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Network analysis of ecological momentary assessment identifies frustration as a central node in irritability

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Background: Irritability presents transdiagnostically, commonly occurring with anxiety and other mood symptoms. However, little is known about the temporal and dynamic interplay among irritability-related clinical phenomena. Using a novel network analytic approach with smartphone-based ecological momentary assessment (EMA), we examined how irritability and other anxiety and mood symptoms were connected. **Methods:** Sample included 152 youth ages 8–18 years ($M \pm SD = 12.28 \pm 2.53$; 69.74% male; 65.79% White) across several diagnostic groups enriched for irritability including disruptive mood dysregulation disorder ($n = 34$), oppositional defiant disorder ($n = 9$), attention-deficit/hyperactivity disorder ($n = 47$), anxiety disorder ($n = 29$), and healthy comparisons ($n = 33$). Participants completed EMA on irritability-related constructs and other mood and anxiety symptoms three times a day for 7 days. EMA probed symptoms on two timescales: "since the last prompt" (between-prompt) versus "at the time of the prompt" (momentary). Irritability was also assessed using parent-, child- and clinician-reports (Affective Reactivity Index; ARI), following EMA. Multilevel vector autoregressive (mlVAR) models estimated a temporal, a contemporaneous within-subject and a between-subject network of symptoms, separately for between-prompt and momentary symptoms. **Results:** For between-prompt symptoms, frustration emerged as the most central node in both within- and between-subject networks and predicted more mood changes at the next timepoint in the temporal network. For momentary symptoms, sadness and anger emerged as the most central node in the within- and between-subject network, respectively. While anger was positively related to sadness *within* individuals and measurement occasions, anger was more broadly positively related to sadness, mood lability, and worry *between/across* individuals. Finally, mean levels, not variability, of EMA-indexed irritability were strongly related to ARI scores. **Conclusions:** This study advances current understanding of symptom-level and temporal dynamics of irritability. Results suggest frustration as a potential clinically relevant treatment target. Future experimental work and clinical trials that systematically manipulate irritability-related features (e.g. frustration, unfairness) will elucidate the causal relations among clinical variables. **Keywords:** Irritability; frustration; anger; mood; anxiety; ecological momentary assessment; network analysis.

Introduction

Irritability is a diagnostic criterion in many pediatric disorders including disruptive mood dysregulation disorder (DMDD), oppositional defiant disorder (ODD), anxiety disorders and major depression (Brotman, Kircanski, & Leibenluft, 2017; Klein, Dougherty, Kessel, Silver, & Carlson, 2021; Vidal-Ribas, Brotman, Valdivieso, Leibenluft, & Stringaris, 2016). Irritability is also a very common presenting symptom in youth with attention-deficit/hyperactivity disorder (ADHD) despite not being a diagnostic criterion (Nigg et al., 2020). However, the temporal dynamics and interrelations between irritability and other anxiety and mood symptoms remain unclear. Similarly, irritability, frustration and anger are interrelated (Leibenluft & Stoddard, 2015; Zik et al., 2022). Frustration, defined as the emotional response to blocked goal attainment (Deveney et al., 2013), has been hypothesized to play an important mechanistic role in pediatric irritability (Leibenluft, 2017). Aberrant responses to frustration are thought to be a critical pathophysiological pathway of irritability (Brotman, Kircanski, Stringaris, Pine, & Leibenluft, 2017). Relatedly, negative prediction error, that is, outcomes that are worse than expected (Schultz, 2016), may be exaggerated in youth with irritability (Kircanski et al., 2019). For example, irritable youth may interpret events or situations as "unfair" because their environment fails to meet their expectation of a desired outcome. Although progress has been made in understanding these irritability-related constructs, little is known about how they are conceptually and temporally linked. Taking an innovative approach, this study integrates smartphone-based ecological momentary assessment (EMA) and network analysis to examine how irritability-related symptoms (i.e. grouchiness/crankiness, annoyance, anger, frustration and feelings of unfairness) are connected to each other and to other mood and anxiety symptoms (i.e. worry, sadness, mood lability and happiness).

Conflict of interest statement: No conflicts declared.

Traditional questionnaire- or rating scale-based assessments of emotional states such as anger, frustration or worry are limited by retrospective report and recall bias (Russell & Gajos, 2020). Here, we used smartphone-based EMA to probe symptoms in real time in participants' natural environments. This increases ecological validity, minimizes recall bias and social desirability, and improves reliability via repeated sampling and assessments (Russell & Gajos, 2020). Previous work has linked irritability in youth to laboratory-induced neural (Deveney et al., 2013; Grabell et al., 2018; Perlman et al., 2015; Tseng et al., 2019), behavioral (Deveney et al., 2013; Rich et al., 2007), and affective (Deveney et al., 2013; Perlman et al., 2015; Rich et al., 2007, 2011) responses to frustration. Using EMA to capture real-time symptoms in vivo, this study innovatively extends past findings by leveraging technology and a novel analytic approach to probe how irritability-related constructs are connected to each other and to other symptoms. Critically, repeated assessments of symptoms facilitate investigations of the temporal order and dynamic process between symptoms. This is particularly relevant for research on mood and emotions (Bringmann et al., 2016), as daily fluctuations of these constructs are common. A more granular understanding of their temporal dynamics has the potential to inform targets and timing for interventions, with clinically relevant downstream implications. If dynamic processes between irritability and related mood symptoms can be captured in everyday life through EMA, interventions could be designed, tailored and delivered in a timely and maximally effective way prior to the emergence of the clinical phenomena.

