Psychological Medicine

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Autonomic indices and loss-of-control eating in adolescents: an ecological momentary assessment study

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Original Article

Cite this article: Ranzenhofer LM, Solhjoo S, Crosby RD, Kim BH, Korn R, Koorathota S, Lloyd EC, Walsh BT, Haigney MC (2023). Autonomic indices and loss-of-control eating in adolescents: an ecological momentary assessment study. *Psychological Medicine* **53**, 4742–4750. https://doi.org/10.1017/S0033291722001684

Received: 27 October 2021
Revised: 11 May 2022
Accepted: 17 May 2022
First published online: 3 August 2022

Key words:
Adolescents; autonomic nervous system; ecological momentary assessment; heart rate variability; heart rate; loss-of-control eating; stress

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Abstract

Background. Loss-of-control (LOC) eating commonly develops during adolescence, and it predicts full-syndrome eating disorders and excess weight gain. Although negative emotions and emotion dysregulation are hypothesized to precede and predict LOC eating, they are rarely examined outside the self-report domain. Autonomic indices, including heart rate (HR) and heart rate variability (HRV), may provide information about stress and capacity for emotion regulation in response to stress.

Methods. We studied whether autonomic indices predict LOC eating in real-time in adolescents with LOC eating and body mass index (BMI) ⩾70th percentile. Twenty-four adolescents aged 12–18 (67% female; BMI percentile mean ± standard deviation = 92.6 ± 9.4) who reported at least twice-monthly LOC episodes wore biosensors to monitor HR, HRV, and physical activity for 1 week. They reported their degree of LOC after all eating episodes on a visual analog scale (0–100) using a smartphone.

Results. Adjusting for physical activity and time of day, higher HR and lower HRV predicted higher self-reported LOC after eating. Parsing between- and within-subjects effects, there was a significant, positive, within-subjects association between pre-meal HR and post-meal LOC rating. However, there was no significant within-subjects effect for HRV, nor were there between-subjects effects for either electrophysiologic variable.

Conclusions. Findings suggest that autonomic indices may either be a marker of risk for subsequent LOC eating or contribute to LOC eating. Linking physiological markers with behavior in the natural environment can improve knowledge of illness mechanisms and provide new avenues for intervention.

Introduction

Loss-of-control (LOC) eating is defined as the sensation that one cannot stop eating or control what or how much one is eating. It is considered a key diagnostic criterion for binge eating disorder (BED) (American Psychological Association, 2013), and is a salient feature of pathological overeating in youth. LOC eating is prevalent, affecting nearly a third of treatment-seeking youth who have overweight or obesity (Decaluwe & Braet, 2003; Glasofer et al., 2007). LOC eating predicts negative physical and psychological health outcomes, including excess weight gain (Sonneville et al., 2013; Tanofsky-Kraff et al., 2009), worsening metabolic parameters (Tanofsky-Kraff et al., 2012), development of full- or partial-syndrome BED (Tanofsky-Kraff et al., 2011), and depressive symptoms (Sonneville et al., 2013; Tanofsky-Kraff et al., 2011). Given its prospective association with obesity and psychopathology, treating LOC eating prior to adulthood may have the potential to reduce BED, major depression, obesity, and obesity-related morbidity and mortality.

Key models of LOC eating (i.e. Hawkins & Clement, 1984; Heatherton & Baumeister, 1991) posit that stress and negative affect play a causal role. The hypothesized function of LOC eating is to alleviate, escape, or avoid a negative emotional state. In adults, support for affective models of LOC eating is robust, stemming from multiple experimental (Leehr et al., 2015) and ecological momentary assessment (EMA) (Haedt-Matt & Keel, 2011) studies. However, in children and adolescents, the role of negative emotions is less clear. Two previous EMA studies of LOC eating in youth failed to support the hypothesis that negative emotions precede and predict LOC eating (Hilbert, Rief, Tuschen-Caffier, de Zwaan, & Czaja, 2009; Ranzenhofer et al., 2014).

Affect-based models may operate differently in youth with LOC eating who may have more difficulty identifying and reporting their emotions, both by virtue of their developmental stage (Hatcher, Hatcher, Berlin, Okla, & Richards, 1990; Meschke, Peter, & Bartholomae, 2012) and by the nature of the disordered eating (Goldschmidt, Lavender, Hipwell, Stepp, & Keenan, 2017; Tanofsky-Kraff et al., 2007). Regarding the impact of development, emotional identification and expression require complex cognitive capacities such as abstract reasoning. Young people may be less able to articulate their emotional states, influencing findings regarding the relationship between negative emotions and eating behavior. Additionally, literature consistently suggests that adults and youth with eating disorders in general (Brockmeyer et al., 2014; Perthes et al., 2021; Svaldi, Griepenstroh, Tuschen-Caffier, & Ehring, 2012) and binge and LOC eating behavior specifically (Carano et al., 2006; Czaja, Rief, & Hilbert, 2009; Whiteside et al., 2007) tend to have poorer emotion regulation, including alexithymia, difficulty identifying and reporting emotions, and deficient and maladaptive emotion regulation strategies. All of these may preclude the ability of self-report studies to fully capture the relationship between negative emotions and eating behavior.

