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Distinguishing dimensions of emotion dynamics across 12 emotions in adolescents' daily lives

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Abstract:

Research on emotion dynamics as indices of emotion functioning has become muddled by conceptual confusion, methodological heterogeneity, and seemingly conflicting results. One way to address this chaos is the study of profiles of emotion dynamics across 12 emotions and how they differ between 246 adolescents. The interpretation of these dynamic profiles was guided by auxiliary variables including age, personality, depressive symptoms, and social experiences.

Method: During 6 days, 246 adolescents (M_{age}=14.20, 65% female) rated 9 times daily the intensity of 12 emotions (cheerful, happy, energetic, joyful, content, relaxed, anxious, worried, irritable, insecure, down, and guilty), and their social experiences with family, friends, and classmates. Additional baseline measures included neuroticism, extraversion (JEPQR-S), and depressive symptoms (CES-D). A three-mode principal component analysis (3MPCA Tucker3-based) model was estimated on the person-specific dynamic parameters of emotional intensity (mean), variability (standard deviation), instability (mean squared successive difference), and inertia (autocorrelation).

Results: The 3MPCA identified three emotion-mode components (positive affect, negative affect, and irritability), three dynamic-mode components (emotional intensity, lability, and inertia). Five individual-mode components captured interactions between these modes, of which positive affect explained most variation in the data. These emotion dynamic profiles correlated differently with social experiences. Additional 3MPCA model structures based on imputed data (correcting missing autocorrelations) and affect scale composites (low and high arousal positive and negative affect) showed strong resemblance.

Conclusion: The identified emotion dynamic profiles capture meaningful interpersonal differences in adolescents' emotional experiences and change. Future work should focus on irritability and positive affect as these were uniquely informative in adolescents' emotional experiences.

Keywords: variability; inertia; affect circumplex; ecological momentary assessment; multiway component analysis

Link to OSF files: https://osf.io/kp95z/?view_only=7b2679275f2741dd926643ba2a46cb28

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Emotion dynamics capture how and how much emotions change over time, which underlies psychological health and well-being across the lifespan (see reviews by Houben et al. (2015) or Reitsema et al. (2021)). Studies of how emotional experiences unfold over time utilize short-term intensive data collection methods which yield data that allow for the calculation of a variety of emotion dynamic measures. Among the most frequently studied measures are emotional intensity, variability, instability, and inertia, each defined in Table 1. The field of emotion dynamics has become muddled with measures that capture partly overlapping information, and seemingly conflicting findings that are difficult to compare because of methodological heterogeneity. For example, mean emotion scores predicted a substantial proportion of individual differences in well-being in healthy adults, while additional dynamic measures including variability, instability, and inertia, were unable to explain incremental variance (Dejonckheere, Mestdagh et al. (2019) and replicated by Wendt et al., 2020). Similarly, complex dynamic measures beyond the mean and variability were shown to be uninformative in explaining incremental variance in depressive symptoms (e.g., Bos et al., 2018; Koval et al., 2013; Wendt et al., 2020) and the personality trait neuroticism (a.k.a. emotional instability, e.g., Kalokerinos et al., 2020; Wenzel et al., 2020), although not in all studies (see Bosley et al., 2019; Sperry et al., 2020).

Artificially restricted scale variability may partly explain why the mean emotion score seems to capture the same outcome variance as the variability measures. Emotion dynamics are captured in intensive data collection methods such as experience sampling studies, which typically measure emotional intensity using Likert scales (e.g., score 1-7). When average scores remain close to the low or high end of the scale, the restricted dispersion of scores can render measures of variability, including the standard deviation (*SD*) or the mean squared successive difference score (*MSSD*), uninformative (Mestdagh et al., 2018). This occurs in healthy population samples as only few people experience frequent intense negative emotions in everyday life (Zelenski & Larsen, 2000), for example, which result in low average negative affect scores that create a low boundary for the variance.

To address these issues, studies increasingly combine multiple emotion dynamic measures in one model and examine their potential overlap across populations (Reitsema et al., 2021; Sperry et al., 2020). The current paper adds to this research by examining the (in)dependence of four emotion dynamic measures across 12 different emotions and whether and how these differ between 246 adolescents. We examined how adolescents' emotional experiences unfold over time in their daily lives using ecological momentary assessment, and investigated whether heterogeneity in such

emotional experiences can be summarized into a smaller number of individual profiles of emotion dynamics. Second, we studied whether these individual profiles are associated with external variables, such as the proportion of positive and negative social experiences over the six days of the assessment period. The next section provides details on our approach and rationale.

Variation Across Individuals and Emotions

Individuals differ in the emotions they experience and how these experiences unfold over time (Barrett, 2017; Fisher et al., 2018). The primacy of mean emotion scores over variability-based measures in predicting psychological outcomes may be specific to certain populations. Emotion dynamic measures might be more informative among individuals with more variable emotional landscapes, such as those with specific mental health problems (e.g., Sperry et al., 2020), or among adolescents, who are characterized by more variable emotions than children and adults (see Reitsema et al., 2021; Somerville et al., 2018). Adolescents have to manage physical, psychological, and social changes all at once, and these challenges contribute to a unique emotional landscape in this phase of the lifespan. Individual differences in emotional experience are likely to manifest over adolescence and eventually cascade into psychopathology (Cole, 2015). Globally, the median age of onset for mental health disorders as a whole is age 14; about half of all mental health conditions start around this age, including emotional disorders (Keeley, 2021). It is therefore important to gain a nuanced understanding of the distinctness of different emotion dynamics in the adolescent population. In this study, we aim to do this using a multiway approach.

Another limitation of the literature on emotion dynamics is the tendency to battle measurement error through combining multiple emotion items into scales of positive affect (PA) and negative affect (NA; e.g., McClure et al., 2021). Such affect scales may include different discrete emotions such as anger or sadness or anxiety, which each tap into a different amalgam of constituent elements (e.g., physiological, behavioral, phenomenological), and therefore differ in their arousal level, timing, context (e.g., trigger), and duration (Barrett et al., 2007; Jeronimus, 2019; Verduyn & Lavrijsen, 2015). PA and NA scales may therefore conceal the unique dynamic patterns of each emotion. Additionally, heterogeneous scales can hamper the comparison between study results (Reitsema et al., 2020; Weidman et al., 2017). We therefore set out to examine emotions as separate entities rather than composite scales, as the overlap between emotion dynamic measures may differ between emotions. Such knowledge may help unravel the conundrum of why mean emotion intensity also captures virtually all variability information when predicting mental health and well-being, and help understand profiles of (mal)adaptive emotion functioning.

