is thought to reflect a more strategic aspect of in-depth processing that involves top-down, goal-directed regulatory processes (as opposed to a more stimuli-driven, bottom-up aspect of in-depth processing as reflected by the posterior LPP; Porter et al., 2021). During the SRET, participants deliberately engage in self-referential processing as dictated by the task's instruction. The SRET-elicited anterior LPP may reflect distinct top-down cognitive processes such as the strategic retrieval of instances from autobiographic memory (Rasmussen and Berntsen, 2011) and the evaluation of the target word in relation to these instances.

A similar "positivity bias" has been observed in the SRET-elicited anterior LPP among healthy youths, such that they showed a potentiated anterior LPP toward positive versus negative self-referential words (Auerbach et al., 2016; Liu and Tan, 2023b). On the other hand, a diminished positivity bias on the neural level, e.g., a larger anterior LPP toward negative self-referential words, has been found in depressed girls (Auerbach et al., 2015), depressed adults (Shestyuk and Deldin, 2010), and eight- to 14-year-old girls with a maternal lifetime history of depression (Speed et al., 2016). Using the same youth sample as that in the current study, our recent work found that a smaller anterior LPP evoked by positive self-referential words was associated with higher depressive symptoms beyond the behavioral SRET metrics (Liu and Tan, 2023b). While self-referential processing involves both top-down, strategic processes and bottom-up, stimuli-driven processes, it is the former (as indicated by the anterior LPP) that shows a meaningful association with depressive psychopathology.

Neural indices of the same cognitive risk factor may reflect distinct aspects of risk processes that emerge prior to, or cannot be captured by, behavioral metrics (Manoach and Agam, 2013). Indeed, some studies observed significant associations between neural, but not behavioral, indices of socioemotional processing and psychopathology in youths (Fu et al., 2017; Liu et al., 2020b). This highlights the importance of examining the bidirectional relationships between the neural substrates

of self-referential processing and depressive symptoms, which may show differential patterns from the behavioral indices. To our knowledge, no extant work has investigated this issue.

The present study aimed to address this gap. We used the same SRET-elicited EEG data collected from a community sample of nine- to 12-year-old youths as reported in our previous work (Liu et al., 2024; Liu and Tan, 2024a, 2023a, 2023b, 2024b), with the addition of one-year follow-up data from the same sample. These two waves of data enabled us to examine the relationships between self-referential processing (with both behavioral and ERP indices) and depressive symptoms in both directions. Specifically, we examined the prospective associations between T1 self-referential processing and T2 depressive symptoms, with T1 symptoms controlled for. We also examined the prospective relationships between T1 depressive symptoms and T2 self-referential processing, with T1 self-referential processing controlled for. Among the various behavioral metrics of the SRET, we focused on two of them that have been found to show most robust relationships with depressive symptoms, the percentage of words endorsed (% endorsed, calculated as the number of positive or negative endorsed words divided by the total number of positive or negative words) and the drift rate in each condition (Dainer-Best, Lee, et al., 2018). For the ERP indices, we focused on the anterior LPP component, which has been most widely studied in the SRET literature.

Based on the literature reviewed above, we expected to find significant relationships between these metrics and depressive symptoms in both directions; e.g., heightened depressive symptoms would be associated with a larger % endorsed, a higher drift rate, or an enlarged anterior LPP in the negative SRET condition, or a smaller % endorsed, a lower drift rate, or a reduced anterior LPP in the positive SRET condition. Importantly, we expected to observe these relationships in both directions. However, given the scarcity of relevant longitudinal studies, we did not have hypotheses concerning the specific patterns of the directionality for each SRET metric.

2. Method

2.1. Participants and procedure

Data are drawn from a larger project investigating the neurobehavioral correlates of cognitive risks for depression in early adolescence. At T1, 115 typically developing youths (66 girls; Mean age/SD = 11.00/1.16 years) and their caregivers were recruited from the community in a Midwestern urban area in the U.S. and invited to a lab visit. None of the youths had any reported major physical diseases, serious mental illness, or neurodevelopmental disabilities. The demographics of the sample lined up with the local demographics (87.5 % White, 3.6 % Asian, 8.9 % multi-racial; 7.2 % Hispanic or Latino; family income range: $15,000-$350,000). During the T1 visit, caregiver consent and youth assent were acquired first. Next, youths completed a battery of four EEG tasks (including the SRET) in a counter-balanced order and an eye-tracking task tapping different cognitive processes. Upon finishing the lab visit, youths completed a questionnaire package reporting their mental health problems, including depressive symptoms, via Qualtrics at home (Qualtrics, Provo, UT).

