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Everyday stress components and physical activity: examining reactivity, recovery and pileup

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Abstract The experience of naturally-occurring stress in daily life has been linked with lower physical activity levels. However, most of this evidence comes from general and static reports of stress. Less is known how different temporal components of everyday stress interfere with physical activity. In a coordinated secondary analysis of data from two studies of adults, we used intensive, micro-longitudinal assessments (ecological momentary assessments, EMA) to investigate how distinct components of everyday stress, that is, *reactivity* to stressor events, *recovery* from stressor events, and *pileup* of stressor events and responses predict physical activity. Results showed that components of everyday stress predicted subsequent physical activity especially for indicators of stress pileup. In both studies, the accumulation of stress responses over the previous 12 h was more predictive of subsequent physical activity than current stress reactivity or recovery responses. Results are compared to the effects of general measures of perceived stress that showed an opposite pattern of results. The novel everyday stress approach used here may be fruitful for generating new insights into physical activity specifically and health behaviors in general.

Keywords Ecological momentary assessment · Everyday stress · Physical activity

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Introduction

Physical activity provides many health benefits, including protection against several chronic diseases and premature death and promotion of greater sense of well-being (U.S. Department of Health and Human Services, 2018). The U.S. Department of Health and Human Services issued the *2018 Physical Activity Guidelines for Americans*, which recommends that adults engage in at least 150 min of moderate-intensity physical activity a week or 75 min of vigorous-intensity activity (or an equivalent combination of the two) to gain substantial health benefits as well as muscle-strengthening activities on 2 or more days each week. They also stated that "benefits can start accumulating with small amounts of, and immediately after doing, physical activity" (p. 2, U.S. Department of Health and Human Services, 2018). Yet, in a large community sample, less than 10% of US adults reached the recommended levels of moderate-to-vigorous intensity, as indicated by accelerometer data (Troiano et al., 2008). One factor that may interfere with physical activity is everyday *stress* such as concerns about work, interpersonal conflicts, or unexpected events that disrupt daily life (Almeida, 2005).

In their meta-analysis, Stults-Kolehmainen and Sinha (2014) report that self-reported stress is associated with lower physical activity. However, most studies from this meta-analysis relied on broad and static reports of stress. It is important to note that stress is a multifaceted, temporal process that is initiated by an external or internal stimulus (e.g., a real or imagined experience; a stressor), which, when perceived as harmful or threatening (i.e., threat appraisal), may or may not result in a stress response (Lazarus & Folkman, 1984; Miller et al., 1992; Smyth et al., 2013). More recent theoretical work, drawing from stress theory in general and laboratory experimental work, suggests that everyday stress can be further decomposed into three components: (1) the magnitude of the initial emotional/biological response (i.e., reactivity), (2) the duration of the responses pending a return to baseline (i.e., recovery), and (3) the patterning of reactivity/recovery episodes over time (i.e., pileup) (Smyth et al., 2018). It remains unknown how these different temporal components of stress responses relate to physical activity. Initial reactivity, lack of recovery or the pileup of stress responses could differentially predict engagement in physical activity. In addition, little systematic research has assessed different time windows in which stress effects occur. Are the effects of stress on physical activity immediate, or do they take time to transpire? These gaps create a barrier to implementing interventions that engage relevant targets within these stress processes and enhance, promote, and/or protect physical activity in everyday life. In a coordinated secondary analysis of data from two studies with adults, we used intensive, longitudinal assessments (i.e., Ecological Momentary Assessments, EMA) to investigate how distinct components of everyday stress, that is, *reactivity* to stressor events, *recovery* from stressor events, and *pileup* of stressor events and responses predict physical activity.