A Multiway Approach to Studying Emotion Dynamics

Understanding emotion dynamics requires researchers to consider multiple dimensions simultaneously (Jolly & Chang, 2018). In the current study, the variation in adolescents' emotion scores over time can be represented in a three-way data-array that consists of the dimensions (or modes) emotion (*e*, with 12 entities), dynamic characteristics (*d*, 4 entities), and individual adolescents (*i*, 246 entities), see Figure 1. We use three-mode principal component analysis (3MPCA, Kiers & Van Mechelen, 2001) to summarize the heterogeneity in this three-dimensional dataset into a smaller number of components, which allows us to examine the redundancy of emotion dynamic measures in adolescents. This 3MPCA method provides a core array which describes the interaction among the components of the three modes. This core array tells us whether individual differences in emotion dynamics organize themselves into identifiable profiles. For example, one profile (of emotions *x* dynamics *x* individuals) might be characterized by low intensity positive emotions and *high* variability of negative emotions, while a second profile might be characterized by low intensity positive emotions and *low* variability of negative emotions. Regular two-mode PCA does not allow for the identification of such profiles because it ignores the heterogeneity on the individual level by averaging over mode *i*.

These emotion dynamic profiles (of emotions *x* dynamics *x* individuals) are also interpreted by examining their correlations with external variables. Previous work showed the *social* domain to be particularly relevant when it comes to adolescents' emotional experiences (Somerville, 2018). For example, positive affect intensity was related to fewer negative social experiences, while negative affect intensity has been found to be related to more negative as well as fewer positive social experiences among adolescent girls (Flook et al., 2011). Physical responses to social evaluation and rejection that are indicative of arousal, such as HPA axis responses and pupil dilation, are also larger in adolescents than children (Silk et al., 2012; Stroud et al., 2009). Such exaggerated responses to emotionally salient stimuli in adolescents have also been found in studies examining brain circuitry (Somerville, 2013). We therefore explore how emotion dynamic profiles identified in the 3MPCA are associated with the proportions of four different social experiences during the study period: feeling comfortable, accepted, judged, and threatened when in the company of other people.

Additionally, we also examine the association between emotion dynamic profiles and depressive symptoms, as well as with the personality characteristics neuroticism and extraversion. Dysregulated emotional functioning is hypothesized to be a transdiagnostic factor underlying many forms of psychopathology (Cole et al., 2008, Miu et al., 2022), and atypical emotion dynamics have been linked to depressive symptoms in youths, both concurrently and prospectively (Reitsema et al., 2021). The personality traits neuroticism and extraversion both contain a strong affective component

(Larsen et al., 2020). For example, neuroticism is frequently described as the opposite of emotional stability, and many studies in adults indeed reported an association between neuroticism and heightened negative affect variability (Houben et al., 2015, but see Kalokerinos et al., 2020). Combined, these analyses allow us to examine the redundancy of emotion dynamic measures in adolescents, identify individual profiles of emotion dynamic patterns, and explore how these profiles associate with individual characteristics and social experiences.

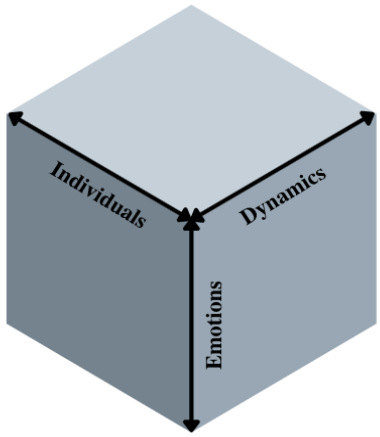
Table 1

Dynamic conceptions of emotions and their components

Measure	Definition	Calculation
Intensity	Average emotional intensity score	Mean (*M*) of emotion or component scores
Variability	Overall amplitude/ range of fluctuations	Within-person *SD* or variance
Instability	Magnitude and temporal dependency of fluctuations	Mean squared successive difference (*MSSD*) scores
Inertia	Temporal dependency or carry over between measurements	Within-person autocorrelation Within-person autoregressive slope

Figure 1

Three-way data array consisting of the modes emotions, dynamics, and individuals



Method

Sample

Data were collected from 329 adolescents aged 13 to 16 years (M_{age}=14.19, 59% female) by Van Roekel and colleagues (2013, 2015). Our inclusion criteria were (1) complete baseline assessment on the variables of interest, namely, demographic information, the personality scales neuroticism and extraversion, and depressive symptoms (excluding 6 participants); and (2) at least 50% completed momentary assessments of emotions and social experiences (≥27 assessments) over

the six day period (excluding 77 participants). These criteria resulted in a final sample of 246 adolescents (75%).

Included participants completed on average 40.9 (*SD*= 7.34) momentary assessments (see Table 1), compared to an average of 18.6 (*SD*= 6.44) for excluded participants. Compliance among both included and excluded participants associated with gender, as women completed slightly more momentary assessments (*M*= 38.24, *SD*= 10.89) than men (*M*= 35.40, *SD*= 11.17, *t*= 2.19, *p*= 0.03), on average, but there was no association between compliance and age, depressive symptoms, neuroticism, or extraversion.

We examined whether excluded participants differed from the selected final sample regarding gender, age, their baseline depression symptoms, neuroticism, and extraversion, and their momentary assessment scores on emotions and social experiences (see Supplementary Table S1A). Included participants did not differ significantly from excluded participants on gender, age, and baseline scores on depression, neuroticism, and extraversion. However, their positive affect ratings were on average slightly higher (*d*= 0.17 across all positive emotions) and their negative affect ratings slightly lower (*d*= -0.13 across all negative emotions) compared to excluded participants. Additionally, included participants reported a slightly higher proportion of social experiences during which they felt comfortable and accepted (see Supplementary Table S1A).

Baseline Assessment

Demographic variables included age and gender. Neuroticism and extraversion were assessed with two 12-item subscales of the Revised Junior Eysenck Personality Questionnaire Short Form (JEPQR-S; Corulla, 1990; Scholte & de Bruyn, 2001). Each item was answered on a binary scale (ranging from *0= no* to *1=yes*). An example item of the Neuroticism subscale is: “Do you worry about things that might happen?”. Depressive symptoms were measured with the Center for Epidemiological Studies Depression Scale (CES-D, Radloff, 1977), which consists of 20 items each answered on a 4-point Likert scale (ranging from *1= rarely or none of the time* to *4= most or all of the time*). An example item of the CES-D is: “I was bothered by things that usually don’t bother me”. The neuroticism, extraversion, and depressive symptoms scales showed satisfactory reliability in this sample, with omega coefficients ω= 0.75, ω= 0.81, and ω= 0.91, respectively.