In this study, we analyzed EMA data using a network approach. Network approaches have the potential to improve current understanding of the complex organization of symptoms and related constructs. Unlike traditional conceptualizations of psychopathology, which posit that symptoms are manifestations of an underlying latent cause or disorder, network approaches conceptualize disorders as systems of causally connected, interacting and mutually reinforcing symptoms (Borsboom et al., 2021; Borsboom & Cramer, 2013). In the case of psychopathology, a network typically consists of multiple "nodes" (i.e. symptoms or constructs) and "edges" that connect the nodes (i.e. conditional associations between pairs of nodes after controlling for all other nodes in the network) (Borsboom et al., 2021). Thus, network approaches can delineate the patterns of interrelations between irritability-related symptoms and mood constructs. This is the first study to use network analysis to investigate the symptomatology of irritability.

There are three notable advantages to using network analyses with EMA data. First, network analysis, with time-series data such as EMA, can elucidate temporal precedence of symptoms, a minimum requirement for causality (Pearl, 2000). That is, the symptoms that precipitate the downstream presence of other symptoms in the network can inform causal mechanistic processes (Fisher, Reeves, Lawyer, Medaglia, & Rubel, 2017). Second, using time-series data in a network analysis can reveal the effect that each symptom has on itself, as well as the effect of one symptom on another, from one timepoint to the next while controlling for all the other symptoms in the network (Bringmann et al., 2016). Third, this approach can also reveal within-subject, in addition to between-subject, symptom dynamics (Bringmann et al., 2016; Epskamp, Waldorp, Mõttus, & Borsboom, 2018; Fisher et al., 2017). Within-subject symptom change refers to the extent to which an individual's symptoms (e.g. irritability, frustration and anxiety) vary over time; between-subject symptom change reflects differences in symptoms across participants. Although between-subject networks provide important information about the nature of average associations between symptoms across individuals, it overlooks information about associations between symptoms within individuals across and within time, which has important implications for personalized treatments (Fisher et al., 2017).

Taken together, this study uses EMA to examine how irritability symptoms and other mood and anxiety symptoms are connected within themselves and with each other across time in a transdiagnostic sample (i.e. DMDD, ODD, ADHD, anxiety disorders, and healthy comparisons without diagnoses) of youth with varied degrees of irritability. Although irritability is not a criterion symptom of ADHD, we included youth with ADHD because a significant proportion (~30%–50%) of youth with ADHD also show marked symptoms of irritability and mood dysregulation (Nigg et al., 2020; Shaw, Stringaris, Nigg, & Leibenluft, 2016). Leveraging EMA's repeated measurement of constructs and granular assessment of within-person variability and fluctuation over time (Russell & Gajos, 2020), we also examine whether and how the mean level and variability of EMA measures of irritability are associated with "trait-like" measures of irritability that probe averaged symptoms over a span of time using clinician- (Haller et al., 2020), child- and parent-reports (Stringaris et al., 2012) of the Affective Reactivity Index (ARI).

Methods

Participants and procedures

A transdiagnostic sample of 152 youth ages 8–18 years (Mean age = 12.28, *SD* = 2.53; 69.74% male; 65.79% White) participated in this study (see Table 1 for sample characteristics). Participants were recruited at the NIMH Intramural Research Program and had a primary diagnosis of DMDD (n = 34), ODD (n = 9), ADHD (n = 47), anxiety disorders (n = 29), and healthy comparisons without psychopathology (n = 33). As mentioned

Table 1 Sample characteristics

Characteristic	Total (N = 152)	Diagnostic group				
		DMDD (n = 34)	ODD (n = 9)	ADHD (n = 47)	ANX (n = 29)	HC (n = 33)
Age, mean (*SD*)	12.28 (2.53)	12.18 (2.31)	10.23 (1.53)	12.14 (2.33)	13.04 (2.98)	12.45 (2.61)
IQ, mean (*SD*)	113.89 (12.71)	112.96 (10.44)	108.75 (26.04)	113.54 (12.25)	115.79 (12.86)	113.84 (13.17)
Sex (male), *N* (%)	106 (69.74)	24 (70.59)	5 (55.56)	30 (63.83)	21 (72.41)	20 (60.61)
Race, *N* (%)						
White/Caucasian	100 (65.79)	28 (82.35)	8 (88.89)	26 (55.32)	17 (58.62)	21 (63.64)
African American	15 (9.87)	3 (8.82)	0 (0.00)	6 (12.77)	1 (3.45)	5 (15.16)
Asian American	7 (4.61)	1 (2.94)	0 (0.00)	2 (4.26)	2 (6.90)	2 (6.06)
American Indian	4 (2.63)	0 (0.00)	0 (0.00)	3 (6.38)	1 (3.45)	0 (0.00)
Multi-race	20 (13.16)	1 (2.94)	1 (11.11)	8 (17.02)	7 (24.14)	3 (9.09)
Unknown	6 (3.95)	1 (2.94)	0 (0.00)	2 (4.26)	1 (3.45)	2 (6.06)
Ethnicity, *N* (%)						
Latino/Hispanic	15 (9.87)	1 (2.94)	2 (22.22)	7 (14.89)	4 (13.80)	1 (3.03)
Not Latino/Hispanic	129 (84.87)	31 (91.18)	7 (77.78)	37 (78.72)	22 (75.86)	32 (96.97)
Unknown	8 (5.26)	2 (5.88)	0 (0.00)	3 (6.38)	3 (10.34)	0 (0.00)
Parental education, *N* (%)[a]						
Graduate Degree	80 (74.07)	19 (82.61)	6 (85.71)	17 (73.91)	24 (82.76)	14 (53.80)
College	17 (15.74)	3 (13.04)	1 (14.29)	6 (26.09)	3 (10.34)	4 (15.40)
Partial College	9 (8.33)	1 (4.35)	0 (0.00)	0 (0.00)	1 (3.45)	7 (26.90)
High School or Less	2 (1.85)	0 (0.00)	0 (0.00)	0 (0.00)	1 (3.45)	1 (3.80)
Household income, *N* (%)[b]						
<$39,999	4 (3.92)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	4 (16.67)
$60,000–89,999	7 (6.86)	1 (4.35)	0 (0.00)	1 (4.50)	1 (3.70)	4 (16.67)
$90,000–179,999	45 (44.12)	8 (34.78)	3 (50.00)	11 (50.00)	14 (51.85)	9 (37.50)
>$180,000	46 (45.10)	14 (60.87)	3 (50.00)	10 (45.50)	12 (44.45)	7 (29.16)
Medication, *N* (%)						
Psychotropic	57 (37.50)	28 (82.35)	5 (55.56)	23 (48.94)	1 (3.45)	0 (0.00)
Antidepressants	24 (15.80)	17 (50.00)	3 (33.33)	3 (6.38)	1 (3.45)	0 (0.00)
Stimulants	46 (30.26)	21 (61.76)	2 (22.22)	22 (46.81)	1 (3.45)	0 (0.00)
Non-stimulant	5 (3.29)	4 (11.76)	0 (0.00)	1 (2.13)	0 (0.00)	0 (0.00)
Mood stabilizers	1 (0.66)	1 (2.94)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Anti-convulsant	3 (1.97)	3 (8.82)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Atypical antipsychotics	6 (3.95)	5 (14.71)	1 (11.11)	0 (0.00)	0 (0.00)	0 (0.00)
Parent-ARI, mean (*SD*)	3.89 (3.69)	8.03 (2.79)	6.44 (2.79)	3.66 (3.00)	2.62 (2.71)	0.36 (0.70)
Child-ARI, mean (*SD*)	2.89 (3.18)	4.82 (3.29)	5.44 (4.13)	2.82 (2.93)	2.45 (2.91)	0.70 (1.29)
Clinician-ARI, mean (*SD*)[c]	26.23 (18.27)	37.46 (15.04)	35.94 (14.46)	19.60 (16.57)	14.56 (15.35)	1.23 (1.75)