We collected follow-up data from the same sample approximately 12 months later (T2; Mean/SD of interval = 12.20/1.72 months), using a highly similar study protocol as T1. Of the initial 115 youths, 92 participated in T2 (53 girls; Mean age/SD = 12.06/1.20 years). At both time points, participants received monetary compensation upon completing the study. The study protocol was approved by the Institutional Review Board of the university.

2.2. Measure of depressive symptoms

At both T1 and T2, youths completed the Youth Self-Report (YSR), a 118-item checklist assessing emotional and behavioral symptoms in four- to 18-year-olds (Achenbach and Rescorla, 2001). The YSR consists of an eight-item withdrawn/depressed subscale, which was used in this study as a measure of youths' depressive symptoms. Youths rated each item (e.g., "There is very little that I enjoy") on a three-point scale (0 = not true, 2 = very true) based on their experiences during the past month. A total score of the eight items was computed to indicate depressive symptoms (Cronbach's α at T1 & T2 = .79 &.77 in the current sample).

2.3. The SRET

At both T1 and T2, youths completed an SRET while their EEG signals were being recorded. The SRET used at T1 and T2 was highly similar to each other but with a few differences. First, the T1 SRET consisted of two self-referential conditions (positive & negative) presented in one block. At T2, the SRET consisted of four conditions, two self-referential conditions (positive & negative) and two "other-referential" conditions (positive & negative) where participants had to decide whether a word described a character well-known to them; the self-referential conditions were presented in one block, followed by the block of the other-referential conditions. Only data from the self-referential conditions at T2 were included in this study. Second, at T1, youths were unexpectedly asked to recall the presented words right after the endorsement task. At T2, considering that the total number of words of the four conditions (128) was too much for free recall, we asked youths to complete an unexpected recognition task where they had to recognize the presented words from a list of words. Finally, the word stimuli used at the two time points were slightly different, with 30 words per condition (positive or negative) at T1 and 32 words per condition at T2. However, at the mean level, the stimuli were matched between T1 and T2 in valence for positive and negative words, respectively; they were also matched in arousal, dominance, and word length based on the Affective Norms for English (Bradley and Lang, 1999).

All other parameters of the SRET were the same between T1 and T2. The positive and negative self-referential words were always presented in a pseudo-random manner, such that no more than two words of the same valence were presented successively. Each trial started with a 500 ms fixation cross, after which a positive or negative word was presented for 1000 ms, followed by another 500 ms fixation cross. Next, a question ("Does this word describe you?") popped up on the screen until youths pressed one of two buttons on a response box (left = yes, right = no).

2.4. Behavioral measures of self-referential processing

Among the array of behavioral metrics that can be extracted from the SRET, we focused on two measures, the % endorsed and the drift rate, in this study. We chose these measures for several reasons. First, these two measures have been found to be most robustly associated with depressive symptoms across large adult and adolescent samples (Dainer-Best, Lee, et al., 2018; Hsu et al., 2020). Second, the calculation of these two measures circumvented the methodological differences between T1 and T2 and therefore were comparable between the two time points. For example, the % endorsed was computed by dividing the number of endorsed positive (or negative) words by the total number of positive (or negative) words, which accounted for the different number of total words in each condition at T1 (30) and T2 (32). Using these two measures also avoided incorporating the incidental memory task, which was different between T1 (free recall) and T2 (recognition). Third, while the number or percentage of words endorsed (and other more traditional behavioral metrics) have been commonly used in the literature, only a couple of SRET studies have examined the drift rate in youths (Castagna et al., 2023; Dainer-Best, Lee, et al., 2018), and no work has examined the bidirectional associations between the drift rate and depressive symptoms in youths.

We computed the drift rate in each condition at the two time points

using the open-source program fast-dm (Voss and Voss, 2007). As stated earlier, the *drift rate (v)* refers to the rate of accumulation of information required until one of two responses can be made (e.g., whether a given word is self-descriptive). In the positive SRET condition, a highly positive drift rate indicates the ease of endorsing positive words, whereas a highly negative drift rate indicates the ease of rejecting positive words. In the negative condition, a highly positive drift rate reflects the ease of endorsing negative words, whereas a negative drift rate indicates the ease of rejecting negative words.