Experience Sampling

Adolescents were assessed 9 times per day at semi-random intervals (of 90 minutes each) during 6 days via smartphones provided by the researchers. This resulted in a total of 54 possible assessments, although eight participants were able to continue with the assessments a day longer

because of a technical difficulty with the questionnaire application. Items were derived from previous experience sampling studies (e.g., Peeters, Berkhof, Delespaul, & Rottenberg, 2006; Wichers et al., 2007; see also van Roekel et al., 2013, 2015).

At each assessment moment, participants rated the intensity of 12 emotions on a 7-point Likert scale, ranging from (1) *not at all* to (7) *very much.* The emotions were feeling cheerful, happy, energetic, joyful, content, relaxed, anxious, worried, irritable, insecure, down, and guilty. Participants also reported whether they were alone or in social company, and specified whether this was either family, friends, classmates, or other company. Split-half analyses of the data (Hektner et al., 2007) showed satisfactory consistency of these items across the measurement period (see Supplementary Table S2A). Ratings from the first half of the study period were positively and significantly correlated with ratings from the second half for all except two items ("With whom are you right now?" and "I feel threatened in this company").

Social experiences were indexed by four items reflecting participants' appraisal of their current company, rated on a 7-point Likert scale ranging from (1) *not at all* to (7) *very much*. These items reflected *acceptance* ("I feel accepted in this company"), *comfort* ("I feel comfortable in this company"), *threat* ("I feel threatened in this company") and *judgment* ("I feel judged in this company"). For the purpose of this study, we dichotomized the responses (ratings higher than 4 were coded as 1) to be able to calculate the proportions of each social experience for each participant across the study period. These proportions were calculated relative to the total number of assessments the participant was in the company of others. Additionally, we calculated the proportions of each type of company; family, friends, classmates, and others. The proportions of social experiences and type of social company could help interpret the profiles of emotional experience we aimed to identify with the 3MPCA model.

Analysis

Preprocessing of the data. The total set of variables can be represented in a three-way data-array, consisting of the modes emotion *e* (with 12 entities), dynamic characteristic *d* (4 entities), and individuals *i* (246 entities). Following our pre-registration (downloadable via https://osf.io/kp95z/?view_only=7b2679275f2741dd926643ba2a46cb28), we calculated the dynamic estimates for each individual on each emotion as follows: Emotional intensity was defined as the mean emotion score (*M*) over all momentary assessments. Emotional variability was defined as the intra-individual standard deviation (*SD*) over all momentary assessments. Instability was defined as the mean squared successive difference score (*MSSD*) over all momentary assessments, calculated by averaging the absolute successive difference scores between all subsequent momentary assessments

per participant. Finally, inertia was defined as the autoregressive correlation coefficient between an emotion at time *t-1* and time *t*. For instability and inertia, overnight assessments were excluded to ensure a relatively equal time window between assessments. The data were centered across individuals for each dynamic measure of each emotion. Additionally, data were normalized (rescaled to standard scores) within emotion dynamic measures to eliminate scale range difference of these measures (Kiers & Van Mechelen, 2001). These calculations were conducted using the statistical software R. The code can be downloaded from https://osf.io/kp95z/?view_only=7b2679275f2741dd926643ba2a46cb28

3MPCA model selection and fitting. On the resulting data, a 3MPCA was conducted based on the Tucker3 model (Kiers & Van Mechelen, 2001) with up to five individual-mode components, four dynamic-mode components, and four emotion-mode components. Selection among component solutions was based on the convex-hull procedure, which automates the visual inspection of the scree plot that displays the complexity of the model under consideration against the model fit (Ceulemans & Kiers, 2006; Wilderjans, Ceulemans, & Meers, 2013). The stability of the final solution was checked using a split-half procedure. Simple component structures for the three modes and their interactions were obtained through orthogonal Joint Orthomax rotation using standard weights, but without weights for the individual-mode. These analyses were performed with Matlab (2019), using the program Tucker.m (Kiers et al., 2001). The script for these analyses can be downloaded from http://kiers.webhosting.rug.nl/.

Interpretation of the components. The individual-mode component structure was interpreted using Pearson correlations with auxiliary variables, which were individual characteristics including age, gender, depressive symptoms, neuroticism, and extraversion, and social experiences such as the proportion of feeling comfortable in other people's company during the sampling period, and the proportion of assessments spent in the company of family, friends, classmates, and other people. Correlations were interpreted as small (.10 to .19), moderate (.20 to .29) or large (.30+) in magnitude (Cohen, 1992); our smallest Effect Size of Interest (SESOI) was r= .10, comparable to the commonly used threshold for a small correlation coefficient.

Results

Data Preprocessing and the Problem of Limited Emotion-item Variance

Basic descriptive statistics for the individual-mode matricization of the dataset are provided in Table 2. For a considerable number of participants, autocorrelation estimates could not be calculated (N= 91, 36%) because their emotion scores showed too little variance over the assessment period (see Table 2 column 7 for the number of missing autocorrelations per emotion), in line with

our introduction paragraphs (i.e., no intense negative emotions). The 155 participants that provided enough variability for autocorrelations constitute a subgroup of adolescents whose reported emotional experiences were more dynamic. The data of this subgroup was used to fit our "primary 3MPCA model".

We addressed the problem of low item-variance leading to many missing autocorrelations in two different ways. First, instead of estimating dynamic parameters for each of the 12 emotions separately, we took a conventional solution and used *composite affect scales* instead (see Introduction, from this point on referred to as the *affect scale 3MPCA model*). The 12 emotions were averaged into four broader affect constructs that covered the valence and arousal dimensions of the affect circumplex model (Russell, 1980, see also Posner et al., 2005 for a review): High-arousal positive affect (composed of cheerful, energetic, happy, and joyful), low-arousal positive affect (content, relaxed), high-arousal negative affect (anxious, insecure, irritable, and worried), and low-arousal negative affect (depressed, guilty). This approach reduced the number of missing autocorrelation estimates to 15 (6% of 246), and allowed us to fit a 3MPCA model with data from 231 participants (Supplement S4).

The second way in which we handled the missing autocorrelations was through data imputation. A 3MPCA model was fitted on a pooled dataset combining five different imputation iterations based on predictive mean matching (N= 246, Supplement S5, from this point on referred to as the *imputed 3MPCA model*). Finally, these three model solutions were compared; the primary 3MPCA model versus the affect scale 3MPCA model versus the imputed 3MPCA model. The results of these three models and their limitations are discussed in detail below.