Temporal dynamics of everyday stress

Research on stress in daily life has often taken a between-person approach. This work typically conceptualizes stress in broad terms and compares *people* who report feeling more stress to people who report less stress. A focus on between-person differences in global measures of stress obfuscates important temporal dynamics of the stress experience itself. We argue that the experience of stress is more than a general feeling state and is best characterized by considering distinct temporal features of stress. Our theoretical frameworks of stress emphasize the within-person temporally dynamic nature of stress that examines *occasions* of stress unfolding within individuals over time (Lazarus & Folkman, 1984; Smyth et al., 2018). Stressors typically, but not always, give rise to stress responses, including elevated negative affect (Scott et al., 2013). Ideally, these stress responses are followed by a rapid return to pre-stressor levels. Prolonged or repeated activations of stress responses, in particular, can be described as chronic stress (Smyth et al., 2013) and may interfere with functioning in daily life, including the enactment of health-related behaviors. Taken together, this within-person approach to daily stress involves an assessment of the temporal patterning of stress occasions—reactivity, recovery, and pileup—and how each of these components might predict the enactment of physical activity.

Everyday stress components: reactivity, recovery, and pileup

To move towards a more temporally sensitive within-person perspective of stress and its effect on health outcomes, Smyth et al. (2018) proposed three distinct components of everyday stress as it unfolds in daily life. This approach distinguishes stressor occurrences and stressor responses. In our examples and analysis we use negative affect as our stress response indicator, but this approach could similarly be applied to a range of other biological (e.g., cortisol) or cognitive (e.g., perseverative cognitions) responses (Smyth et al., 2018). *Reactivity* is the magnitude of immediate change in an indicator of stress (e.g., negative affect) during a stressor moment compared to non-stressor moments. Thus, within-person reactivity can vary in magnitude and even direction across occasions. Recovery is the extent to which negative affect returns to baseline following the stressor moment. Strong recovery means a large drop equal to or lower than baseline levels in negative affect following initial reactivity to the next non-stressor moment (i.e., no stressor reported), whereas weak recovery means that stress responses did not improve—or even worsened—post-stressor. The latter might occur if, for example, the person continued to dwell, or ruminate, on the stressor long after it occurred (Brosschot et al., 2006). *Pileup* of stress refers to the accumulation of either stressor events (e.g., work conflict), stress responses (e.g., elevated negative affect), or a combination of stressor events and responses across time. In other words, greater pileup refers to a temporal pattern of increased activations within a certain time window, such as the number of stressors over the last 24 h.

Linking everyday stress components to physical activity

In a review of research examining whether stress predicts physical activity, most studies (60%, N = 78) were cross-sectional and thus limited to a between-subjects approach to estimating relations between stress and physical activity (Stults-Kolehmainen & Sinha, 2014). The authors of the review concluded that people with greater stress were less physically active compared to people with less stress. The within-person studies (N = 55) cited in that review generally found results in the same direction, namely that on occasions when individuals reported greater stress they engaged in less physical activity compared to occasions with less stress. Yet there was considerable heterogeneity in these associations. For example, 9 of the prospective studies found a positive relation between stress and physical activity despite the overall conclusion being that a negative relation existed. One explanation for this heterogeneity may be that few studies distinguished between different components of stress. One exception was a 6-week study investigating the relations between both daily stressor frequency and severity on physical activity in a community-residing sample of women (Stetson et al., 1997). They found that weeks of high stressor *frequency*, were characterized by fewer minutes spent on exercising compared to weeks with low stressor frequency. Stress *severity* was not associated with minutes spent exercising. Another ecological momentary assessment (EMA) study found that moderate-to-vigorous activity was predicted by negative affect, but not stressful events, although the events were measured during the same 4-h time interval as the activity, whereas negative affect was measured in the preceding interval (Dunton et al., 2009). Each of these studies assessed stress as a general state and did not attempt to disentangle the contributions of the temporal dimensions of stress reactivity, recovery, and pileup to engagement in physical activity.