However, emotions are also thought to involve physiologic changes in addition to the more accessible and commonly studied cognitive-affective dimension (e.g. 'I feel sad') (Appelhans & Luecken, 2008). Physiologic changes that occur in response to stress are mediated by the sympathetic and parasympathetic branches of the autonomic nervous system (ANS). Higher heart rate (HR), reflecting greater sympathetic nervous system activity and/or lower parasympathetic activity, is associated with, and can be indicative of, emotional stress or distress (Kreibig, 2010). Higher heart rate variability (HRV), on the other hand, predominantly reflects parasympathetic activity (Porges, 1995) and is considered a marker of capacity for adaptive responding to stress and inhibitory control (Beauchaine & Thayer, 2015; Holzman & Bridgett, 2017; Porges, 1995; Thayer & Lane, 2000). Therefore, higher HR and/or lower HRV may reflect increased distress, decreased capacity for adaptive responding to stress, lower inhibitory control, and consequent increased susceptibility to LOC eating (Bottera, Mancuso, Kambanis, & De Young, 2021; Holzman & Bridgett, 2017).

Most studies examining autonomic functioning in patients with binge eating have examined baseline differences in HRV between patients and controls. In a meta-analysis of resting state HRV and disordered eating, there was no effect in patients with BED (three studies) or patients with subthreshold disordered eating (14 studies) (Watford, Braden, & O'Brien, 2020). In studies focusing on stress response and eating behavior, physiologic changes in response to stress have been shown to be associated with dimensions of disinhibited eating. In women, including those with BED, greater cortisol reactivity to a laboratory stressor was positively associated with food intake (Epel, Lapidus, McEwen, & Brownell, 2001), and similarly, greater cardiovascular (blood pressure, HR) reactivity to a laboratory stressor was associated with increases in hunger (Klatzkin, Gaffney, Cyrus, Bigus, & Brownley, 2015). In adolescents with and without LOC eating who viewed a sad or neutral film clip, food intake during a post-meal *ad libitum* buffet was predicted by cortisol level (area under the curve) regardless of experimental condition (Radin et al., 2016).

An important step in developing interventions for LOC eating is identifying momentary predictors of the behavior; specifically, the psychological and contextual variables that result in LOC eating in the short term (i.e. minutes or hours). In recent decades, methodologic innovation has facilitated the ability to not only tap into additional dimensions of human emotions and behavior, but also to do so outside the constraints of the laboratory, in peoples' day-to-day lives. We previously conducted a pilot study in adolescent girls with recurrent LOC eating, in which HR was higher, and HRV lower, within the 30 min prior to high-LOC eating episodes, compared to non-LOC eating episodes (Ranzenhofer et al., 2016). These data were promising but limited by the small sample size ($n = 17$), short duration of recordings per participant (2 days), and lack of control for potential confounding variables like physical activity. The goal of the present study was to examine the *within-participants* associations between autonomic activity (HR, HRV) prior to eating and self-reported level of LOC, in a larger number of participants, with a longer duration of recording per participant, and the consideration of additional possible confounding variables. Our primary hypotheses were that there would be a positive within-person association between HR prior to eating and LOC eating and there would be an *inverse* within-person association between HRV prior to eating and LOC eating. Secondarily, we tested the overall effect and the between-subjects effects.

Methods

Participants

Adolescents were recruited via advertisements in print and electronic media and through direct mailings to families. Recruitment strategies targeted parents and adolescents who were concerned about the adolescent's LOC eating and/or weight gain. Participants were adolescents aged 12–18 years with a body mass index (BMI; kg/m^2) over the 70th percentile for age and sex who reported LOC eating episodes at least twice during the month prior to assessment. Adolescents were required to be English-speaking and cognitively capable of completing study procedures. Exclusion criteria included major psychiatric disorders, including anorexia nervosa and bulimia nervosa; taking psychoactive medication or any other medication with known impact on ANS or body weight; and pregnancy. Individuals with BED or subthreshold BED were included. Participants without a smartphone were provided with one.

Procedure

Adolescents and their parents completed a telephone screening to determine initial eligibility (e.g. self-reported height and weight and LOC eating). Adolescents meeting study inclusion criteria were scheduled for an in-person visit. Baseline visits took place in the morning, and adolescents were instructed not to eat or drink anything, except water, for 8 h prior to the appointment. Informed assent and consent were obtained from adolescents and parents, respectively, prior to participation. The present study was approved by the Intramural Review Board at the New York State Psychiatric Institute.

Height and weight were measured in a fasted state. Adolescents completed screening interviews and questionnaires assessing eating-related and general psychopathology. Participants who were interested and eligible for the study were provided instructions for wearing the biosensors and completing the EMA ratings on a smartphone.