Table 2

Descriptive statistics of the final sample (N= 246)

	Mean (*SD*)	**Range**	**Proportion (*M*, *SD*)**	***SD* (*M*, *SD*)**	***MSSD* (*M*, *SD*)**	**Autocorrelation (*M*, *SD*, $N_{missing}$)**	
Baseline assessment							
Age	14.20 (0.50)	13-16					
Gender (female, %)	65%						
Depression	30.0 (8.18)	20-66					
Neuroticism	4.32 (2.88)	0-12					
Extraversion	8.38 (2.12)	0-10					
Experience sampling							
Measurements	40.7 (7.49)	23-63					
Time between measurements[a]	100.61 (76.02)	3-875					
Social experiences							
In company	25.3 (7.68)	8-45	0.62 (0.16)				
Family	9.30 (5.92)	0-27	0.35 (0.16)				
Friends	4.49 (4.00)	0-26	0.18 (0.14)				
Classmates	10.08 (3.33)	0-20	0.42 (0.14)				
Others	1.00 (1.58)	0-14	0.05 (0.07)				
Feeling comfortable	23.12 (8.26)	4-44	0.91 (0.14)				
Feeling accepted	23.46 (8.30)	5-44	0.93 (0.13)				
Feeling judged	1.63 (3.49)	0-30	0.06 (0.23)				
Feeling threatened	0.26 (0.74)	0-7	0.01 (0.03)				
Emotions							
Cheerful	4.83 (0.85)	1.96-6.97		1.27 (0.43)	2.95 (2.14)	0.19 (0.21)	0
Content	5.40 (0.75)	3.07-7		1.08 (0.41)	2.28 (1.82)	0.12 (0.22)	1
Happy	5.63 (0.73)	3.29-7		0.92 (0.38)	1.64 (1.41)	0.17 (0.21)	4
Energetic	4.80 (0.87)	1.98-6.87		1.26 (0.39)	2.91 (1.86)	0.17 (0.21)	0
Relaxed	5.07 (0.85)	2.11-6.92		1.23 (0.39)	2.94 (2.01)	0.12 (0.21)	0
Joyful	5.34 (0.73)	3.44-6.97		1.10 (0.39)	2.27 (1.72)	0.16 (0.23)	0
Insecure	1.48 (0.57)	1-5.39		0.72 (0.46)	1.22 (1.29)	0.13 (0.22)	29
Anxious	1.27 (0.38)	1-3.39		0.51 (0.44)	0.78 (1.08)	0.08 (0.19)	62
Irritable	1.82 (0.72)	1-4.64		1.12 (0.57)	2.75 (2.53)	0.09 (0.19)	11
Worried	1.62 (0.65)	1-4.76		0.85 (0.47)	1.54 (1.48)	0.14 (0.24)	17
Depressed	1.55 (0.59)	1-4.07		0.83 (0.50)	1.49 (1.48)	0.14 (0.24)	23
Guilty	1.32 (0.42)	1-3.27		0.58 (0.48)	0.93 (1.17)	0.13 (0.24)	65

Note. N= 246. Average proportion calculated across the EMA study period. [a]Within days, in minutes.

The Primary 3MPCA Model

The Tucker3 analysis reached a good balance between fit and complexity at 11 components; three emotion-mode components, three dynamic-mode components, and five individual-mode components. This "primary model" explained 61.64% of the variation in emotion data. To scrutinize the stability of this mode component structure, we fit the model twice, using two random halves of the data, and observed high congruence (all Tucker's congruence coefficients >.96).

Simple component structure. The emotion-mode and dynamic-mode component scores helped identify profiles of emotional experiences. The first emotion-mode component comprised intense positive emotions and was coined *positive affect* (see Table 3). The second emotion-mode component captured the intensity of the negative emotions (see Table 3) and was therefore labeled *negative affect*. The third emotion-mode component was characterized by high intensity irritability, and therefore labeled as *irritability*.

The dynamic-mode component structure was formed by three components (see Table 4). The first component was characterized by strong autocorrelation between emotion ratings and therefore labeled *inertia*. The second component combined high scores on the *SD* and the *MSSD* of emotion ratings and was labeled the *lability* component. Finally, the third component comprised high mean intensity of emotion ratings and was coined *intensity*.

Table 3
Emotion-mode component scores for the 3MPCA.

	Positive affect	Negative affect	Irritability
Cheerful	**0.42**	-0.05	0.03
Content	**0.41**	0.01	-0.01
Happy	**0.39**	0.05	-0.07
Energetic	**0.43**	0.00	-0.06
Relaxed	**0.40**	-0.07	0.10
Joyful	**0.41**	0.02	-0.00
Insecure	-0.02	**0.48**	-0.10
Anxious	0.02	**0.41**	-0.05
Irritable	0.00	0.00	**0.98**
Worried	0.01	**0.46**	0.06
Depressed	0.01	**0.49**	0.08
Guilty	0.01	**0.38**	0.02

Note. Component scores equal to or higher than 0.20 are printed in **bold**.

Table 4

Dynamic-mode component scores for the 3MPCA.

	Inertia	Lability	Intensity
Mean	-0.00	-0.00	**1.00**
SD	0.19	**0.71**	0.01
Autocorrelation	**0.96**	-0.00	-0.00
MSSD	-0.19	**0.70**	-0.01

Note. Component scores equal to or higher than 0.20 are printed in **bold**. *MSSD*= mean-squared successive difference score; *SD*= standard deviation.

Core-array: individual-mode components. Individual-mode components were interpreted by inspecting the core-array, which shows the interactions between emotion- and dynamic-mode components. The elements in this array can be thought of as regression weights that show how important each combination of emotion- and dynamic-mode components are in predicting the original data (Kroonenberg, 2008). Individuals are not clustered into separate subgroups but each individual has their own unique profile of individual-mode component scores in the core-array. For example, an individual may have high scores on one of these components but low scores on another. The elements in the core-array and the percentage of explained variance associated with each are shown in Table 5. In total, five individual-mode components were identified with the 3MPCA model. Most variance was explained in the second individual-mode component, by the interaction between the emotion-mode *positive affect* and the dynamic-mode *lability* (*SD*/*MSSD*; 17.11%). Second most variance was explained in the first individual-mode component by the interaction between the emotion-mode *positive affect* and dynamic-mode *intensity* (9.84%).

First, an individual-mode component *high intensity PA* was identified for adolescents who reported high levels of positive affect (vs. low PA for adolescents with a negative score). Second, an individual-mode *emotional stability* component was identified for adolescents who reported low lability across all three emotion-mode components. The third individual-mode component which we called *stable irritability* combined low *emotional lability* with *irritability*. Adolescents scoring high on this component were characterized by low variability and instability of irritability (vs. low scorers reporting highly variable and instable irritability). The fourth individual-mode component was called *PA/NA inertia* and combined high *inertia* with the *positive affect* and *negative affect* components. Fifth and finally, a *high intensity and lability NA* component captured the interaction of *negative affect* with the *emotional intensity* and *lability* dynamic-mode components. To conclude, these results suggest that lability and inertia are rather general phenomena that cut across the specific

emotions, while individual differences in positive affect and irritability stand out as major forces in adolescent emotion landscapes.