2.5. EEG data acquisition and processing

At T1 and T2, youths completed the SRET in the same electrically shielded chamber with their EEG being recorded by the same equipment and protocol: a 64-channel HydroCel GSN Electrical Geodesics Inc. (EGI) net, an EGI 200 NetAmps Amplifier, a 250 Hz sampling rate, a vertex (Cz) reference, and electrode impedance below 50 kΩ. EEG data of both time points were processed following the same protocol using the EEGLab (Delorme and Makeig, 2004) and ERPLab (Lopez-Calderon and Luck, 2014) toolboxes in MATLAB 9.10.0 (Mathworks, Inc., Natick, MA). Raw data were first subjected to offline filter (0.1–40 Hz) and re-referenced to the average of the two mastoid electrodes. An independent component analysis approach was used to remove ocular artifacts. Next, the processed continuous EEG data were time-locked to the onset of each word and segmented into epochs from 200 ms before to 1000 ms post the word onset, with a 200 ms baseline correction. We further rejected segments with (1) voltage beyond ±100 μV, (2) a > 50 μV change of voltage between time points, or (3) a > 300 μV change of voltage between the most positive and most negative time points within a 200 ms moving window. Out of the 115 youths at T1, 101 youths with ≥ 10 trials in each condition were retained for subsequent analyses. Of the 92 participating at T2, 87 with ≥ 10 trials in each condition were retained.

Following the common practice in the SRET literature, we computed the average ERPs across all positive or all negative words for each youth, irrespective of whether the word was endorsed. This was based on the fact that (1) it was not feasible to isolate words endorsed from those not endorsed given the limited number of words in each condition and (2) even when individuals reject a word as self-descriptive, they have also processed the word in reference to themselves (hence "self-referential" processing).

2.6. Principal component analysis of the ERP data

We focused on the anterior LPP component that has been found to be associated with depressive psychopathology in the literature (e.g., Allison et al., 2021; Auerbach et al., 2015; Liu and Tan, 2023b, 2023a; Shestyuk and Deldin, 2010; Speed et al., 2016). For both time points, the anterior LPP was quantified via the same principal component analysis (PCA). The PCA is a factor-analytic approach that isolates underlying ERP components by accounting for variances across all time points and electrodes, maximizing the utility of the data and generating more accurate temporo-spatial information (Dien, 2010; Dien et al., 2005; Dien and Frishkoff, 2005). We used a two-step temporo-spatial PCA via the ERP PCA Toolkit in MATLAB (Dien, 2010; Dien et al., 2005; Dien and Frishkoff, 2005). A temporal PCA was first performed on the averaged ERP data using Promax rotation to reduce the temporal dimensions of the data, treating time points as variables and participants, experimental conditions (positive & negative), and electrodes as observations. Next, a spatial PCA was performed on each temporal factor generated by the first step using Infomax rotation to reduce the spatial dimensions of the data, treating electrodes as variables and participants, conditions, and temporal factors as observations.

For the T1 ERP data, the PCA generated a total of 105 temporo-spatial factors (21 temporal factors × five spatial factors). Nineteen of the 105 factors, each accounting for ≥ 0.5 % of the variance, were retained for further inspection (Dien, 2012). Among the 19 factors, the TF02SF1 factor (peak channel FC1, peaking latency 956 ms, 8.20 % variance, Fig. 1a) appeared temporally and spatially analogous to the anterior LPP reported in the literature. The T1 PCA results have been reported in our previous publications (Liu and Tan, 2024a, 2023a, 2024b). For the T2 ERP data, the PCA generated 65 temporo-spatial factors in total (13 temporal factors × five spatial factors). Twenty of the 65 factors accounted for ≥ 0.5 % of the variance. Among the 20 factors, the TF01SF1 factor (peak channel Fp1, peaking latency 860 ms, 8.24 % variance, Fig. 1b) was temporally and spatially analogous to the anterior LPP. The factor scores of TF02SF1 at T1 and TF01SF1 at T2 were extracted for each participant in each condition as indicators of the anterior LPP amplitude in subsequent analysis (SPSS 29.0, IBM, Armonk, NY).[1]

Paired-samples *t*-tests showed that the anterior LPP at T1 (TF02SF1) did not differ between the positive (Mean/SD = 6.24/7.29) and negative (Mean/SD = 5.68/7.26) SRET conditions, $t(100) = 1.13$, $p = .26$, Cohen's $d = 0.11$. The anterior LPP at T2 (TF01SF01) was larger in the positive condition (Mean/SD = 3.45/6.49) than the negative condition (Mean/SD = 1.33/6.64), $t(86) = 3.76$, $p < .001$, Cohen's $d = 0.40$.

2.7. Missing data imputation

Of the 115 youths at T1, 16 had missing data for at least one study variable (four missing symptom data, two not completing the SRET, 12 with unusable ERP data). Of the 92 youths who returned for T2, 10 had missing data for at least one variable (six missing symptom data, five with unusable ERP data). Little's Missing Completely at Random Test (Little, 1988) showed that data were missing completely at random ($\chi^2 = 363.09$, $df = 334$, $p = .13$). Further, to ensure that participant attrition occurred at random across the two time points, we compared the 92 youths who returned for T2 data collection and the 23 youths who did not, by conducting independent-samples *t*-tests on a series of T1 variables, including age, depressive symptoms, and the SRET measures in the two conditions (endorsement rate, drift rate, PCA scores of the anterior LPP). We also ran a non-parametric Mann-Whitney U Test on sex. None of these tests generated significant differences between the two subsets of participants ($ps > .06$).