For 1 week beginning the day of the baseline visit, adolescents wore the biosensors for the continuous recording of the

https://doi.org/10.1017/S0033291722001684 Published online by Cambridge University Press

electrocardiogram (ECG) and the accelerometry data, and they completed EMA using a web-based application on a smartphone. The EMA protocol included event-contingent ratings before and after all eating episodes, defined as 'any time of eating that you consider to be a meal or snack', regardless of the amount of food or level of LOC. Adolescents also responded to signal-contingent recordings when they received a programmed text message, between 3 and 5 times per day. To ensure adequate sampling throughout the day, the entire sampling period was stratified into five intervals (9:30–12, 12–14:30, 14:30–17:00, 1700–19:30, 19:30–22:00), and each of the five daily signals occurred randomly within each interval. On school days, participants did not receive a notification in the first or second interval. Thus, signal-contingent texts occurred three times per day on weekdays, beginning after school, and five times per day on weekends and during the summer. This approach was expected to reasonably capture most episodes of LOC eating, as prior work indicates that such episodes typically occur after school hours and in the evenings (Tanofsky-Kraff et al., 2007). All random prompts began by asking the participant if they had eaten since the last text message and forgotten to report on it. If yes, and if the episode had occurred in the previous hour, the adolescent answered questions pertaining to the eating episode. Adolescents were contacted by a member of the research team the day after they initiated EMA, and the study team member provided feedback regarding the adolescent's compliance. Adolescents were contacted by the study team if they had not recorded an eating episode for 24 h or more, or if they did not respond to five consecutive texts.

At the end of the 1-week period, participants returned all devices and completed questionnaires related to the typicality of their eating behavior during the study. Adolescents were compensated $25.00 for the screening visit, $0.75 per hour of device wear, up to $126 for the full week based on a 168 h week. Adolescents earned $1.00 for each text message to which they responded. They were not compensated for before- or after-meal ratings to avoid incentivizing false reports. Total compensation was up to $176.00. Following completion of the EMA period, adolescents could select to participate in a single-session psychoeducation/motivational interviewing session about stress management and/or eating behavior.

Measures

Baseline measures

Demographic information. Parents completed a questionnaire assessing family demographic information, including race and ethnicity.

BMI and body composition. Height was measured via a stadiometer. Weight was measured to the nearest 0.1 kg using a calibrated digital scale. BMI was calculated and BMI percentiles were determined based on the Center for Disease Control Growth Charts (Kuczmarski et al., 2002).

Eating pathology. Presence and frequency of LOC eating were assessed using the overeating section of the Eating Disorder Examination (EDE) interview (Fairburn & Cooper, 1993). The total number of objective and subjective LOC eating episodes occurring within the past month was determined. Eating-related psychopathology was assessed using the EDE – Questionnaire (Fairburn & Beglin, 1994), a commonly used 40-item self-report measure that yields subscale scores for restraint, eating concern, shape concern, and weight concern, as well as a global score.

Psychopathology. Psychopathology was assessed using the Patient Health Questionnaire-9 (PHQ-9) (Kroenke, Spitzer, & Williams, 2001) and the Kiddie Schedule of Affective Disorders and Schizophrenia-5 (KSADS) (Kaufman et al., 2016). The PHQ-9 is a nine-item well-validated measure whose questions correspond with the DSM-5 diagnostic criteria for depression, each rated on a Likert-type scale ranging from 0 to 3. Scores range from 0 to 27, with scores of 10 and above indicative of moderate depression symptoms. The KSADS is a semi-structured clinical interview used to assess psychiatric symptoms and diagnoses in children and adolescents. The KSADS and PHQ-9 were administered to the adolescent only. A parent or guardian initially reported on the adolescent's psychological functioning (i.e. diagnoses, treatments received) during the telephone screening, and any discrepancies between the adolescent and parent report were discussed with the parent and the adolescent together.

Self-report ecological momentary assessment

EMA ratings were collected using the Real-Time Assessment In the Natural Environment (ReTAINE) system (Neuropsychiatric Research Institute, Fargo, ND, USA). Adolescents were instructed to self-initiate assessments before and after eating. Before eating, adolescents were asked to report if they intended to eat a 'meal', 'snack', or 'other'. After eating, LOC-relevant items from the EDE (Fairburn & Cooper, 1993) were used to assess LOC eating in an EMA-compatible format. Questions included: 'During the meal/snack…', '…did you feel a sense of loss of control?', 'To what degree did you lose control?', and 'Did you feel like your eating was out of control AT ANY POINT?' All items were rated on a 100-point visual analog scale (VAS) anchored by 'No, not at all' and 'Yes, very much'. The questions were averaged to create a composite LOC rating ranging from 0 to 100 (a continuous variable), which was the dependent variable in all analyses. Cronbach's α for the three items comprising the scale was 0.93.