Table 5

Core array of the 3MPCA model showing the component scores and the percentages of explained variance.

	Individual-mode components:									
	Component 1		**Component 2**		**Component 3**		**Component 4**		**Component 5**	
	Scores	% EV	Scores	% EV	Scores	% EV	Scores	% EV	Scores	% EV
Positive affect component										
Inertia	-5.41	0.31	3.04	0.19	-1.02	0.04	**18.63**	4.98	-4.38	0.20
Lability	-2.85	0.15	**-35.47**	17.11	-3.87	0.15	-0.27	0.00	4.90	0.18
Intensity	**26.93**	9.84	9.77	1.30	-0.44	0.00	1.20	0.02	-7.08	0.52
Negative affect component										
Inertia	-2.79	0.08	2.83	0.11	0.28	0.00	12.53	1.84	6.50	0.61
Lability	-2.56	0.09	**-14.12**	3.73	-7.11	0.32	3.15	0.09	**20.45**	5.54
Intensity	-4.92	0.33	-1.73	0.11	-2.55	0.05	1.33	0.01	**17.31**	4.02
Irritability component										
Inertia	-1.16	0.00	2.79	0.05	-0.13	0.01	4.95	0.24	-0.80	0.00
Lability	-5.22	0.23	-12.05	1.81	**-19.96**	5.06	0.29	0.00	3.32	0.16
Intensity	-4.69	0.24	1.07	0.02	-9.58	1.27	-1.076	0.02	6.35	0.58

Note. %EV = percentages explained variances of rotated components for each combination of components. Core elements with loadings higher than 10 are highlighted, and with more than 2% explained variability are in **bold**. *Individual-mode component labels: 1*= high intensity PA; *2*= emotional stability; *3*= stable irritability; *4*= high PA/NA inertia; *5*= high intensity and labile NA.

External correlations of the individual-mode components. The five individual-mode components were now contextualized using Pearson's correlations (*r*) with individual characteristics and social experiences. Among the individual-mode components, only the third component *stable irritability* was unrelated to external factors (see Figure 2 and Supplementary Table S3A). Age was unrelated to individual-mode components, perhaps because the variable was restricted (age 11-16).

High intensity PA. The first individual-mode component ("*high intensity PA*") was negatively correlated with depressive symptoms (r= -0.25, p< .01) and neuroticism (r= -0.26, p< .01) but not with extraversion, and positively with feeling accepted as well as comfortable in other people's company (r= 0.30 and r= 0.37, respectively, both p's< .001), but not with feeling threatened nor with feeling judged. This means that adolescents who more frequently experienced social situations in which they felt comfortable or accepted also reported higher mean levels of PA.

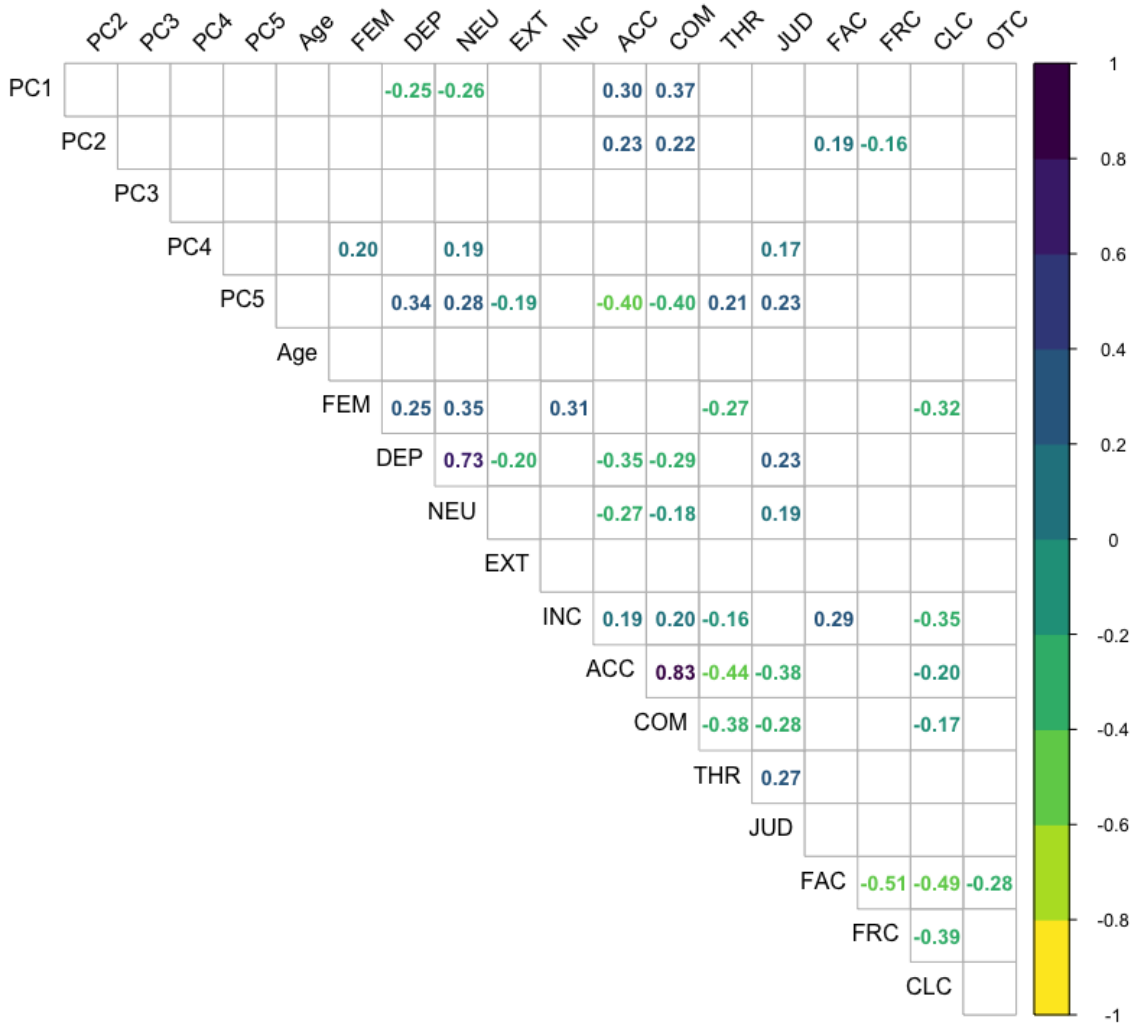
Emotional stability. The second individual-mode component ("*emotional stability"*) correlated positively with feeling accepted as well as feeling comfortable in social situations (r= 0.23 and r= 0.22, respectively, both p's< .01) and also with family contact (r= 0.19, p< .05). However, it correlated negatively with the proportion of social experiences with friends (r= -0.16, p< .05). Surprisingly, this component did not associate with neuroticism.