To account for the missing data, we implemented multiple imputation using the R mice package (van Buuren and Groothuis-Oudshoorn, 2011). Fifty imputations with ten iterations per imputation were conducted for each variable; averaged data were then calculated across the 50 imputed datasets. The imputed data (N = 115) were used for the subsequent analyses to increase power. For data missing completely at random, multiple imputation can provide relatively unbiased estimates with improved efficiency regardless of the proportion of missingness (Madley-Dowd et al., 2019).

2.8. Statistical analysis

We first inspected the distribution of our data. For each variable, outliers exceeding three standard deviations (SD) above or below the group mean were Winsorized by replacing the original values by the values of group mean+ 3 SD or group mean-3SD. This approach mitigates the biases induced by outliers while retaining the individual differences represented by these outliers (Ruppert, 2014). Following the Winsorization of outliers, all variables showed a relatively more normal-like distribution with an absolute value of skewness ≤ 2 (Hair

[1] We also scored the anterior LPP at T1 and T2 via the more traditional approach by computing the mean amplitude of the 600–1000 ms time window post-stimulus onset averaged across eight frontal channels (FCz, FC1, FC2, Fz, F1, F2, F3, F4). The same statistical analyses were conducted on the mean amplitude of the anterior LPP, which generated highly similar results (see Table S1 and Table S2 in supplemental materials).

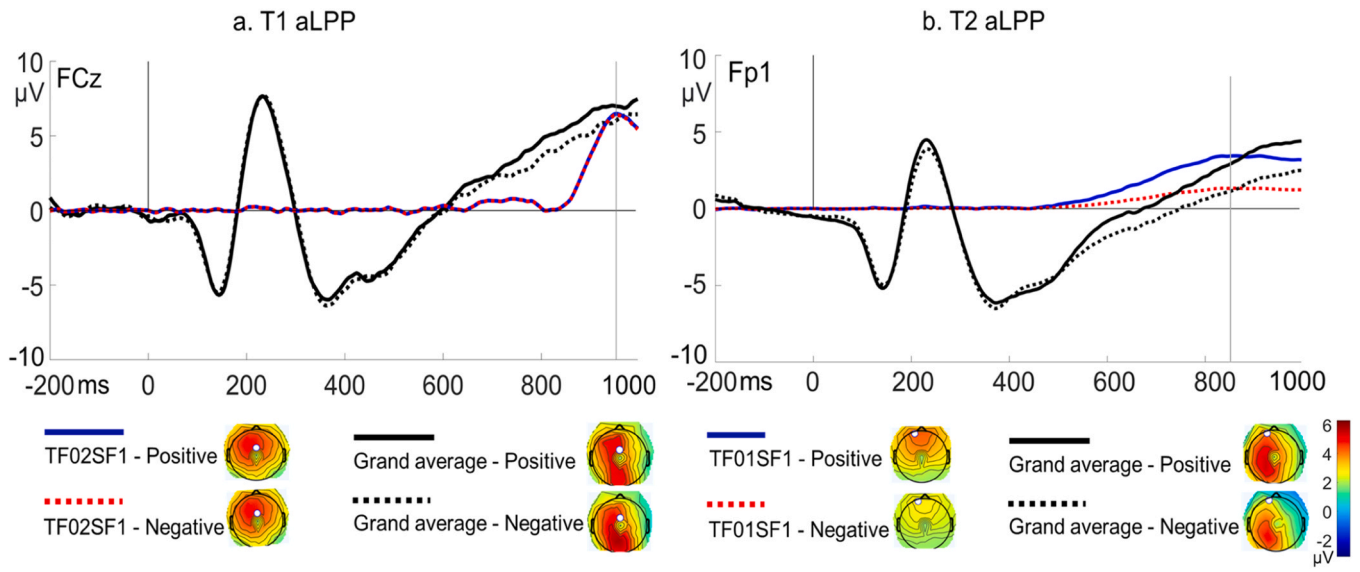


Fig. 1. ERP waveforms and topographic maps of T1 anterior LPP (TF02SF1) and T2 anterior LPP (TF01SF1) in each condition superimposed on the grand average of the original data. Note. anterior LPP: anterior late positive potential; ms: millisecond.

et al., 2022).