Passive recording

For the continuous recording of the ECG signal, participants wore the Cardea SOLO^{TM} device (Cardiac Insight, Bellevue, WA, USA), which is a single-lead, wire-free, waterproof patch that can continuously record the ECG data for up to 7 days. It was applied during the baseline visit to the left side of the chest, over the heart, by a study team member, and worn continuously for the entire ambulatory assessment phase. Adolescents were instructed to refrain from swimming or submerging the device in water. The ECG recordings were subsequently processed using Amark (Koorathota & Sloan, 2020), software developed in MATLAB (Mathworks, Natick, MA, USA), where each heartbeat was identified in the ECG waveform through template matching and peak detection methods. The Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology recommend that RMSSD (the root mean square of successive differences in beat-to-beat intervals), pNN50 (the proportion of consecutive beat-to-beat intervals differing by greater than 50 ms), and HF HRV (high-frequency HRV) best represent HRV mediated by parasympathetic innervation, and the time-domain measures are recommended for ambulatory settings due to non-stationarity of the data (Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Therefore, RMSSD and pNN50 measures were calculated over 5 min epochs.

https://doi.org/10.1017/S0033291722001684 Published online by Cambridge University Press

Participants wore a separate device to monitor posture and movement (ActivPAL™, PAL Technologies Ltd, Glasgow G1 1XO, Scotland, UK). ActivPAL was applied by a study team member during the initial visit to the front of the mid-thigh using transparent medical tape (Tegaderm™). ActivPAL contains a microprocessor, accelerometer (sensor), recorder, associated electronics, and a power supply. The system uses proprietary algorithms to classify activity, including time spent sitting/lying, standing, stepping, cadence, and activity counts. ActivPAL has been validated for the measurement of physical activity and sedentary behaviors in female adolescents (Dowd, Harrington, & Donnelly, 2012).

Data analysis

Data for all independent and dependent variables were visualized and there were no obvious outliers for either electrophysiologic parameters or LOC ratings. Thirty-minute ECG segments recorded immediately prior to each eating episode were identified, and the average HR and average HRV (over six 5 min epochs) were calculated. Eating episodes occurring within 1 h of a prior eating episode were excluded due to potential post-prandial effects of eating on HR and HRV (Friesen, Lin, Schurman, Andre, & Mc Callum, 2007; Lu, Zou, Orr, & Chen, 1999). Associations between variables were analyzed using linear mixed models (LMM). The independent variables were time of day [analyzed categorically (00:00–05:59, 06:00–11:59, 12:00–17:59, 18:00–23:59)], physical activity, and one of the cardiac electrophysiologic variables (in separate models): HR, RMSSD, or pNN50. The dependent variable was the self-reported LOC composite score, with each item rated on a 0–100 point VAS (sliding bar) scale. To parse between- and within-subjects effects, a second set of models was run in which predictors included time of day, physical activity, the subject's average HR (or HRV), and the deviation of HR (or HRV) from the subject's average for each individual eating episode. Specifically, the grand mean (mean across all subjects for all eating episodes) for each variable (HR, RMSSD, and pNN50) was calculated and subtracted from each subject's mean (mean across all eating episodes for a single subject), in order to calculate a mean-centered between-subjects mean per subject. To calculate the within-subjects effect, the HR, RMSSD, and pNN50 averaged within the 30 min prior to eating, for each eating episode, was calculated. In order to calculate the within-subjects effect, the subject mean was subtracted from the value for each eating episode. Positive values reflected HR, RMSSD, and pNN50 that are above that subject's average value, and negative values reflected HR, RMSSD, and pNN50 that are below the subject's average value. Random intercepts and slopes for each primary variable of interest were included and tested. If the variance estimate differed significantly from 0, the random effect was retained in the model. A variance components correlation structure was used. Statistical analyses were conducted using SPSS software (IBM, Armonk, NY, USA), version 26.0. For the first primary hypothesis, that HR is positively related to LOC, consisting of one statistical test, statistical significance was defined as $p < 0.05$. For the second primary hypothesis, that HRV parameters (RMSSD and pNN50) are negatively correlated with LOC, consisting of two statistical tests, we used the group-wise Bonferroni–Holm method to adjust for multiple comparisons. For secondary hypotheses, including testing the overall effect and testing the between-subjects effect, we also used group-wise Bonferroni–Holm method.

Results

Forty-one participants were eligible for the study out of 51 screened. The first 11 participants wore a device that, due to technical problems, did not capture time-stamped ECG data. After multiple futile attempts at problem-solving with the developer, a different device (Cardea SOLO) was selected for subsequent data collection. Of the 30 remaining participants, 24 contributed data to the analyses. Reasons for missing data were: participant removed or did not return the device ($n = 3$); no valid eating episodes (before + after meal rating, at least 2 min apart) ($n = 1$); EMA web-app did not work ($n = 1$); missing physical activity data ($n = 1$). Participant characteristics, compliance rates, and average electrophysiologic parameters (during the 30 min before eating) are reported in Table 1.

Heart rate and loss-of-control eating

Higher mean HR in the 30 min before eating predicted higher LOC ratings (Table 2). Based on the LMM adjusted for time of day and physical activity, a 25-beats per minute (bpm) increase in HR was associated with an approximate 10-point increase in LOC rating (on a 100-point scale). Parsing between- and within-subjects effects, the between-subjects effect was not significant, meaning that an individual's average HR before eating was not associated with their average LOC ratings after eating. The within-subjects effect was significant, meaning that when an individual's HR prior to eating was higher than their own average HR prior to eating, they reported a higher LOC rating for that eating episode (Table 2).