ADHD, Attention-Deficit/Hyperactivity Disorder; ANX, Anxiety Disorders; ARI, Affective Reactivity Index; DMDD, Disruptive Mood Dysregulation Disorder; HC, Healthy Comparisons; ODD, Oppositional Defiant Disorder.
[a]Missing data in n = 44; % was based on available data.
[b]Missing data in n = 50; % was based on available data.
[c]Missing data in n = 53.

in the introduction, we included youth with ADHD because irritability is an important clinical correlate of ADHD despite not being a diagnostic criterion (Nigg et al., 2020). All participants, except for healthy comparisons, had at least one diagnosis. Secondary diagnosis and comorbid conditions are described in Table S1. Of note, 21 participants with DMDD and 10 participants with ADHD also met criteria for ODD. Participants and their parents were informed of the voluntary nature of study participation and provided written assents and consents prior to enrollment. Study procedures were approved by NIMH IRB. Participants were compensated for their participation.

Youth-reported EMA data were collected between August 2017 and March 2022. The assessment included 21 prompts: 3 prompts per day (morning/before school, afternoon/after school, evening/before bedtime) for 7 days (see Naim et al., 2021; Smith et al., 2022 for details) for a total of 3,192 planned assessments. Prior to data collection, research assistants provided standardized training to familiarize participants with the EMA procedure (e.g. smartphone, protocol, items and a practice prompt). For example, research assistants reviewed each item by providing examples, differentiating between different emotions and feelings (e.g. anger vs. frustration), and guiding participants through a practice prompt. Participants used either a personal or a study-provided smartphone to complete the EMA. During the COVID-19 pandemic, EMA training occurred remotely over a video platform, and smartphones were mailed to participants as needed. Following the week of EMA, participants and their parents completed the ARI as a retrospective rating scale (Stringaris et al., 2012) and clinicians completed the clinician-rated ARI (Haller et al., 2020) assessing irritability over the past week. Length of EMA period and number of prompts per day are consistent with previous EMA studies assessing mood symptoms (Hall, Scherner, Kreidel, & Rubel, 2021). To be consistent with the commonly used standards in EMA compliance threshold (Fred Wen, Schneider, Stone, & Spruijt-Metz, 2017) and our prior EMA studies (Naim et al., 2021; Smith et al., 2022), only participants with ≥6 completed prompts were included (3 participants were excluded from the final N = 152). The mean compliance rate of the sample was 79.39% (*SD* = 18.31%), consistent with the average compliance rate of 78.3% across 42 studies using EMA in youth (see Fred Wen et al., 2017 for a review).

Measures

EMA items. The full EMA protocol assessed various dimensions of mood and anxiety symptoms (Naim et al., 2021; Smith et al., 2022). The current analyses focused on irritability-related symptoms (i.e. grouchiness/crankiness, annoyance/anger, frustration and feelings of unfairness) and other mood and anxiety symptoms (i.e. worry, happiness, sadness and mood lability), sampling across two different affective chronometries: momentary (i.e. at the time of the prompt) versus between-prompt (i.e. since the previous prompt) symptoms. Items at these two different time scales were designed to capture symptoms that are fleeting or occur more momentarily (e.g. annoyed/angry, happy, sad) versus symptoms that take time to develop or tend to linger throughout the entire day (e.g. frustration).

Five items assessed symptoms *at the time of the prompt* (i.e. momentary symptoms). These items were: (1) "I felt *annoyed or angry*"; (2) "I felt *worried or scared*"; (3) "I felt *happy*"; (4) "I felt much *more giddy, silly, or happy than usual*"; and (5) "I felt *unhappy, sad, or miserable*". Items were rated on a 5-point Likert scale from 1 = "not at all" to 5 = "extremely."