To test the directional associations between SRET metrics and depressive symptoms, we conducted cross-lagged panel modelling (CLPM) on the two waves of data using the "lavaan" package in R (Rosseel, 2012). We first conduced an omnibus model including all SRET measures (endorsement rate, drift rate, anterior LPP) and depressive symptoms at both time points, with autoregressive paths (stability over time) and cross-lagged paths (temporal influences across variables) estimated. This model demonstrated poor fit to the data ($\chi^2(42) = 230.381$, $p < .001$, CFI = .775, TLI = .512, RMSEA = .197, 90 % CI = [.173,.223], SRMR = .160). To improve model fit and preserve statistical power, we removed % endorsed in the two SRET conditions from the model, which did not show any significant cross-lagged associations with other variables in the initial model. The modified model demonstrated an excellent fit to the data: $\chi^2(16) = 16.93$, $p = .39$, CFI = .997, TLI = .993, RMSEA = .023, 90 % CI = [.000–.091], SRMR = .044. Results of this modified model were reported in detail below.[2]

3. Results

3.1. Descriptive statistics and bivariate correlations

Table 1 shows the means, standard deviations, and Pearson bivariate correlations of study variables. We ran the correlations for the purpose of describing the patterns of the data rather than making statistical inferences; therefore, we did not correct for multiple comparisons for the correlation results. As shown in Table 1, compared to boys, girls were older, endorsed a higher percentage of negative words at T1, showed a smaller anterior LPP in the negative SRET condition at T1, and reported greater depressive symptoms at T1. Age at T1 was correlated with a larger anterior LPP in the positive SRET condition at T2. The two behavioral SRET measures (% endorsed and drift rate) showed stability (i.e., significant positive correlations) from T1 to T2 in both conditions; higher % endorsed or drift rate in the positive condition were correlated with lower % endorsed or drift rate in the negative condition across time points. The % endorsed and drift rate were also meaningfully correlated with each other across conditions and time points (e.g., higher % endorsed in the positive condition was correlated with higher drift rate in the positive condition, but lower drift rate in the negative condition). T2 % endorsed of positive words was correlated with a smaller anterior LPP in the positive condition at both T1 and T2. T2 % endorsed of negative words was correlated with a larger anterior LPP in both conditions at T2. T1 drift rate in the negative SRET condition was negatively correlated with the anterior LPP in the positive condition at T2. More details about the distribution of depressive symptoms in the current sample are reported in the supplement.

The % endorsed and drift rate also showed expected associations with depressive symptoms across time points, such that the % endorsed and drift rate in the positive condition were correlated with lower depressive symptoms, whereas the % endorsed and drift rate in the negative condition were associated with higher depressive symptoms. The PCA factor scores of anterior LPP (as indicator of the amplitude) in both conditions showed stability from T1 to T2; the factor scores of anterior LPP were positively correlated with each other between conditions. The anterior LPP in both conditions at T2 was positively correlated with T2 depressive symptoms. Depressive symptoms showed stability over time, as indicated by a positive correlation between T1 and T2.

3.2. Results of CLPM

Supporting stability of constructs over time, all autoregressive paths in the CLPM were significant ($ps < .05$) except for that of the anterior LPP in the positive SRET condition ($\beta = -0.027$, $SE = 0.103$, $z = -0.201$, $p = .841$), likely reflecting a suppression effect (Tzelgov and Henik, 1991). Among the cross-lagged effects, a larger anterior LPP in the negative condition at T1 predicted higher depressive symptoms at T2 ($\beta = 0.402$, $SE = 0.043$, $z = 3.762$, $p < .001$). A smaller anterior LPP in the positive condition at T1 predicted greater symptoms at T2 ($\beta = -0.289$, $SE = 0.043$, $z = -2.692$, $p = .007$). Higher depressive symptoms at T1 predicted higher drift rate in the negative condition at T2 ($\beta = 0.205$, $SE = 0.047$, $z = 2.214$, $p = .027$). No other cross-lagged path between SRET metrics and depressive symptoms was significant.

[2] We conducted alternative analyses by running a series of linear regression, which generated highly similar results. We also quantified the anterior LPP by computing the mean amplitude of the 600–1000 ms time window post-stimulus onset averaged across eight frontal channels (FCz, FC1, FC2, Fz, F1, F2, F3, F4), which, again, yielded similar results. Details of these analyses are reported in the supplement.