Heart rate variability and loss-of-control eating

There was an inverse relationship between RMSSD during the 30 min before eating and LOC ratings (Table 2). Based on the LMM adjusted for time of day and physical activity, every 50 ms decrease in RMSSD was associated with an approximate 10-point increase in the LOC rating. The same relationship was seen between pNN50 in the 30 min before eating and LOC ratings. In the model parsing between- and within-subjects effects, neither the between- nor within-subjects effect was significant.

Relationship between physical activity and loss-of-control eating

In both HR models, there was a significant (p's $\leqslant 0.03$) inverse association between physical activity and LOC ratings, where lower physical activity was associated with higher LOC. In the overall model of the relationship between pNN50 and LOC, LOC was negatively associated with physical activity ($p = 0.049$). In the remainder of the HRV models, the effect of physical activity was not significant ($0.05 < p$'s < 0.08).

Discussion

This study aimed to build upon our prior pilot data suggesting that HR and HRV were associated with LOC eating in the natural environment. Here, we showed a positive association between HR and LOC, and an inverse association between HRV and LOC, in a larger sample with nearly five times as many total eating episodes as the pilot study. Also, in line with our previous findings, these associations were significant for HR at the within-subjects level,

https://doi.org/10.1017/S0033291722001684 Published online by Cambridge University Press

Table 1. Participant demographic and clinical characteristics

	Mean ± s.d.	Range
Age (years)	15.6 ± 1.7	12.1–18.5
Body mass index (kg/m^2)	30.4 ± 5.6	22.4–41.7
Body mass index percentile (%)	92.6–9.4	68–99
Sex		
Female	16 (66.7%)	
Male	8 (33.3%)	
Race		
African American	8 (33.3%)	
Caucasian	5 (20.8%)	
Native American	1 (4.2%)	
Other race[a]	4 (16.7%)	
More than one race[b]	5 (20.8%)	
Missing (declined to respond)	1 (4.2%)	
Ethnicity		
Hispanic	9 (37.5%)	
Non-Hispanic	14 (58.3%)	
Other[c]	1 (4.2%)	
Mother highest education		
High school or some high school	6 (25.0%)	
Some college or vocational degree	5 (20.8%)	
College degree or graduate degree	11 (45.9%)	
Missing or declined	2 (8.3%)	
Father highest education		
<8th grade	2 (8.3%)	
High school or some high school	8 (33.4%)	
Some college or vocational degree	5 (20.9%)	
College degree or graduate degree	6 (25.5%)	
Missing or declined	3 (12.5%)	
Diagnosis		
Binge eating disorder (full criteria for BED met)	3 (12.5%)	
Subthreshold BED or BED of low frequency	9 (37.5%)	
Recurrent loss-of-control eating (<4×/month)	12 (50%)	
LOC episode frequency (month prior to assessment)	8.4 ± 7.3	2–28
Depression symptoms (PHQ-9)	5.4 ± 3.9	0–14
Eating Disorder Examination (global)	2.1 ± 1.1	0.3–4.0
Restraint	1.4 ± 1.1	0.0–4.0
Eating concern	1.4 ± 1.1	0.0–4.2
Shape concern	3.0 ± 1.5	0.6–5.1
Weight concern	2.6 ± 1.3	0.3–4.0
Compliance		
Days in study	6.8 ± 0.8	4–8
Compliance with event-contingent notifications	78 ± 16%	24–100%
Before meal ratings/day	2.7 ± 1.3	0.9–5.2
After meal ratings/day	2.4 ± 1.2	0.8–5.0
Total eating episodes included in analysis[d]	10.1 ± 7.1	1–28
Electrophysiologic variables		
HR (30 m before eating)	93.2 ± 10.4	76.9–119.1
RMSSD (30 m before eating)	50.8 ± 16.7	26.5–82.4
pNN50 (30 m before eating)	18.9 ± 9.3	2.9 ± 34.2

PHQ-9, Patient Health Questionnaire-9.
[a]Three participants marked 'other race' and wrote 'Hispanic'; one participant marked 'other race' and did not indicate their race, but this individual reported Hispanic ethnicity.
[b]Two participants checked more than one race category (one indicated African American and Caucasian; the other indicated African American, Caucasian, and Native American); two participants marked 'other race' and wrote in African American and Caucasian; one participant marked 'other race', and reported 'mixed race'.
[c]One subject wrote in 'mixed ethnicity'.
[d]Before + after meal rating with concurrent physiologic data.

meaning that when an individual's HR was higher before eating (reflective of higher sympathetic and lower parasympathetic activation, which can indicate stress), their reported LOC rating was higher.