Another possibility for the heterogeneity of results in the stress-physical activity literature is the choice of time window for associating stress with physical activity. For instance, one EMA study examined whether perceived stress at the time of the prompt predicted different physical activity intensities in the next 15 min (Jones et al., 2017). They found that stress predicted lower sedentary time but greater light-intensity physical activity duration in the next 15 min, whereas stress and subsequent moderate-to-vigorous physical activity (MVPA) duration were not associated within the same time window. In contrast, Dunton et al. (2009) found that negative affect predicted less MVPA in the next 4 h. A 12-month EMA study with 79 healthy young adults analyzed the data at the day-level (Burg et al., 2017). They observed that stress predicted lower frequency of physical activity the next day, but also observed significant heterogeneity in these associations across individuals—reporting that significant negative associations were observed for 22% of the individuals, and a significant positive association for 1%. It is difficult to compare these studies to determine if the results are due to the choice of time intervals or other study-specific characteristics. The present study starts to address these issues by assessing how reactivity, recovery and pileup of naturally occurring daily stress predict subsequent physical activity across multiple time intervals.

Differentiating the temporal components of everyday stress (i.e., reactivity, recovery and pileup or RRP) may be vital in determining how stress interferes with everyday physical activity. A stressor moment accompanied by strong stress reactivity induces a highly stressful state (i.e., very intense negative affect). The frequency of the stressor and the intensity of the response could each affect behavior. Stressor frequency and intensity might each require increased attentional resources, reprioritization of goals, and other adaptations to deal with the stressor and or response. As such, strong reactivity might disrupt the plans for the day, including leisure-time physical activity, in order to prioritize the threat. In contrast, quick recovery from a stressor might allow the individual to return to homeostasis and pursue the daily life activities as planned. Furthermore, pileup of stress (e.g., high frequency of stressor events within the last 12 h) may over burden the system with few resources available to rearrange plans.

Physical activity could conceivably be disrupted by any of these components of the stress process (e.g., in that they dysregulate motivation). For example, these components could contribute to the well-documented gap between intentions and behavior by impairing the executive functions needed to translate motivation into action or causing self-regulatory processes that guide action control to fail (Hall & Fong, 2007; Rhodes, 2017; Rhodes & Dickau, 2012). Prior to testing mechanisms through which features of stress processes affect physical activity, it is necessary to demonstrate the feasibility and potential utility of examining stress response components in daily life and determining which RRP components are linked to physical activity across very short (i.e., minutes) and somewhat longer time intervals (i.e., hours).

Ecological Momentary Assessments (EMA) studies are well suited to assessing the within person associations of stress responses and physical activity. This design measures time-varying and contextual effects of stress on health and health behaviors. The within-person approach focuses on events that elicit immediate emotional and cognitive responses (i.e., stress reactivity), the momentary appraisals that influence the duration of responses (i.e., stress recovery), and the temporal patterns of responding to and recovering from stressors (i.e., pile-up).

The present study

The present study takes an everyday stress approach to examine the within-person associations between components of the stress responses and physical activity. Within day we tested if stress RRPs—indicated by the dynamics of stressors and negative affective experiences—predicted subsequent physical activity across 10 min, 1 h, and 2 h time windows. Although others have used a longer time window (e.g., Dunton et al., 2009) we chose these shorter time windows to assess and understand proximal temporal links between stress and physical activity that transpire over relatively short time frames. We conducted analyses on two independent EMA studies to allow for replication.

Both of these studies included several within-day assessments of stress responses and device-measured physical activity.

Method

The analyses utilized two independent datasets that included self-reported negative affect and stress in daily life accompanied by accelerometer data on physical activity. The Work & Daily Life study (WDL, hereafter referred to as Study 1) evaluated the association between stress and health in the workplace (see Damaske et al., 2014 for details). The North Texas Heart study (NTH, hereafter referred to as Study 2) sought to evaluate social vigilance as a predictor of subclinical atherosclerosis (see Ruiz et al., 2017, for details).