Table 1
Descriptive statistics and bivariate correlations of main study variables.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Sex (1 =boys, 2 =girls)	–															
2	T1 age	.18*	–														
3	T1 % endorsed-positive	-.07	-.06	–													
4	T1 % endorsed-negative	.24**	.04	-.60**	–												
5	T2 % endorsed-positive	.12	-.09	.53**	-.32**	–											
6	T2 % endorsed-negative	.06	.12	-.29**	.46**	-.33**	–										
7	T1 drift rate-positive	-.03	.07	.76**	-.43**	.46**	-.22*	–									
8	T1 drift rate-negative	.15	-.09	-.43**	.73**	-.23*	.31**	-.48**	–								
9	T2 drift rate-positive	.14	.09	.46**	-.34**	.77**	-.32**	.48**	-.32**	–							
10	T2 drift rate-negative	-.13	-.14	-.27**	.35**	-.35**	.63**	-.33**	.36**	-.45**	–						
11	T1 anterior LPP-positive	-.14	-.13	-.15	.04	-.29**	.01	-.12	.02	-.17	.06	–					
12	T1 anterior LPP-negative	-.21*	-.05	-.10	.03	-.18	.08	-.02	-.03	-.08	-.05	.76**	–				
13	T2 anterior LPP-positive	.02	.24**	-.09	.00	-.20*	.22*	.06	-.20*	-.16	.10	.32**	.40**	–			
14	T2 anterior LPP-negative	.02	-.10	-.01	-.04	-.03	.24*	.05	-.10	-.09	.07	.33**	.37**	.62**	–		
15	T1 depressive symptoms	.22*	.05	-.52**	.47**	-.22*	.29**	-.36**	.40**	-.26**	.29**	-.03	-.07	-.05	-.06	–	
16	T2 depressive symptoms	.00	.12	-.26**	.27**	-.36**	.57**	-.18*	.18*	-.35**	.34**	.00	.13	.22*	.20*	.48**	–
	Mean		10.98	0.76	0.20	0.73	0.15	1.17	-1.23	1.06	-1.86	6.46	5.77	3.57	1.49	3.53	3.82
	Standard Deviation		1.18	0.18	0.17	0.17	0.16	1.06	1.20	1.01	1.39	6.93	6.84	5.21	5.95	2.79	2.72

Note. % endorsed: percentage of words endorsed; LPP: late positive potential; T1 anterior LPP: TF02SF1; T2 anterior LPP: TF01SF1.

4. Discussion

By using two waves of EEG data collected in an SRET paradigm, we for the first time examined the directional associations between self-referential processing and depressive symptoms in a community sample of early adolescents. We observed significant associations between self-referential processing and depressive symptoms in both directions, but with different patterns manifested in different indices of self-referential processing (behavioral or ERP). Results of CLPM showed that with autoregressive paths accounted for, the anterior LPP elicited by negative self-referential processing at T1 predicted greater depressive symptoms a year later at T2. The anterior LPP elicited by positive self-referential processing at T1 predicted lower depressive symptoms at T2. On the other hand, depressive symptoms at T1 predicted higher drift rate during negative self-referential processing at T2. The % endorsed was not associated with depressive symptoms in either direction. We provided novel evidence concerning the bidirectional relationships between self-referential processing and depressive symptoms in early adolescence, adding to our mechanistic knowledge of the development of depressive psychopathology during this important developmental stage.

4.1. SRET-elicited anterior LPP predicted depressive symptoms a year later

Controlling for autoregressive stability, the anterior LPP in the negative SRET condition at T1 predicted greater depressive symptoms at T2. In other words, a larger anterior LPP elicited by negative self-referential processing predicted increases in depressive symptoms a year later. As discussed earlier, while the late positivity in general reflects in-depth, sustained processing of motivationally salient information (e.g., Cuthbert et al., 2000; Foti et al., 2009; Foti and Hajcak, 2008; Kujawa et al., 2013; MacNamara et al., 2009, 2019), the anteriorly located LPP (as opposed to the posteriorly located LPP) may reflect a more strategic facet of in-depth information processing that involves top-down regulatory processes (Porter et al., 2021). During the SRET, individuals need to retrieve instances about themselves from autographical memory and compare the given word to the retrieved instances. An enlarged anterior LPP in the negative SRET condition, therefore, might suggest that these youths were engaging greater cognitive resources to strategically retrieve negative instances of themselves and deliberate on the self-relevance of the negative word stimuli in comparison with these instances. This heightened deliberation on negative personal traits might have conferred greater risks for subsequent increases in depressive symptoms in the next year.

We also found that a larger anterior LPP in the positive SRET condition at T1 predicted decreases in depressive symptoms a year later. A potentiated anterior LPP elicited by positive self-referential processing suggested that these youths were mobilizing greater cognitive resources when retrieving positive instances of themselves and engaging in greater deliberation on the self-relevance of the positive words relative to the retrieved instances. This deliberation on positive trait words in relevance to themselves might have protected them from the development of depressive symptoms in the following year.