Current study findings extend prior EMA studies of LOC eating in youth by examining physiologic, rather than self-report, predictors. While prior self-report-based findings suggest that negative affect does not precede and predict LOC eating (Hilbert et al., 2009; Ranzenhofer et al., 2014), the current study suggests that electrophysiologic indices indicative of stress (higher HR, lower HRV) are associated with LOC. The finding of an association between electrophysiologic measures of stress and LOC eating is in partial agreement with a recent laboratory study examining autonomic indices and measured food intake (Bottera et al., 2021), where, in adults with and without binge eating who underwent either neutral or guilt mood induction, associations among feelings of guilt, milkshake consumption rate, and ANS parameters were examined. Findings suggested that, following guilt induction, individuals with lower HRV during the mood manipulation reported higher guilt prior to milkshake consumption. Additionally, compared to all individuals in the neutral mood induction group and those in the guilt induction group with high HRV, those in the guilt induction group with low HRV had the greatest reduction in guilt after milkshake consumption (Bottera et al., 2021), supporting an affect-regulation model of palatable food consumption.

One possible mechanism underlying the present findings is that increased sympathetic and/or reduced parasympathetic tone, indicative of stress, may increase the risk for LOC eating, and this may be at least partially driven by stress-related physiologic changes affecting appetitive hormones. The ANS prepares the body to respond to a stressor in part via its role in glucose homeostasis in metabolically active organs such as liver, muscle, gut, and adipose tissue. Initially, increased sympathetic and/or reduced parasympathetic tone causes a rise in circulating glucose, followed by compensatory glucoregulatory processes including increased insulin production and corresponding intracellular glucose uptake

https://doi.org/10.1017/S0033291722001684 Published online by Cambridge University Press

Table 2. Estimates of fixed effects of pre-meal heart rate/heart rate variability and physical activity on loss-of-control eating

	HR					RMSSD					pNN50				
(a) Pre-episode HR/HRV predicting LOC rating															
n, *k*	*n* = 24, *k* = 217					*n* = 24, *k* = 217					*n* = 24, *k* = 217				
CovP	Estimate	s.e.	95% CI			Estimate	s.e.	95% CI			Estimate	s.e.	95% CI		
Residual	470.64	48.64	375.31–565.97			473.04	48.87	377.25–568.83			471.91	48.76	376-34–567.48		
Intercept	139.74	66.65	9.11–270.37			156.56	71.95	15.54–297.58			154.46	71.26	14.79–295.13		
AIC/BIC	1960.58/1967.29					1964.45/1971.57					1962.73/1969.43				
	Estimate	s.e.	df	*t*	Sig*	Estimate	s.e.	df	*t*	Sig	Estimate	s.e.	df	*t*	Sig
Intercept	17.06	12.60	193.0	1.35	0.77	55.60	10.31	188.9	5.39	<0.001	54.74	9.85	187.5	5.56	<0.001
Time (18:00–23:59 reference)															
00:00–05:59	0.72	9.63	205.6	0.08	0.940	−0.67	9.66	205.9	−0.07	0.945	−0.83	9.62	205.2	−0.09	0.931
06:00–11:59	−14.30	4.30	197.4	−3.32	0.001	−13.98	4.33	196.2	−3.23	0.001	−14.51	4.31	196.8	−3.37	<0.001
12:00–17:59	−7.97	3.46	196.8	−2.30	0.022	−7.45	3.49	197.3	−2.13	0.034	−7.68	3.47	196.9	−2.21	0.028
HR/HRV (subject average)	0.40	0.15	182.1	2.71	0.007 (0.021)	−0.17	0.08	194.6	−2.11	0.036 (0.048)	−0.32	0.14	199.7	−2.27	0.024 (0.048)
Physical activity	−0.93	0.38	209.4	−2.48	0.014	−0.61	0.34	208.8	−1.80	0.074	−0.69	0.35	210.4	−1.98	0.049
(b) Subject average + deviation from average HR/HRV predicting LOC rating															
n, *k*	*n* = 24, *k* = 217					*n* = 24, *k* = 217					*n* = 24, *k* = 217				
CovP	Estimate	SE	95% CI			Estimate	SE	95% CI			SE	Estimate	95% CI		
Residual	471.56	48.75	376.01–567.11			473.72	48.98	377.72–569.72			472.50	48.85	376.75–568.25		
Intercept	137.03	66.98	5.75–268.31			162.57	75.63	14.34–310.80			159.82	74.62	13.56–306.08		
AIC/BIC	1959.99/1966.68					1965.47/1972.17					1962.54/1969.23				
	Estimate	s.e.	df	*t*	Sig	Estimate	s.e.	df	*t*	Sig	Estimate	s.e.	df	*t*	Sig
Intercept	52.50	9.52	193.6	5.51	<0.001	47.08	8.62	185.4	5.46	<0.001	48.36	8.80	188.9	5.50	<0.001
Time (18:00–23:59 reference)															
00:00–05:59	−0.39	9.72	202.3	−0.04	0.968	−1.40	9.80	202.1	−0.14	0.887	−1.64	9.75	202.1	−0.17	0.866
06:00–11:59	−14.29	4.31	197.3	−3.32	0.001	−13.97	4.34	195.7	−3.22	0.001	−14.45	4.32	196.1	−3.35	<0.001
12:00–17:59	−8.19	3.47	195.8	−2.36	0.019	−7.57	3.50	195.8	−2.16	0.032	−7.82	3.49	195.5	−2.24	0.026
HR/HRV (subject average)	0.66	0.30	20.1	2.16	0.043 (0.129)	−0.25	0.20	20.0	−1.23	0.234 (0.386)	−0.48	0.36	19.3	−1.35	0.193 (0.386)
HR/HRV (deviation from the average for each subject)	0.33	0.17	195.5	1.98	0.049	−0.16	0.09	190.4	−1.73	0.086 (0.128)	−0.29	0.15	190.8	−1.87	0.064 (0.128)
Physical activity	−0.84	0.39	209.6	−2.18	0.030	−0.60	0.34	206.8	−1.76	0.080	−0.67	0.35	207.5	−1.90	0.059