Study 1

Participants

The initial sample comprised 122 employed adults recruited from the Syracuse, NY, community, based on local phone directories, websites, and public listings on a university email news alert. Participants were invited to participate if they were above 18 years old, fluent in English, employed between 6:00 AM and 7:00 PM on Monday through Friday, not employed on weekends, no report of psychiatric therapy or drug treatment within the last 3 months, and able to visit the laboratory on a Wednesday and the following Monday. In addition, females were not invited if they were pregnant. EMA data for seven participants were lost, yielding 115 participants with analyzable data. Table 1 shows sample characteristics. A majority of participants were female and well-educated with about half of the sample having a college degree.

Measures

Actiheart monitors (CamNtech Ltd., Cambridge, United Kingdom) were used to measure physical activity in daily life. This device is chest-worn and includes a piezo-electric accelerometer that samples activity at 32 Hz as well as a heart rate monitor. Activity count data was stored in 15 s epochs. Previous research has supported the validity and reliability of this device (Assah et al., 2011; Brage et al., 2005; Villars et al., 2012). Total activity counts in 1 min epoch were used as a measure of physical activity volume. To estimate energy expended during physical activity we used the branched equation model reported in the Actiheart user manual. Each 1-min epoch was first coded as sedentary, light, moderate, or vigorous according to pre-specified cut offs. We then estimated the amount of time spent doing *continuous* moderate to vigorous activity by summing up those 1-min epochs for which at least the 10 last minutes were coded as moderate or vigorous.

Handheld computers (Palm Pilot Z22, Palm Inc., Sunnyvale, CA, USA) were used to collect EMA reports of negative affect and experience of stress in daily life using custom software (see Table 1 for items). Negative affect is the mean of two items (i.e., tired and sad) measured at each momentary assessment by asking how the participant was feeling right now. Responses ranged from not at all (0) to extremely (6). Compliance rate was high as participants answered 89.5% of the administered beeps (SD = 12.7, see Table 1).

Procedure

In the first laboratory session, participants completed a battery of questionnaires inquiring about health behaviors and symptoms, demographic information, job satisfaction and contents, and stress. Participants then carried the handheld computer for 3 days, completing 6 assessments a day in response to a beep occurring at random 2-h intervals starting from self-specified wake time (See Table 1). Participants were trained to use the Palm Pilot by a research assistant. Participants subsequently completed 3 days of EMA (Thursday–Saturday) using the handheld computer and the Actiheart monitor.

Study 2

Participants

Study 2, the North Texas Heart study (NTH), is comprised of 300 community adults. Three people were excluded in NTH because the different datasets (accelerometer and EMA) did not match. As shown in Table 1, NTH had an equal distribution of males and females, with education level fairly high (about 60% of the sample having obtained a college degree or higher).

Procedure

Participants first visited a vascular medicine clinic on Thursday mornings. Those participants who exhibited acute illness/infection at the time of this visit were rescheduled. The laboratory sessions were conducted at a single-site vascular medicine clinic located in the community and it functioned as a general clinical research center. During this visit participants underwent brief physical exams, which included reviewing medical and chronic disease history,