Another five items assessed symptoms *since the previous prompt* (i.e. between-prompt symptoms) to capture irritability and related symptoms throughout the entire day. These items are: (1) "I was feeling generally *grouchy or cranky*"; (2) "I felt *frustrated*"; (3) "Something was *unfair*"; (4) "I felt *worried or scared*"; and (5) "My *mood changed a lot.*" Items were rated on 5-point Likert scales (1 = "none of the time" to 5 = "the whole time" for Item 1, and 1 = "not at all" to 5 = "extremely" for Items 2–4).

Child-, parent- and clinician-reported irritability. - Following EMA, irritability symptoms over the past week were also assessed using the ARI (Stringaris et al., 2012), completed by multiple informants including children themselves, their parents, and a clinician. The child- and parent-report of ARI is a 6-item short scale assessing the frequency, duration, and severity of irritability with good psychometrics (Mulraney, Melvin, & Tonge, 2014; Stringaris et al., 2012; Tseng et al., 2017). Items were rated on a 0–2 scale (0 = not true, 2 = certainly true) and yielded a total score of 0–12. Internal consistency in this sample was .90 for both the child- and parent-ARI. The clinician-rated ARI is a 12-item semi-structured interview with parents and children about the child's irritability, including the frequency, severity and duration of temper outbursts and irritable mood between outbursts, and associated functional impairment in home, school and peer settings (Haller et al., 2020). It has good validity, inter-rater reliability (kappa = .90), and internal consistency (α's = .89) (Haller et al., 2020). Internal consistency of the clinician-ARI in this sample was .74.

Data analyses

We conducted network analysis on EMA data using the multilevel vector autoregressive (mlVAR) model as implemented with the *mlVAR* package in R (Epskamp, 2020; Epskamp, Waldorp, et al., 2018), which estimates how well each variable at one timepoint predicts all other variables at the next timepoint within a multilevel framework to account for data dependence due to timepoints within subjects. Analyses were conducted separately for items assessing symptoms *at the time of the prompt* (5 nodes) versus *since the previous prompt* (5 nodes), given the different chronometries. The mlVAR model generated three networks. The first is a *temporal (within-subject) network* that estimates the lag-1 associations between nodes from one timepoint to the next while controlling for all other nodes in the network (Epskamp, Waldorp, et al., 2018). The second is a *contemporaneous (within-subject) network* that estimates within-subject associations between nodes within one timepoint, controlling for temporal relationships and all other nodes in the model; this is thought to capture causal processes that occur faster than the interval between timepoints (Epskamp, Waldorp, et al., 2018). The third is a *between-subject network* that estimates associations between means of the variables across timepoints and across subjects, akin to network obtained using cross-sectional data (Epskamp, Waldorp, et al., 2018).

All network structures were graphed using the *qgraph* package in R (Epskamp, Cramer, Waldorp, Schmittmann, & Borsboom, 2012). Networks consist of circles (i.e. nodes) representing variables, and blue and red edges indicating positive and negative associations (at $p < .05$), respectively, with thicker edges indicating stronger associations. Further, node strength (i.e. the sum of absolute edge weights) was computed as the centrality index to quantify node importance (Epskamp et al., 2012). Higher values indicated greater centrality (Bringmann et al., 2016). The most central nodes are the ones most strongly connected to other nodes and therefore assumed to influence the entire network.

To evaluate whether and how EMA measures of irritability-related symptoms were associated with stable, "trait-like" measures of irritability using rating scales, we examined the mean level and variability (i.e. *SD*) of EMA measures of irritability (i.e. grouchiness/crankiness, annoyance/anger, frustration and feelings of unfairness) across 21 data points and their correlations with clinician-, child- and parent-reports of the ARI. We also examined root mean square of successive differences (RMSSD), which captured both variability and temporal dependency (Jahng, Wood, & Trull, 2008; Schoevers et al., 2021), as an index of symptom fluctuations.

Results

Descriptive statistics

Table 2 presents means and SDs for all EMA items across 21 timepoints for the total sample. See Table S2 for results by diagnostic groups.

Momentary mood symptoms

The *temporal within-subject* network indicated that feeling "more giddy, silly, or happy than usual" at one timepoint predicted feeling "worried or scared" at the next timepoint (fixed effect coefficient = .07, $p = .03$; Figure 1A). The *contemporaneous within-*

Table 2 Descriptive statistics of the EMA measures

EMA constructs	Range	Mean	*SD*
Momentary mood symptoms			
Annoyed or angry	1–5	1.38	0.55
Worried or scared	1–5	1.22	0.34
Happy	1–5	3.07	0.84
More giddy, silly, or happy than usual	1–5	1.49	0.61
Unhappy, sad, or miserable	1–5	1.32	0.42
Between-prompt mood symptoms			
Grouchy or cranky	1–5	1.44	0.49
Frustrated	1–5	1.61	0.68
Something was unfair	1–5	1.49	0.62
Worried or scared	1–5	1.29	0.37
Mood changed a lot	1–5	1.68	0.68

EMA, Ecological Momentary Assessment.