n, number of subjects; *k*, number of episodes; CovP, estimate of covariance parameter; s.e., standard error; CI, confidence interval; AIC, Akaike's Information Criteria; BIC, Schwarz's Bayesian Criterion; df, degrees of freedom; *t*, *t* statistic; *sig, *p* value (parentheses indicate group-wise Bonferroni–Holm adjusted *p* value); HR, heart rate; HRV, heart rate variability; RMSSD, root mean square of successive differences; pNN50, proportion of consecutive beat-to-beat intervals differing by greater than 50 ms.

with a resultant drop in serum glucose levels (Rodriguez-Diaz et al., 2012). Reduced blood glucose, whether induced by insulin injection (Nakai & Koh, 2001) or glucose-clamp (Schultes et al., 2003), has been shown to robustly increase appetite. This pathway, however, does not explain individual differences in eating behavior (i.e. between individuals with and without binge eating), and it also assumes that the biological sequelae of stress promote LOC specifically, rather than eating in general. Notably, the present study did not evaluate measured intake nor did it examine associations in adolescents who do not experience LOC, both of which would inform the possible impact of stress-related metabolic changes on the specific behavior of LOC eating.

A second model to explain the associations between autonomic indices and LOC eating involves inhibitory control. Some models of LOC and binge eating suggest that an impairment in the cognitive process of inhibitory control, possibly reflected by low HRV (Holzman & Bridgett, 2017), may promote LOC eating by making it more difficult to inhibit a maladaptive response. In adult women and men with obesity and recurrent LOC eating, HRV at rest (but not in response to stress) was associated with the severity of LOC eating (Godfrey et al., 2019), but there is a relative dearth of studies examining resting HRV parameters in eating disorders outside of anorexia nervosa and bulimia nervosa. Most existing literature on HRV as a measure of inhibitory control (Holzman & Bridgett, 2017) conceptualizes HRV as reflective of an individual's trait capacity for inhibitory control, but, to date, there is insufficient evidence to say that a temporary reduction in HRV reflects lower inhibitory control at a particular moment in time. Extending Godfrey et al. (2019) to the 30 min period before eating, we found an overall inverse relationship between HRV and LOC ratings; however, neither the within- nor between-subjects effects were significant. Nevertheless, the present study is among the first to describe a within-subjects effect for momentary HR on LOC eating.

Finally, findings may also be explained by a third latent variable influencing both autonomic indices and LOC eating. For example, anticipation of eating, which was not measured, may both increase HR and lead to greater LOC eating. Another possibility is that post-prandial autonomic shifts may influence subsequent eating behavior. Specifically, recent eating itself may increase HR, decrease HRV, and capture the experience of LOC (i.e. eating very soon after completing a meal or snack). While there is a dearth of data on pre- to post-prandial shifts in HR and HRV, studies in both adults and children suggest that these effects – an increase in HR and a decrease in HRV – can last up to an hour or more (Friesen et al., 2007; Lu et al., 1999), although other studies suggest absence of any statistically significant changes (Ambarish, Barde, Vyas, & Deepak, 2005; Harthoorn & Dransfield, 2008). In the current study, episodes occurring within 1 h of a prior eating episode were excluded, minimizing the chances that immediate post-prandial shifts explain study findings; however, further research should explore this possibility.

Notably, the relationship between HR/HRV and LOC ratings was only present when adjusting for physical activity. An obvious reason for this may be that elevated HR/reduced HRV in the presence of high physical activity reflects the expected increase in HR during exercise, rather than the presence of mental or psychological stress. Thus, only in the absence of high activity would we expect HR/HRV to predict LOC eating. We also observed, unexpectedly, a significant inverse relationship between the level of physical activity and the level of LOC. While not *a priori*, this finding aligns with accumulating evidence supporting a potential protective effect of acute bouts of exercise on mood and eating behavior (Leow, Jackson, Alderson, Guelfi, & Dimmock, 2018). Given that this finding was not *a priori*, it should be considered hypothesis-generating.