Neither behavioral SRET measure (% endorsed or drift rate) at T1 prospectively predicted depressive symptoms a year later with autoregressive paths controlled for, although both behavioral measures showed significant bivariate correlations with symptoms at both time points. In other words, unlike the anterior LPP, the behavioral measures did not serve as early risk markers that preceded the changes of symptoms in the following year. A key functional difference between the anterior LPP and the behavioral measures was that while the anterior LPP reflected the *online* in-depth processing of self-referential information regardless of the endorsement responses, both behavioral measures

directly involved participants' endorsement decisions – whether it was the % endorsed or the rate of making the endorsement decisions (i.e., drift rate). This suggested that it was the online deliberation of self-referential information, rather than the final yes or no decisions, that mattered in conferring risks for (or protecting youths from) the subsequent development of depressive psychopathology.

4.2. Depressive symptoms predicted the drift rate in the negative SRET condition a year later

While maladaptive self-referential processing is conceptualized as an early risk marker of depression, elevated depressive symptoms may also predict subsequent patterns of self-referential processing. We tested the SRET-symptom associations in the other direction, with T1 depressive symptoms as the predictor and T2 SRET metrics as the outcomes. The only significant relationship was observed between T1 symptoms and T2 drift rate in the negative condition. Specifically, elevated symptoms at T1 predicted heightened, or more positive, drift rate during negative self-referential processing at T2, with autoregressive effects controlled for.

The drift rate indicates the rate or ease of evidence accumulation until one of two responses can be made during cognitive decision making - in the context of the SRET, whether a given word is self-descriptive. In the negative SRET condition, a more positive value of the drift rate indicates that it is easier for this individual to respond "yes" and endorse the negative words as self-descriptive. Therefore, our results suggested that for youths with elevated depressive symptoms at T1, it became easier, or less effortful, for them to endorse negative traits as self-descriptive a year later – a more maladaptive pattern of self-referential processing as a "consequence" of earlier symptoms. This "consequence" was demonstrated in youths' behavioral decisions of endorsement, rather than their online processing of self-referential information as indicated by the anterior LPP.

However, we did not find significant associations between T1 symptoms and the % endorsed at T2, although the latter also directly indicated youths' behavioral endorsement decisions. This might be related to the relatively limited inter-individual variability in the % endorsed in both conditions – youths generally endorsed a majority of the positive words (77 % at T1, 73 % at T2) but only a minority of the negative words (20 % at T1, 15 % at T2). The % endorsed also appeared to be relatively more skewed in distribution (absolute values of skewness ranging 0.9–2.0) compared to the drift rate (absolute values of skewness ranging 0.6–1.0). While the % endorsed reflected the yes or no responses amalgamated across all trials, the drift rate accounted for the trial-level RT *and* trial-level responses. The drift rate was likely to reflect richer, more refined information of self-referential processing and decision making that could not be captured by the % endorsed. It was therefore unsurprising that it was the drift rate, but not the % endorsed, that showed a significant directional relationship with depressive symptoms.

T1 symptoms predicted the changes in drift rate in the negative, but not positive, SRET condition. One possible explanation was that during early adolescence, there were more pronounced changes and variability in negative self-referential processing than in positive self-referential processing. A longitudinal study found that throughout adolescence, positive self-referential processing did not show group-level changes, whereas negative self-referential processing showed a quadratic trajectory characterized by an increase followed by a decrease (McArthur et al., 2019). In our data, paired-samples *t*-tests showed that while the drift rate in the positive SRET condition did not change from T1 to T2 ($p = .28$), the drift rate in the negative condition decreased from T1 to T2 on the group level ($p < .001$). Therefore, the different patterns observed between the two conditions might be related to the higher variability in negative, and lower variability in positive, self-referential processing over time in early adolescents. This speculation was consistent with the ERP results: while the association between T1 anterior LPP and T2 symptoms was significant in both conditions, the relationship in the negative condition was stronger than that in the positive condition, as indicated by the standardized β.

For all SRET measures, we observed medium-to-strong correlations between T1 and T2 ($rs > .30$), attesting to the stability of these measures over a one-year period in early adolescents (see also Auerbach et al., 2016). While conducting a thorough psychometric analysis of the SRET paradigm is beyond the scope of the current paper, we aimed to do so in our next step of research by examining psychometric properties of the SRET measures including test-retest reliability, internal consistency, and construct validity. Although psychometric examination is equally important for questionnaire measures and experimental paradigms, relevant work on the latter – especially neurophysiological measures – has been scant (Clayson, 2024). Using the same dataset, our next step of work will provide novel evidence on the psychometric properties of the SRET paradigm in early adolescents, addressing an important gap in the literature.