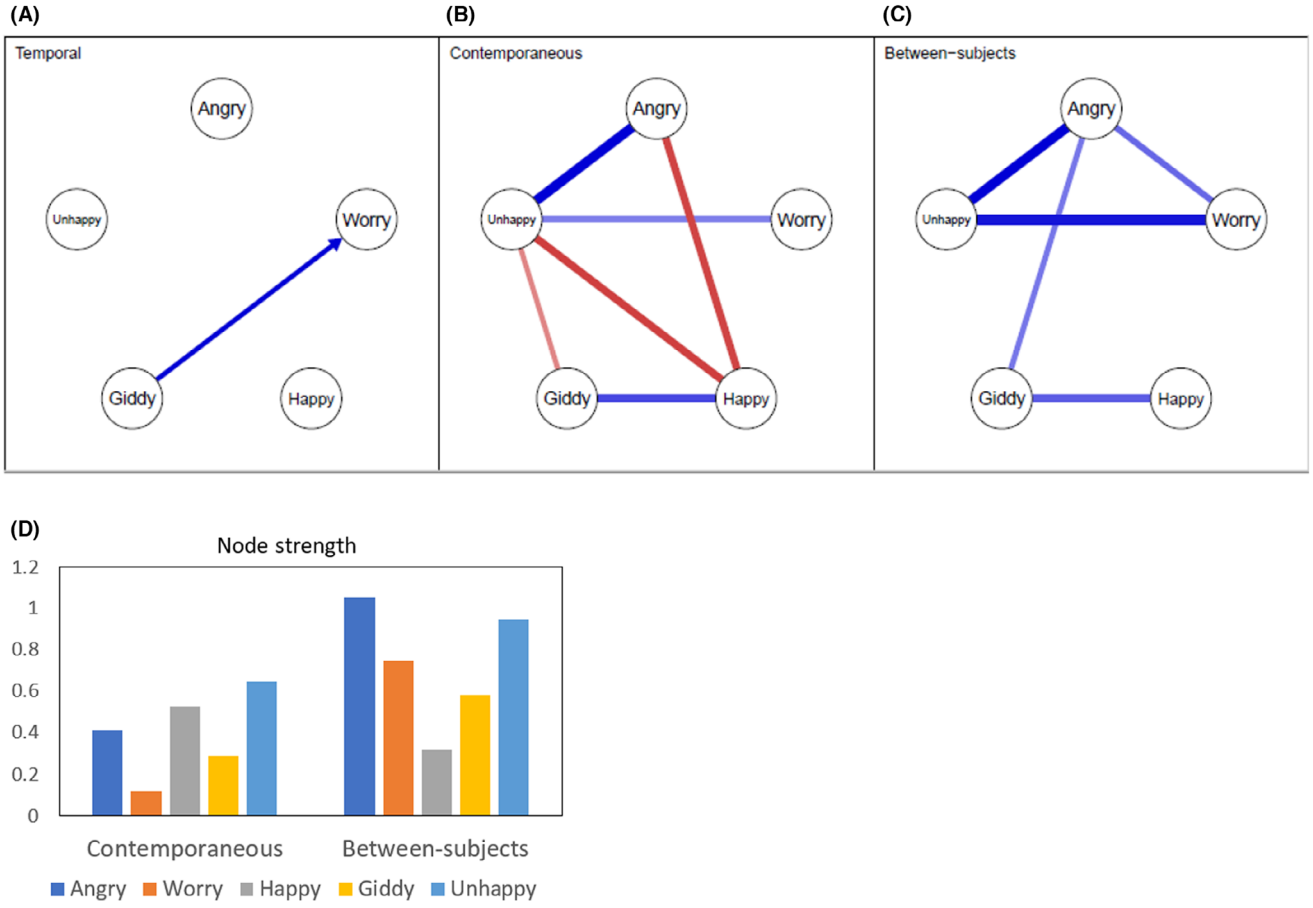

Figure 1 Time-series networks of momentary mood symptoms: (A) Within-subject temporal network, (B) Within-Subject Contemporaneous Network, (C) Between-Subject Network and (D) Node Centrality. Circles (i.e. nodes) represent symptoms, and blue and red edges indicating positive and negative associations (at $p < .05$), respectively, with thicker edges indicating stronger associations. Node strength (i.e. the sum of absolute edge weights) indicated the centrality and importance of the node; higher values indicated greater centrality. "Angry" = "I felt annoyed or angry"; "Worry" = "I felt worried or scared"; "Happy" = "I felt happy"; "Giddy" = "I felt much more giddy, silly, or happy than usual"; "Unhappy" = "I felt unhappy, sad, or miserable"

subject network identified feeling "unhappy, sad, or miserable" as the most central node (Figure 1D), which was positively associated with feeling "annoyed or angry" and "worried or scared" (partial correlations: $r = .24$ and $r = .12$, respectively) and negatively associated with feeling "happy" and "more giddy, silly or happy than usual" (partial correlations: $r = -.18$ and $r = -.11$, respectively) within subjects and within timepoints (Figure 1B). The *between-subject* network identified feeling "annoyed or angry" as the most central node (Figure 1D), which was positively associated with feeling "unhappy, sad, or miserable", "worried or scared" and "more giddy, silly, or happy than usual" (partial correlations: $r = .49$, $r = .29$, and $r = .26$, respectively; Figure 1C).

Between-prompt mood symptoms

The *temporal within-subject* network indicated that feeling "frustrated" at one timepoint predicted mood changes at the next timepoint (fixed effect coefficient = .09, $p = .03$) and that mood changes appeared to persist from one timepoint to the next (fixed effect coefficient = .09, $p = .03$; Figure 2A). The *contemporaneous within-subject* network identified feeling "frustrated" as the most central node (Figure 2D), which was positively associated with all the other nodes in the network, especially feeling "grouchy or cranky" and "something was unfair" (partial correlations: $r = .30$ and $r = .26$, respectively) within subjects and within timepoints (Figure 2B). The *between-subject* network also identified feeling "frustrated" as the most central node (Figure 2D), which was positively associated with feeling "grouchy or cranky" and "something was unfair" (partial correlations: $r = .63$ and $r = .50$, respectively) and, to a lesser extent, feeling "worried or scared" ($r = .20$; Figure 2C).