Table 1 Overview of sample characteristics, study design, and measures

	Study	
	Study 1 (WDL)	Study 2 (NTH)
Sample		
Sample size	115	297
Age [$M \pm SD$ (range)]	41.2 ± 11.6 (19–63)	42.4 ± 12.8 (21–70)
Gender (% females)	74.8	50
Education (%)		
Less than high school (and N/A)	1.7	2.7
High school or received GED	8.7	10.7
Some college or technical school	40.9	27.0
College degree	31.3	42.7
Graduate or professional degree	17.4	17.0
Sample type	Community, employed	Community
Design		
Study period	3 days	2 days
Beep scheduling	6 random beeps per day, 2-h intervals starting from self-specified wake time	Every 45 min, fixed intervals
Average beeps per person	16.1 ± 2.3 (8–18)	26.0 ± 7.46 (1–40)
Measures		
Physical activity		
Device	Actiheart	Actiwatch Spectrum
Outcome	Activity counts/min	Activity counts/min
Self-report (at each beep)		
Stressor	Since the last prompt, did you experience any of these? (check all that apply)	Since the previous cuff inflation, has anything stressful occurred?
	Argument	Yes/no
	Work stress	
	Traffic Jam	
	Deadline trouble	
	Paying bills	
	Running late	
	Other	
	None	
	Coded as Yes/no	
Perceived stress	At the time of the prompt, how were you feeling? Stressed? 0 (*not at all*) to 6 (*very much*)	In general, how stressed have you been since the previous cuff inflation? 1 (*not at all*) to 7 (*extremely*)
Negative affect	At the time of the prompt, how were you feeling? Sad?	How sad do you feel right now?
	0 (*not at all*) to 6 (*very much*)	How depressed do you feel right now?
	At the time of the prompt, how were you feeling? Tired?	How nervous do you feel right now?
	0 (*not at all*) to 6 (*very much*)[a]	How tense do you feel right now?
		How angry do you feel right now?
		How hostile do you feel right now?
		Each item uses 1 (*not at all*) to 7 (*extremely*)[b]

GED general equivalency development

[a]Negative affect is the mean of two items (tired, sad)

[b]Negative affect is the mean of six items (tense, angry, nervous, hostile, depressed, sad)

current medications and conditions, and health behaviors. They were then asked to carry a smartphone, and wear an actigraphy monitor and an ambulatory blood pressure monitor for the next 2 days and one night (see Table 1). On the first night, participants were instructed to detach the device measuring blood pressure at bedtime and attach and reactivate it upon awakening the next morning. During the days, the ambulatory device sampled blood pressure randomly within 45 min intervals throughout the day, and participants were instructed to complete the EMA questionnaire right after the blood pressure sample.

Measures

The Actiwatch Spectrum (Phillips-Respironics Inc., Bend, OR, USA) was used to measure physical activity in daily life. This wristband device includes a piezo-electric accelerometer that samples activity at 32 Hz as well as sensors for detecting light (color sensitive photodiodes) and off-wear time. Total activity counts in 1-min epochs were used to represent physical activity volume. To our knowledge there are no well-established thresholds for classification of activity levels (sedentary, light, moderate, vigorous activity) based on this device. We therefore focused on activity counts to be able to compare the results across both studies.

The self-report variables were completed on a provided smartphone using custom study software and are shown in Table 1. Experience of stressors were obtained by asking participants, "Since the previous cuff inflation, has anything stressful occurred?". Tense, angry, nervous, hostile, depressed, and sad were also measured as negative affect following each cuff inflation by asking how the participant was feeling right now. Negative affect (NA) is the mean of six items. Responses ranged from not at all (1) to extremely (7). NA and Stressed items have been rescaled in NTH from 1–7 to 0–6 to match the 0–6 scales in WDL. Although the frequency of beeps per participants depended on what time the blood pressure device was turned on and off during the day, participants completed on average 26 beeps across the two study days, which suggests high compliance (see Table 1).

Analyses

Coding everyday stress components using EMA self-report data

Baseline NA To address specific changes in stress in response to stressor moments, the negative affect (NA) levels at those moments need to be contrasted with a baseline, such as non-stressor moments (Smyth et al., 2018). For the present analyses, we used a proximal baseline that corresponds to NA level of the previous EMA prompt that represents a non-stressor moment prior to the stressor (i.e., $t - 1$).[1]

Reactivity to a stressor To measure the extent to which a person reacted negatively to a given stressor moment, we subtracted the baseline from the NA score at a given stressor-moment. This score reflects the NA on a given stressor moment (n) minus the proximal baseline ($n - 1$). For instance, if an EMA observation indicated a stressor event and a NA score of 5, whereas the non-stressor moment prior to that stressor had an NA score of 2, proximal reactivity at that moment would be 3.