Although beyond the focus of this paper, it was also interesting to note that the anterior LPP differed between positive and negative SRET conditions at T2 but not T1 as indicated by paired-sample *t*-tests. The SRET literature has reported inconsistent results concerning the valence effect on the anterior LPP: while some studies observed a larger anterior LPP toward positive versus negative self-referential words in healthy youths (Auerbach et al., 2015, 2016) or adults (Shestyuk and Deldin, 2010), others did not find any valence effects on this component in healthy youths (Hudson et al., 2021; Ke et al., 2020) or adults (Hudson et al., 2020). Multiple factors – differences in the samples and/or methodologies – might have contributed to these inconsistencies. In the current study, it is unclear why the valence effect was non-significant at T1 but significant at T2 in the same youth sample. We suspected that this might be related to socioemotional development during early adolescence, e.g., youths became more sensitive to valence over time in the context of self-referential processing. Of note, conducting the same paired-samples *t*-tests on the imputed data of T1 ($n = 115$) yielded a marginally significant difference between the two valences ($t(114) = 1.47$, $p = .072$), with the anterior LPP larger in the positive (Mean/SD = 6.35/6.87) than the negative (Mean/SD = 5.70/6.82) condition. This suggested that the trend of the valence effect might have emerged at T1 and then became stronger a year later at T2.

One limitation of this study was that in the ERP data, we were not able to isolate words endorsed from words not endorsed due to the limited number of word stimuli in each condition. We contended that rejecting a word as self-descriptive still involved processing the word in reference to oneself. However, the neural activity underlying the self-endorsement of a word may be distinct from that underlying the self-rejection of a word, which, in turn, may show differential associations with depressive symptoms. Future studies using a longer list of words are needed to guarantee a sufficient number of usable trials to isolate the ERPs of self-endorsement from the ERPs of self-rejection, shedding light on the more nuanced neural signatures of self-referential processing and their relationships with depressive psychopathology in youths.

The SRET protocol we used was not completely identical between T1 and T2. To circumvent the methodological differences, we focused on selected SRET metrics (% endorsed, drift rate, anterior LPP) that were comparable between the two time points. However, because different incidental memory tasks were used at T1 (free recall) and T2 (recognition), we were not able to examine the bidirectional associations between participants' memory performance and depressive symptoms. This is a limitation, as the memory metrics may tap into a unique, more implicit facet of self-referential processing that cannot be captured by the metrics we used here. This facet of self-referential processing may show distinct patterns in association with depressive psychopathology. Future research using identical SRET paradigms with the same memory task at different time points is needed to shed light on this issue. Future research will also benefit from longitudinal data with more than two time points. Maladaptive information processing and depressive psychopathology may predict each other and generate a reinforcing loop

over time, eventually leading to clinically significant disorders (Wittenborn et al., 2016). Multi-wave longitudinal data spanning longer periods of time will elucidate the complex nature of such loops, enriching cognitive models of depression and providing critical knowledge for developing prevention/intervention strategies to break the loops.

It is also worth noting that our findings differed from those of our recent study based on the same dataset (Liu and Tan, 2025), which reported that the anterior LPP in the negative SERT condition at baseline predicted faster increases in social anxiety but not depressive symptoms in the next year. This discrepancy likely reflected differences in study design and analytic approaches: the previous study modeled the individual intercepts and slopes of symptoms across three waves and used only one wave of SRET data at baseline, whereas the current two-wave CLPM tested bidirectional associations between SRET metrics and depression only. These analytic approaches might have captured somewhat different developmental processes: overall symptom trajectories versus directional, time-ordered associations between constructs. Conceptually, the present paper focused on depression because the goal of this study was to clarify the neurocognitive correlates of the emergence of depression. Finally, although multiple papers have been published using this dataset, each has addressed a distinct research question by examining different combinations of constructs via different analytic approaches. The current manuscript contributed novel information by testing bidirectional associations between self-referential processing metrics and depressive symptoms over time, which has not be examined in any of our previous publications.

By using two waves of EEG data collected during the SRET, we provided the first evidence regarding the bidirectional relationships between two indices of self-referential processing, the drift rate and anterior LPP, and depressive symptoms in early adolescents. While the SRET-elicited anterior LPP served as a precursor that predicted subsequent changes of depressive symptoms, the drift rate in the negative SRET condition appeared to be a consequence of earlier depressive symptoms. Our findings added to our mechanistic knowledge of depressive psychopathology during early adolescence and will shed light on the development of prevention/intervention strategies for youth depression.

CRediT authorship contribution statement

Pan Liu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tan Jaron X. Y.:** Project administration, Methodology, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2025.101658.

Data availability

Data will be made available on request.

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