High PA/NA inertia. The fourth individual-mode component ("*high PA/NA inertia*") exhibited a positive correlation with being female (r= 0.20, p< .05) and with neuroticism (r= 0.19, p< .05), and also with a higher proportion of feeling judged in social situations (r= 0.17, p< .05). In other words, adolescents who experienced more "mood spillover" between measurements also felt judged more frequently in other people's company.

High intensity and labile NA. Out of all the individual-mode components, the fifth one ("*high intensity and labile NA")* correlated with most of the auxiliary variables; higher neuroticism (r= 0.28, p<.001) and depressive symptom scores (r= 0.34, p< .001) and lower extraversion (r= -0.19, p< .05). It also correlated negatively with feeling accepted and feeling comfortable in other people's company (both r's= -0.40, both p's< .001), but positively with feeling threatened and feeling judged (r= 0.21 and r= 0.23, respectively, both p's <.01). The inverse correlations of this component with feeling accepted and feeling comfortable (-0.40) were the largest correlations between all individual-mode components and auxiliary variables in this study.

Figure 2

Pearson's correlations (r) between individual-mode components, individual characteristics, and social experiences.



Note. Correlations $p<.05$ shown in color. All values are provided in Supplement Table S1A. **ACC**= feeling accepted (prop.); **CLC**= with classmates (prop.); **COM**= feeling comfortable (prop.); **DEP**= depressive symptoms; **EXT**= extraversion; **FAC**= with family (prop.); **FEM**= female; **FRC**= with friends (prop.); **INC**= in company (prop.); **JUD**= feeling judged (prop.); **NEU**= neuroticism; **PC**= individual-mode component (1-5); **OTC**= with other people (i.e., not family, friends, or classmates, prop.); **THR**= feeling threatened (prop.).

Solutions to the Problem of Limited Emotion-Item Variance

In this section we present the results of two solutions to account for the problem of limited emotion-item variance (see section *Data preprocessing and the problem of limited emotion-item variance* on page 10 for details). First, we averaged the 12 emotions into four composite affect scales of low versus high arousal PA or NA (the affect scale 3MPCA model). Second, we imputed the missing autocorrelations using a multiple imputation procedure (the imputed 3MPCA model). The estimated model structures were largely similar to that of the primary 3MPCA model, as we derived a 2x3x5 model using composite affect scales and a 3x3x5 model using imputed autocorrelations (for the complete results, see Supplement S4 and S5).

Dynamic-mode and emotion-mode structures. All models identified the same three dynamic-mode components: an intensity component, a lability component (*SD*/*MSSD* combination), and an inertia component. The emotion-mode structures were similar as well, except that the *irritability component* dissolved in the affect scale 3MPCA model, because the irritability item was part of the composite high-arousal negative affect scale. In this model, two emotion-mode components were identified: one corresponding to positive affect and one to negative affect. The individual-mode component structures were also highly similar, and often only differed in sign of the loading patterns (positive versus negative). In a PCA model, the relative magnitude and sign *patterns* are thought to be meaningful, while the signs of loadings and scores are arbitrary (Jolliffe & Cadima, 2016). Geometrically, the principal components for each mode can be viewed as a coordinate system into which the elements of the mode are projected, with the loadings as coordinates. Changing the sign pattern (i.e., flipping the signs of all loadings) does not change the relation between the variables in this geometrical space, it only reverses the interpretation of the component.

Core array: Individual-mode components. Three differences between the core-arrays stand out. First, in the primary model, PA and NA inertia combined into one individual-mode component, whereas the affect scale 3MPCA model yielded two separate combinations of dynamic mode (inertia) and emotion-mode (PA and NA) in the 3MPCA core-array. This resulted in an individual-mode component characterized by high NA inertia (component 3 in Supplementary Table S4C) and one characterized by low PA inertia (component 4 in Supplementary Table S4C). Second, whereas low lability of irritability (*stable irritability*) was an individual-mode component in the primary 3MPCA model, this component was absent in the affect scale model, due to irritability being now part of the NA scale. Third, the dynamic-mode component *intensity* was more substantial in the imputed 3MPCA model, as evidenced in higher *intensity* component loadings on four individual-mode components, although these explained only little variation in the data.

Correlations with external variables. The correlations between the individual-mode components from the two additional 3MPCA models (the affect scale 3MPCA and imputed 3MPCA, see Supplement S4 and S5 for the results) with external variables were generally similar to those found for the primary 3MPCA model (see Figure 2 and Supplementary Table S3A). The individual-mode component *high-intensity PA* correlated negatively with depression and neuroticism, and positively with feeling accepted and comfortable in other people's company in all three models. The individual-mode component *emotional stability* from the affect scale 3MPCA correlated positively with feeling accepted and comfortable in other people's company, similar as was found for the primary 3MPCA. Additionally, this component also showed a negative association with being female, neuroticism (which we did not see with the primary 3MPCA model), and depressive symptoms. As would be expected, the individual-mode component *emotional lability* from the imputed 3MPCA model characterized by the opposite emotion-dynamic combination (i.e., high variability and instability as opposed to low variability and instability) also showed an opposite pattern of correlations with the external variables.

Discussion

In this study, we utilized an ecologically valid data collection method to gain insight into how emotions change over time in adolescents' daily lives, and specifically, to examine the distinctness of different emotion dynamic measures in this population. We used an analytical approach that allowed for the simultaneous decomposition of heterogeneity in the intensity of 12 different emotions (three components) and their dynamics (three components), and individual differences in the interactions between these components (with five individual-mode components). These individual-mode components, or emotion dynamic profiles, were subsequently characterized via their associations with demographic and personality differences and social experiences.

Our models yielded six main findings; (1) the underlying structure of adolescents' emotional experiences could be summarized into three different components for PA, NA, and irritability, while (2) the dynamic nature of these experiences was captured with separate components for emotional intensity, lability, and inertia; (3) the interaction between the PA component and the two dynamic-mode components intensity and lability explained most variation in the data; (4) adolescents' experiences of feeling comfortable and accepted in other people's company associated positively with high intensity PA and emotional stability, and inversely with high intensity and labile NA. Feeling judged and threatened in the presence of others, in contrast, associated positively with high intensity and labile NA. Finally, (6) restricted single-item variance proved to be a substantial

problem and requires more attention from emotion dynamics researchers. These findings are now discussed in detail below.