Recovery from a stressor This score reflects the degree to which a person's NA recovered from a given stressor moment. This score corresponds to the NA score on a given stressor moment (n) minus the NA score the subsequent non-stressor moment ($n + 1$). For instance, if a stressor moment had NA of 4 and the subsequent non-stressor moment had an NA of 1, the Recovery was 3. That is, greater scores mean better recovery, or greater drop of NA following the last stressor moment.

Pileup To measure the accumulation of stress at a given moment, we drew on three operational definitions of stress. We then created three pileup variables by summing each of these three indicators over a moving 12-h window. This includes all beeps within the last 12 h up to and including the current beep. We chose a moving time to be able to detect how within-person changes in accumulation of stress over time relate to physical activity.

Pileup events We coded (and summed) observations in which a stressor event was reported (since the last assessment) as 1 and observations in which no stressor event was reported as 0.

Pileup responses We coded (and summed) observations in which the NA score was higher than 1.5 *SD*s of the person's own global baseline as 1; all other values were coded 0. With this operationalization we sought to indicate whether a given moment reflected a strong momentary stress departure from one's own baseline.

[1] We also calculated a baseline that corresponded to the person mean of NA on non-stressor moments that satisfy one of the following criteria: To be qualified for the global baseline the observations needed to occur on days that either: (a) contained no reports of stressor moments (i.e., "resting days"), or (b) contained stressor moment(s) but those moments *preceded* the first stressor event that day. In other words, this baseline did not include non-stressor moments that occurred after the first stressor that day. This exclusion aimed to minimize the risk that prior stressors on those days would elevate NA on subsequent non-stressor moments, for instance, in the case of incomplete recovery, and thus underestimate reactivity. Using this baseline made no difference to the pattern or significance of the findings. For the sake of parsimony, we report the occasion specific baseline in the tables and text.

Pileup event and responses We coded (and summed) EMA observations as 1 if both aforementioned conditions were met; all other patterns were coded 0. This variable permits the assessment of having both events and responses differentially predicts PA compared to only events or responses.

Thus, three pileup variables were created by summing each of these three indicators over a moving 12-h window (the end of which includes the current EMA observation). To exemplify, a pileup event score of 3 on a given EMA observation would mean that for all those reports being collected within the last 12 h, the person indicated three moments with at least one stressor.

Analytic strategy

We used multilevel modeling using SAS PROC MIXED (SAS 9.4, SAS Institute Inc., Cary, NC). Multilevel models, in which intercept addressed as a random effect and predictors as a fixed effect, were tested using 2-level model (i.e., within- and between-person levels) in this study. A $p < .05$ was considered significant. Because components of the stress response were measured on different moments we were unable to simultaneously examine RRPs in a single model. We used each of the RRP variables as predictors of physical activity count in separate multilevel models with moments of assessments nested within people. To assess the usefulness of our approach, we compared the effects of RRP to the effects of occasion level negative affect and perceived stress (general stressfulness). Each predictor was centered at its person-mean to elucidate the within-person variability. Person-mean of each predictor was also included in the model to adjust for between-person differences.

We report the results of three time windows for total activity counts; 0–10 min, 0–60 min, 0–120 min after a given EMA observation. The choice of time intervals may be important because it could have a significant impact on the robustness of the statistics (i.e., mean activity count across different periods) and their temporal coincidence with related variables (i.e., RRPs). We carefully considered this and varied the time interval to test the immediate (10 min), medium (1 h), and relatively long (2 h) within-day associations between physical activity and stress components. The mean activity counts during each time interval were calculated to provide an index of total activity accounts adjusted for interval length that would be comparable across models.

That is, we included the within-person and between-person effect simultaneously in each model, but RRP variables were analyzed in separate models. An example of the detailed multilevel model we used in this study is listed below.