Although over 200 total eating episodes were included in the analysis, the small number of participants is a significant limitation of this study. Because the sample size was less than planned due to device and other issues, we calculated power from the effect sizes derived, which is problematic because power will always be equal to or lower than 50% when observed effect sizes of non-significant tests are used (Goodman & Berlin, 1994; Zhang et al., 2019). Therefore, while this method suggested that there was adequate power to detect the overall effect but insufficient power for the between- and within-subjects effects, it is also possible that this method (calculating power from empirically derived effect sizes) underestimates power. As a result, it is not possible to determine whether there was a lack of an association between autonomic indices and LOC at the between-subjects level or if there was simply insufficient power to detect an effect. An additional limitation is that, because we did not explicitly model an autoregressive effect for equidistant measurement, we assumed absence of auto-regressive effects on LOC eating. It is possible that prior LOC eating may influence subsequent LOC eating, in which case this assumption would be violated. Subgroup differences (i.e. by sex, race, ethnicity, socioeconomic status, depression score, or other potential moderators) could not be examined by virtue of the small number of participants per group. The sample included adolescents with and without BED, and the relationship between autonomic indices and LOC may be different in these two groups. Additionally, participants contributed different numbers of eating episodes, where some adolescents reported several episodes per day, several reported fewer than five total, and two adolescents only reported one eating episode. The present study only included adolescents whose BMI was over the 70th percentile, meaning that findings may not generalize to peers with lower weight strata. Finally, the magnitude of the effects of each electrophysiologic parameter on LOC ratings was small. For HR, for example, a 25-beat increase (e.g. from 75 to 100 bpm) would predict an approximate 10-point increase in LOC. The small effect size, particularly relative to the myriad of factors influencing HR, might hinder the ability to translate findings to momentary interventions.

Although the present study is among the first in mental health to integrate objective assessments of stress physiology with specific problematic behaviors in the natural environment, several technological limitations hindered data collection and our ability to draw definitive conclusions regarding all study hypotheses. The most salient of these was difficulty identifying and tailoring commercial devices to precise data collection needs, in our case the integration of HR/HRV, physical activity, and self-report data. In the present study, after detecting a flaw with the device used by ~1/3 of the sample, three separate devices were used by the remainder of participants (comprising the sample presented in this paper), requiring multiple programs/software for data processing, merging, and analysis. Collaboration with biomedical engineers *at early phases* of the research process, such as study design, is an important step in subsequent naturalistic research aiming to test associations between biomarkers and behavior. Additionally, testing associations between biological markers and behavior in larger samples in the natural environment may require more sophisticated instruments that integrate several data types within a single device – such technological advancements would minimize loss of data due to device error, improve

https://doi.org/10.1017/S0033291722001684 Published online by Cambridge University Press

data integrity, and increase the feasibility of large sample sizes through more seamless data collection/merging/processing. Nevertheless, integrating these data types is a burgeoning methodology across fields of behavioral health and psychiatry (Reinertsen & Clifford, 2018), and in spite of its limitations, this paradigm provides a model of methodology for characterizing micro-temporal (i.e. day-to-day) dynamics that influence dysregulated behaviors in the moment.

Conclusions

The present study points to the utility of continuous physiologic monitoring for identifying within-person precipitants of behavior, and potentially detecting differences between patients regarding these precipitants. Mechanistically, the present findings highlight a potential biological marker or predictor of LOC eating which may help identify novel targets for neurocognitive or other interventions. Research directions include probing this possible mechanism in controlled laboratory settings combined with continuous glucose monitoring and potentially examining other measures of inhibitory control. Given that in the present study, LOC eating was measured using a VAS scale, another important research direction is testing relationships with objectively measured eating behavior, such as total intake, either in a laboratory setting or, as alluded to above, with more sophisticated instruments. If results are replicated in larger studies, the ability to identify and predict behavior based on biological markers (or other markers) in the real world points to the potential utility of real-time interventions. Just-in-time adaptive interventions tailor intervention delivery to the user in real time based on previously collected data, and they are commonly used and demonstrate feasibility in weight management interventions to address dietary lapses (Forman et al., 2019) and are being developed in the field of eating disorders (Juarascio, Parker, Lagacey, & Godfrey, 2018).

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

Acknowledgements. The authors thank Drs Katherine Dimitropoulou, Richard Sloan, and William Fifer for consultation regarding commercial devices for ambulatory monitoring of heart rate variability.

Financial support. National Institute of Child Health and Human Development R03 HD090206 (LMR); National Institutes of Mental Health K23 MH121780 (LMR); National Institute of Mental Health T32 MH096679 (BTW); Defense Health Agency HU00011920029 (MH, SS); National Institute of General Medical Studies P20 GM134969 (RDC). The opinions and assertions expressed herein are those of the authors and are not to be construed as reflecting the views of the Uniformed Services University of the Health Sciences or the United States Department of Defense.

Conflict of interest. Dr Crosby is a paid statistical consultant for Health Outcomes Solutions, Winter Park, Florida, USA. The remaining authors have no conflict of interest to declare.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0033291722001684.

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