The Underlying Structure of Adolescents' Emotional Experiences

The primary 3MPCA model helped to identify PA, NA, and irritability as the three cardinal components of adolescents' emotional lives. The circumplex model of affect organizes emotions across valence (positive to negative) and arousal (low to high) dimensions (Russell, 1980), which underlies measures such as the Positive and Negative Affect Schedule (Watson et al., 1997) and the Affect Grid (Russell et al., 1989). One core assumption of such measures was that emotions with the same valence show positive intercorrelations, whereas emotions with opposite valence are independent or show weak negative correlations (Russell, 1980; Watson et al., 1997). Cross-sectional studies using factor analyses and multidimensional scaling also often observe this pattern of covariation of emotions across individuals (Posner et al., 2005), although the within-person link between PA and NA over time can differ markedly between individuals (Fisher et al., 2018).

Although irritability clearly is a negatively valenced emotion, the 3MPCA model presented in this paper identified irritability as a separate third component of adolescent emotional landscapes, next to a NA component composed of the (low-arousal) emotions insecure, down, and guilty, and the (high-arousal) emotions anxiety and worry. Irritability is a universal human emotion with typical developmental manifestations and references to being touchy or easily annoyed, and is close to frustration (Jeronimus et al., 2017) and a precursor to anger (Russell, 2003). During adolescence, irritability is a normative and common experience (Copeland et al., 2015), arguably due to changes in reward and social threat sensitivity (Brotman et al., 2017), and irritability typically declines from early- to late-adolescence (Copeland et al., 2015; Stringaris, 2011). Adolescent depression can be diagnosed by irritability alone, while adult major depressive disorder also requires anhedonia or depressed mood (DSM-5, American Psychiatric Association, 2013). Irritability is a general risk factor in the etiology and course of adolescent psychopathology and is implicated in both internalizing (i.e., behaviors focused inwards) and externalizing difficulties (i.e., behaviors directed outwards; see Evans et al., 2017; Klein et al., 2021).

The circumplex model suggests that irritability and anger are closely related to anxiety and worry, but in the present study, adolescent irritability showed different dynamics over time than other negative emotions. The position of this emotion in the circumplex model might obfuscate how irritability differs from anxiety and worry regarding cognitive appraisals, action tendencies, attributions, and timing, among others (e.g., Russell & Feldman Barrett, 1999, p. 807). For example, irritability and anger precede reactive aggression (aroused/hot) when a contextual trigger elicits an

emotional, impulsive, and defensive or hostile/retaliatory reaction (Warburton et al., 2015). Proactive aggression, in contrast, tends to be calm and deliberated (unaroused/cold) and instrumental to a desired outcome (gain/dominance), and is associated with adolescent's popularity, delinquency, and psychopathy, but not irritability (Hubbard et al., 2010; Warburton et al., 2015). Future research may help us to better understand the prominent role of irritability in the emergence and severity of psychopathology (Evans et al., 2017; Stringaris, 2011).

The Dynamics of Emotions in Adolescence

The 3MPCA model identified three dynamic-mode components in adolescents' emotional experiences, namely, emotional intensity, emotional lability, and emotional inertia. Because the *SD* and *MSSD* loaded on the same component (*lability*), they captured partially overlapping information in emotional change, in keeping with the two-mode PCA analyses conducted by Dejonckheere, Mestdagh et al. (2019) and Wendt et al. (2020). The autocorrelation, often used as an operationalization of emotional inertia, is mathematically related to the *SD* and *MSSD*, although the 3MPCA identified *inertia* as a separate component, also in line with aforementioned two-mode PCA findings. The autocorrelation captures the extent to which an emotion is predictable from its prior state, or in other words, its resistance to change, which has previously been associated with adolescent depression (Kuppens et al., 2010, 2012) and dynamic state transitions (Wichers et al., 2015). Functional emotions show optimal response to context, somewhere in the middle of a hypothetical continuum that runs from being insensitive or "rigid" (emotional inertia) to being "flexible" or "overwhelmed" (emotional instability), see Bos et al. (2018) and Bosley et al. (2019).

The core-array of the primary 3MPCA revealed five individual-mode components describing the interaction between the emotion-mode and dynamic-mode components. Separate individual-mode components for the intensity of positive affect and for general emotional stability (i.e., reflecting both positive and negative affect) were found, as well as one for the intensity and lability of negative affect. Similar results were found by Dejonckheere, Mestdagh et al. (2019) and by Wendt et al. (2020). The interrelation between the *SD*/*MSSD* and the mean of negative affect is most likely partly due to a skewed distribution of negative affect, via the low scores that are common in general population samples, in which cases the *SD* is confounded by the mean (Mestdagh et al., 2018). This was illustrated in the imputed 3MPCA model, where the participants without emotional changes (and thus low emotion-item *SD*'s) reported mean emotion scores at the low poles (in the case of negative emotion items) or high poles (for positive emotion items) of the Likert scales. This magnified the dependency of the *SD* on the mean, and resulted in the conclusion that the dynamic-mode component *intensity* plays a more substantial role in the 3MPCA, via four individual-mode components.

In summary, our results corroborate previous research that showed that emotional intensity is the central character in emotion dynamic data. Although variability indices such as the *SD* and *MSSD* can provide additional information about adolescents' emotional change, this is generally the case when researchers also include the adolescents who report a minimum amount of variability to begin with, and in practice are marked by more intense negative emotions.

The Importance of Positive Emotions During Adolescence

As can be seen in the core array of the primary 3MPCA model solution, the interactions between positive affect (emotion-mode) and the two dynamic-mode components lability and intensity explained most variance in the data (see Table 5). Additionally, these two individual-mode components (*high PA intensity* and *emotional stability*) showed robust associations, including fewer depressive symptoms, lower neuroticism, and higher frequencies of feeling accepted and comfortable in other people's company (Figure 2). Positive emotions signal safety and the fulfillment of primary needs while negative emotions have an alarm function (Tugade, 2010). Negative emotions are therefore more informative than positive emotions, because the price of failing to notice a major threat easily outweighs the costs of a missed opportunity (Öhman & Mineka, 2001; Rozin & Royzman, 2001). In line with this, the dynamics of negative emotions have also been found to play a larger role in explaining psychological well-being in adults (Houben et al., 2015).

A recent meta-analysis of emotion dynamics in children and adolescents identified positive affect intensity (but not negative affect intensity) as a key difference between youth with mental health problems and typically developing youth (Reitsema et al., 2021). These results and our first individual mode component both suggest that the positive interpersonal processes captured by extraversion play a prominent role in adolescence (Larsen et al., 2020). Reward responsiveness and saliency appears to follow an inverted U-shape pattern during adolescence, with a peak in mid-adolescence (Cauffman et al., 2010). Adolescents are typically more sensitive to monetary and social rewards and exhibit reduced impulse control compared to younger and older groups (Spear, 2011). Also anhedonia, an inability to experience pleasure, often emerges over adolescence, and is implicated in depression (Heininga & Kuppens, 2021). Positive affect and interpersonal processes seem to dominate adolescent emotional landscapes.