EMA measures of irritability and ARI

As shown in Figure 3, the variability (i.e. *SD*) in EMA measures of irritability-related constructs were moderately associated with child-ARI (r's = .36–.41), weakly to moderately associated with parent-ARI (r's = .21–.33), and non-significantly or weakly associated with clinician-ARI (r's = .13–.22). In contrast, the means of EMA measures of irritability-related

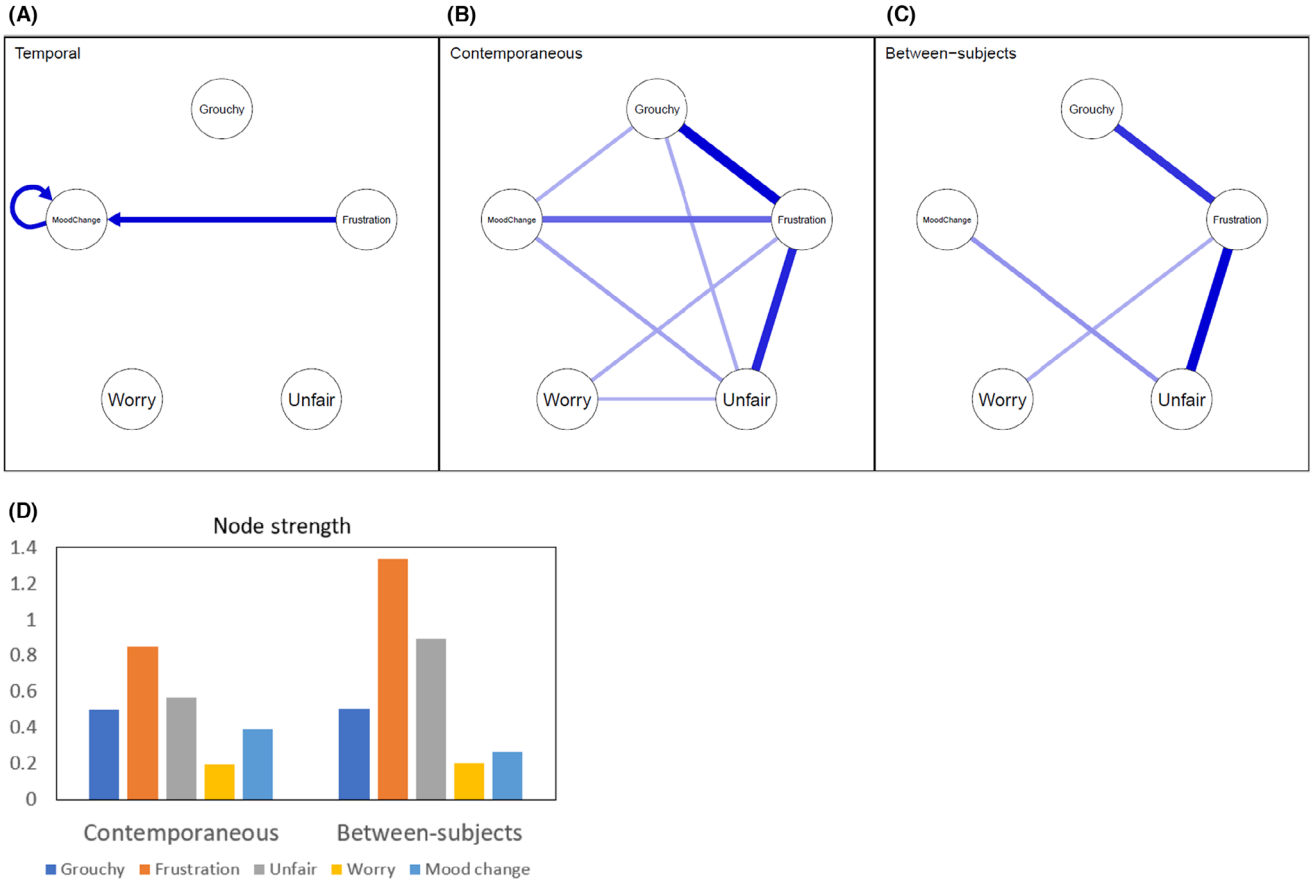

Figure 2 Time-series networks of between-prompt mood symptoms: (A) Within-subject temporal network, (B) Within-subject contemporaneous network, (C) Between-subject network, (D) Node centrality. Circles (i.e. nodes) represent symptoms, and blue and red edges indicating positive and negative associations (at $p < .05$), respectively, with thicker edges indicating stronger associations. Node strength (i.e. the sum of absolute edge weights) indicated the centrality and importance of the node; higher values indicated greater centrality. "Grouchy" = "I was feeling generally grouchy or cranky"; "Frustration" = "I felt frustrated"; "Unfair" = "Something was unfair"; "Worry" = "I felt worried or scared"; "MoodChange" = "My mood changed a lot"

constructs were more strongly associated with child- (*r*'s = .50–.56), parent- (*r*'s = .39–.48), and clinician-ARI (*r*'s = .23–.30; Figure 3). Results using RMSSD were similar to those with *SD* (*r*'s = .35–.37 for child-ARI, *r*'s = .18–.30 for parent-ARI, and *r*'s = .15–.21 for clinician-ARI).