Social Experiences and Emotion Dynamics in Adolescence

The most salient rewards (and threats) during adolescence appear to be those relevant to the social context, for example, opportunities or threats to social status and acceptance (Crone & Dahl, 2012). Our individual-mode component scores showed that positive social experiences were

positively associated with high intensity PA and negatively with emotional lability and with high intensity and labile NA. High intensity and labile NA (the fifth individual-mode component) was also associated with more frequent negative social experiences.

The type of company was remarkably unrelated to the specific profiles of emotional change. The proportion of contact with family members has previously been associated with emotional stability, although the effect size was small (Jeronimus, 2015). Adolescence is a time of increased independence during which adolescents shift focus from their parents to peers, and spend less time at home (Csikszentmihalyi & Larson, 1984; Schneiders et al., 2007). The family context remains important, however, and being around a parent may help to influence and regulate adolescent's emotions (Silk et al., 2011; Waller et al., 2014). Future studies may help identify differences between categories of social company that are most intimately connected to positive life outcomes.

Limited Emotion Variance Hampers Emotion Dynamics Research

A subset of participants (~40%) reported on their emotions with so little variability that autocorrelations could not be estimated, predominantly with respect to negative emotions. We may have failed to capture certain emotion-eliciting experiences, such as situations leading to feelings of guilt or anxiety, because of the short sampling period (six days) and/or because these experiences are infrequent in general population samples (Zelenski & Larsen, 2000). Furthermore, some adolescents may not have used the full range of responses over time, due to habitual responding, loss of motivation, and lack of understanding (e.g., guilt), which are common problems in ESM research (Scollon et al., 2003; Stone et al., 1991). Early-to-mid adolescence is a developmental period during which formal operational and abstract reasoning skills solidify (Larson et al., 1999) and insight into one’s emotions and abilities to comprehend and recognize complex emotions are still developing.

The primary 3MPCA model was therefore based on two-thirds of the original sample size. These results were compared to two 3MPCA models that were adjusted for the limited variability, using a four-factor emotion scale (combinations of 12 single emotions) which consequently showed more variability and resulted in fewer missing autocorrelation estimates, and additionally, an imputed dataset. The choice for broad emotion constructs based on the convention that each emotion captures a combination of both valence and arousal seems obvious (e.g., Russell, 2003). However, we assert that the richness of emotional experience is not captured by the valence (how positive or negative) and arousal (how exciting or calming) of the emotion alone, which indeed capture ~30% of the variance in emotional experience and expression (see Cowen et al., 2017, 2019). Third, we used a dataset with imputed autocorrelations, which reduced the problem of missingness, but left the *SD*'s of the emotion items untouched, which reduces their relationship (despite their mathematical overlap),

and may introduce bias in the dataset (Jahng et al., 2008). Additionally, as mentioned above, including participants who reported no emotional change in this imputed 3MPCA model magnified the dependency of the *SD* on the mean, and resulted in dynamic-mode component *intensity* playing a more substantial role in the 3MPCA in three individual-mode components.

One approach to reduce single-item lack of variability in emotion-dynamic research could be to assess multiple emotions that are conceptually related (Cowen et al., 2019), for example, feeling angry, mad, or outraged. The counterargument that this does not capture the "category prototype" emotion of anger denies that anger is primarily "a statistical abstraction (…) and not a biological essence" (Barrett et al., 2017, p. 98). Individuals can experience anger differently, also between instances, such as in terms of facial movements, autonomic nervous system activation, intensity, feeling colour, and duration (Barrett, 2017; Darwin, 1872), among others. Perhaps the best remedy to these problems would be a multi-method approach in which ESM is combined with other-reports (e.g., parents, peers, teachers), observation, or auxiliary variables such as physiological measures. Effectively, this means considering additional dimensions beyond the three (emotions, dynamics, adolescents) that were the focus of this analysis.

Limitations of the Study and Future Directions

The major strength of this study is that the variation in adolescents' emotion scores over time was represented and analyzed in a three-way data-array, which allowed us to examine heterogeneity between different emotions, dynamic characteristics, and individual adolescents. Additionally, instead of resorting to the common approach of examining composite negative and positive affect scales, we focused on single emotions in our multiway analysis; the model results were subsequently compared to a similar model based on composite scales. This revealed that, at least among the adolescents in this sample, only using broad affective scales would conceal the major role of irritability in their emotion dynamics. Future research should take into consideration that using broad composite affect scales could obscure the existence of different patterns of dynamics of the single emotions that these scales contain (also see Ernst et al., 2019), and more specific predictors may help us understand the link with differences in health and well-being. Furthermore, while we focused only on correlations between the emotion dynamic profiles and external variables, future research should consider non-linear relationships with outcome measures.

Aside from the limited single-item variance, a few other limitations of our study deserve consideration. First, the momentary assessment sampling period lasted only six days, a short period during which the experiences of some participants differed from their typical experiences. Additionally, a longer assessment period might have enabled us to capture more variance in some

participants' emotion scores. Second, our analysis did not account for varying time intervals between beeps other than excluding overnight intervals. The average time in between measurements was close to two hours (*M*= 100.61 minutes) but the variability was wide (*SD*= 76.02), and this could affect the interpretability of the calculated dynamic measures. Third, most participants reported very few negative social experiences (1/8 or 12.5% of all instances in social company could be coded as negative). In these assessments, participants endorsed both items (i.e., "I feel threatened by this company" and "I feel judged by this company") at least somewhat. The low frequency of negative social experiences may have underpowered the analysis of associations with individual-mode component scores. Another limitation is the relatively narrow age range of 11-16 years for the adolescents in this study which limits the generalizability of our findings, as emotional development is not a linear process and the structure of emotion dynamics may be different in children or younger or older adolescents (Reitsema et al., 2021). Future research should compare individual profiles of emotion dynamics across populations.

Conclusion

Our study identified five distinct individual profiles that describe patterns of adolescents' emotion dynamics through combinations of emotional intensity, lability, and inertia on the one hand, with positive affect, negative affect, and irritability on the other. These individual profiles correlated in different ways with adolescents' positive and negative social experiences, indicating that these profiles capture meaningful interpersonal differences in emotional change. However, our results also illustrate that in short-term momentary assessment studies, capturing within-person change in single emotions is not easy. Future research can expand on this multidimensional approach (e.g., 3MPCA) to emotion data and take this problem of limited variation into account in the study design. We identified key differences in adolescents' emotional experiences and suggest that future work focuses on irritability and positive affect.

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