Discussion

While irritability, frustration, anger and aggression are interrelated (Leibenluft & Stoddard, 2015; Zik et al., 2022), which in turn co-occur with other mood and anxiety symptoms (Vidal-Ribas et al., 2016), this is the first study to quantify and examine the temporal dynamics among these constructs using network analysis and EMA. Several key findings emerged. First, frustration was identified as the most central node in both within- and between-subject networks of between-prompt (i.e. since the previous prompt) irritability-related (i.e. grouchiness, unfairness) and other mood and anxiety symptoms (i.e. mood changes, worry). Critically, frustration at one time-point positively predicted mood changes in the next timepoint. Second, among momentary (i.e. at the time of the prompt) mood symptoms, sadness and anger emerged as the most central node in the within and between-subject network, respectively. Third, both differences and similarities in the within-subject and between-subject processes exist between irritability and other anxiety and mood symptoms. Moreover, mean levels, compared to variability and fluctuations, of EMA-indexed irritability-related symptoms were more strongly related to trait-like measures (i.e. rating scales) of irritability. These findings contribute to our understanding of the temporal dynamics of symptom-level irritability and associated anxious and mood symptoms in youth, highlighting the central role of frustration in irritability-related clinical phenomena.

Using network analysis, we identified frustration as the most central node in both within- and between-subject network of between-prompt irritability-related and other mood and anxiety symptoms. Frustration also predicted increases in mood changes at the subsequent timepoint. These findings provide empirical support for the critical role of frustration in the clinical presentation and pathophysiology of childhood irritability (Brotman, Kircanski, Stringaris, Pine, & Leibenluft, 2017). Central symptoms in a network are theorized to drive other symptoms (Borsboom et al., 2021) and

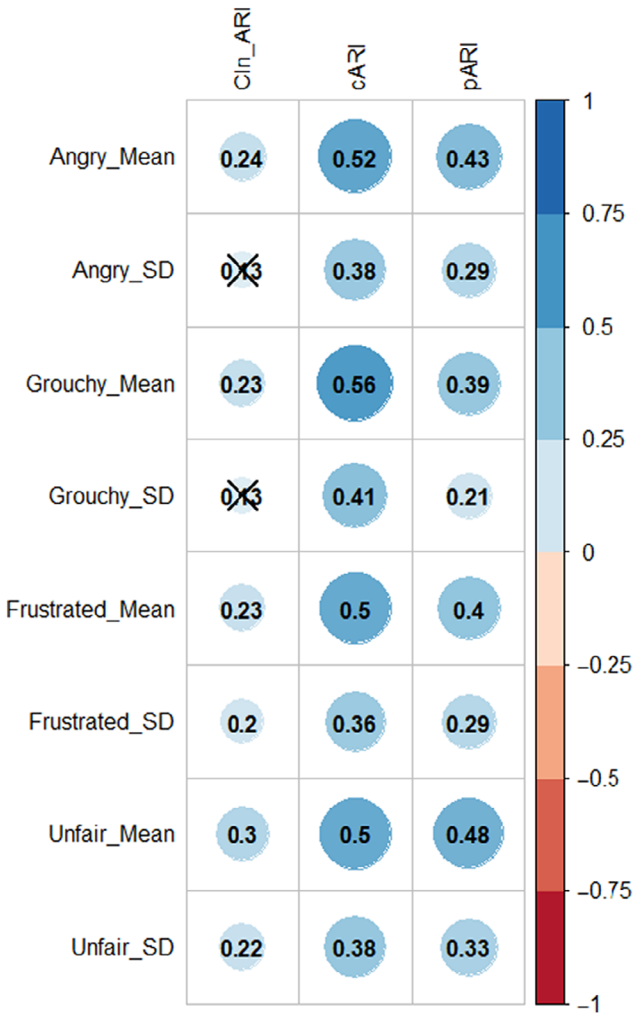

Figure 3 Correlations between EMA measures of irritability and clinician-, child-, and parent-reported ARI. ARI, Affective Reactivity Index; EMA, Ecological Momentary Assessment. Non-significant correlations at $p < .05$ were crossed out. Missing clinician-reported ARI in $n = 53$; no missing data in child- or parent-reported ARI

may be prioritized as the target of intervention (Epskamp, Waldorp, et al., 2018; Rodebaugh et al., 2018). Clinically, our results suggest that a decreased threshold for behavioural and emotional manifestations of frustration influences both irritability-related symptoms and other anxiety and mood symptoms. Interventions that increase the child's threshold for experiencing frustration and/or their ability to tolerate it, and/or decrease the severity and duration of the child's responses to frustration, may reduce irritability and associated symptoms. Three existing treatments are consistent with this conceptualization. First, preliminary evidence demonstrates the potential efficacy of an exposure-based cognitive behavioral therapy for irritability that targets youth's tolerance and regulation of anger and frustration (Kircanski et al., 2019). Second, cognitive skills training targets youth's interpretation of potentially frustrating stimuli and unfairness. Third, parent management training teaches caregivers skills to not reinforce children's maladaptive responses to frustration (Sukhodolsky, Smith, McCauley, Ibrahim, & Piasecka, 2016; Waxmonsky et al., 2016). With the use of EMA, future interventions could be designed and delivered right when youth become frustrated and before frustration influences other mood symptoms downstream, thus intervening in a timely and maximally effective way. Individual network derived from time-series EMA data would be particularly useful for understanding the dynamics between symptoms at an individual level, critical for personalized treatment (David, Marshall, Evanovich, & Mumma, 2018; Fisher et al., 2017).

We found both similarities and differences in the within- and between-subject processes between irritability-related symptoms and other anxiety and mood symptoms. In terms of similarities, momentary anger/annoyance was positively related to unhappiness/sadness in both the within-subject contemporaneous and between-subject networks. That is, when an individual youth reports feeling angry or annoyed, they also tend to report feeling unhappy, sad, or miserable at the same time. Across individuals, youth who, on average, feel angry or annoyed also tend to feel unhappy, sad, or miserable. In terms of differences, momentary anger/annoyance was negatively related to happiness in the within-subject contemporaneous network within measurement occasions while positively related to mood lability and worry in the between-subject network. This means that when an individual youth feels angry or annoyed, they are less likely to feel happy at the same time. However, across individuals, youth who, on average, feel angry or annoyed tend to feel more giddy, silly or happy than usual (i.e. mood lability) and worried or scared. These results demonstrate the complex, dynamic processes between symptoms at the intra-individual and inter-individual levels and supports that associations identified at the individual, within-subject level may be different from the overall average network across subjects (Bringmann et al., 2016; Epskamp, Waldorp, et al., 2018; Fisher et al., 2017). While between-subject processes may help identify targets of treatment that have maximal effects across large groups of individuals, within-subject processes provide the foundation for precise individualized targeted treatments (Fisher et al., 2017).

Another advantage of EMA is that it allows for fine-grained assessment of within-person variability and fluctuation in psychological constructs, which could then be used to investigate how these within-person variability relate to individual differences in traits and behaviors (Russell & Gajos, 2020). For example, using EMA, past research has linked greater variability (i.e. intra-individual *SD*) in negative affect to major depression in youth (Silk et al., 2011). We found that variability (i.e. *SD* and RMSSD) in EMA-indexed irritability-related constructs were moderately associated with retrospective child-reports, weakly to moderately associated with parent-

reports, and non-significantly or weakly associated with clinician-reports of "trait-like" irritability (i.e. ARI). Compared to variability, the mean level of EMA-indexed irritability was more strongly associated with retrospective "trait-like" measures of irritability. The agreement between the mean level of EMA measures and ARI rating scales supports the validity of ARI as an aggregated, average reflection of irritability symptoms over a pre-specified timeframe, as demonstrated in prior work with a partially overlapping sample (Naim et al., 2021). Future research is needed to link EMA-derived within-person variability and mean symptom levels to other behavioural, physiological or neural measures of irritability. Moreover, studies could use EMA to study whether and how irritability varies across environmental context (e.g. at home, school or with peers).

Strengths of this study include (a) the use of EMA, which minimizes recall bias and increases ecological validity and reliability via repeated sampling/assessment; (b) deep clinical phenotyping using parent, child and clinician assessments; and (c) combination of EMA and network analysis, which allows for modelling the temporal order and dynamics between symptoms. Despite these strengths, several limitations are worth noting. First, our analyses did not include other relevant irritability symptoms, such as temper outbursts or reactive aggression, or information about environmental triggers or contexts when the symptom occurs. Network structures and centrality measures may change, depending on which variables are included in the network (Borsboom et al., 2021). Thus, it is unclear if the associations identified in our networks would remain the same if other irritability-relevant or contextual variables were included. Relatedly, although beyond the scope of this study, future research would benefit from including ADHD symptoms to investigate the dynamic interplay between these commonly co-occurring symptoms of irritability and associated mood/anxiety symptoms. Second, the stability of our networks remains unclear. Time-series network analysis is a relatively new field (Blanchard, Contreras, Kalkan, & Heeren, 2022). Methods are being developed to assess stability and accuracy of multilevel and temporal networks, which is more complicated and difficult to assess than that of cross-sectional networks (Epskamp, Borsboom, & Fried, 2018). Future research should evaluate the network stability to ensure replicability of results. Third, EMA was completed by youth. Network structures may differ when using parent-reported EMA. Fourth, our sample was largely White non-Hispanic with high income and education. Results may not generalize to more diverse samples. Finally, the small size of each diagnostic group prevented us from comparing networks between groups, which may differ across diagnoses. Of note, very few participants with a primary diagnosis of ODD (n = 9) were included, although 21 participants with DMDD and 10 participants with ADHD also met criteria for ODD. The dimensional approach taken in the current study allowed us to explore irritability-related symptoms transdiagnostically, above and beyond the presence of one or more specific diagnosis. However, network structures may change if more participants with a primary diagnosis of ODD were included. Research is needed to test if symptom networks are similar or different across DMDD and ODD given their overlap in symptomatology, that is, DMDD criteria center on irritability, whereas ODD criteria include irritability and an oppositional/headstrong dimension.

Conclusion

This study advances our understanding of the symptom-level and temporal dynamics of irritability and demonstrates the central role of frustration in youth across multiple diagnoses. An important future direction is to test the efficacy of interventions/treatments targeting frustration given its high centrality. Do treatments targeting tolerance and regulation of frustration lead to reduction in irritability, anger/grouchiness, feeling of unfairness, mood changes and other related symptoms? If they do, this provides support for the central node, that is, frustration, as the "cause" or driving factor of other irritability and associated symptoms.

Supporting information

Additional supporting information may be found online in the Supporting Information section at the end of the article:

Table S1. Psychiatric comorbidities by diagnostic group.
Table S2. EMA scores by diagnosis.

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Key points

- Irritability commonly co-occurs with anxiety and other mood symptoms; however, little is known about the dynamic interplays between them. Using network analysis with smartphone-based EMA to increase ecological validity, this study examined how irritability and other anxiety and mood symptoms were connected.
- Frustration emerged as the most central node in the network of irritability (i.e. grouchiness, unfairness) and other related mood and anxiety symptoms (i.e. mood changes, worry). Frustration at one timepoint also positively predicted mood changes in the next timepoint.
- Both differences and similarities exist in the within- and between-subject networks of irritability and associated symptoms.
- Compared to variability, mean levels of EMA irritability were more strongly associated with retrospective "trait-like" measures of irritability.
- Frustration may be a promising treatment target to reduce irritability.

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