Level-1 equation (within-person level):

$$\mathrm{PA}_{ij} = \pi_{0j} + \pi_{1j}(\mathrm{RRP}_{ij} - \overline{\mathrm{RRP}}_j) + \varepsilon_{ij}$$

Level-2 equations (between-person level):

$$\pi_{0j} = \gamma_{00} + \gamma_{01j}\overline{\mathrm{RRP}}_j + \zeta_{0j}$$

$$\pi_{1j} = \gamma_{10}$$

where PA_{ij} indicates the dependent variable (i.e., mean activity count from 0–10, 0–60, or 0–120 min time window) at the ith observation for the jth subject; RRP_{ij} is the predictor (i.e., each RRP) corresponding to the ith observation for the jth subject; the $\overline{\mathrm{RRP}}_j$ variable in the level-1 equation is the person mean of the predictor used for centering the predictor to estimate the within-person effect on the dependent variable; π_{0j} and π_{1j} are the subject j's intercept and B coefficient (i.e., slope) of the predictor, respectively; γ_{00} is the average intercept across all subjects; γ_{10} is the average slope across all subjects; the $\overline{\mathrm{RRP}}_j$ in the level-2 equation is the person mean of each RRP to estimate the between-person effect; the random terms ζ_{0j} is the between individual residual, meaning that the intercept varies across individuals; and ε_{ij} is the within individual residual. To make it easier to compare results across the two accelerometer devices we standardized activity counts by subtracting the grand M of all 1-min epoch scores from the observed score, then dividing this difference by the grand SD of all epoch scores.

Results

The descriptive summary of the measures for each study is shown in Table 2. The upper section presents information for the stress variables. The positive reactivity scores indicate that stressor moments were accompanied by increased NA relative to the prior non-stressor moments. The positive recovery mean score indicates that NA generally dropped on non-stressor moments compared to the prior stressor moments. The means for pileup event scores indicate that, on average, participants had reported about 1 stressor event within the last 12 h. The individual standard deviations (iSD) indicate a high degree of within-person variation in each component of the stress response across the days. The amount of within person variability is roughly equal to the amount of between-person variation (*SD*). The lower section summarizes the activity counts. Across the entire study 1 sample, 12.5% of the days yielded at least 30 min of moderate-to-vigorous physical activity.

Table 3 presents the between- and within-person correlations of the stress-related variables in both studies. At the

Table 2 Descriptive summary of stress and physical activity measures

Variables	Study 1 (WDL)			Study 2 (NTH)		
	M	*SD*	*iSD*	*M*	*SD*	*iSD*
Stress						
Reactivity	0.22	0.85	0.74	0.45	0.62	0.64
Recovery	0.07	0.82	0.89	0.41	0.54	0.51
Pileup stressor events	1.06	0.61	0.89	1.13	1.10	0.92
Pileup stress responses	0.43	0.47	0.53	1.19	1.10	1.07
Pileup events and responses	0.19	0.31	0.27	0.52	0.69	0.51
Perceived stress	1.30	0.88	1.22	0.99	0.87	0.94
Negative affect	1.43	0.83	0.88	0.45	0.61	0.39
Physical activity (post-EMA average activity counts/min)						
0–10 min window	27.31	22.55	33.85	228.0	60.07	127.2
0–60 min window	29.22	17.36	27.01	252.2	60.04	92.43
0–120 min window	29.08	18.00	23.64	256.4	58.93	75.28

M is calculated by taking the mean of all personal means. *SD* is calculated based on *M* and thus reflects variability of personal means, whereas *iSD* is calculated by taking the mean of all within-person SDs. Pileup is the sum of events or responses over the last 12 h, including current EMA beep

between-person level, individuals with greater stress reactivity had greater recovery scores (that is, those who had stronger initial reactions to stressors also had greater drops in NA post stressor moment). Stress reactivity and recovery were unrelated to pileup of stressor events, but reactivity was associated with pileup of stress responses in both studies (*rs* = .16, and .20). At the within-person level the stressor variables showed low to modest associations with each other suggesting some independence of these variables as they are experienced by an individual over time. The one exception is the high correlations of the stressor reactivity with negative affect. This is expected, given that negative affect variable is used as the indicator to construct the reactivity variable.

Table 3 Correlation matrix with reactivity, recovery, pileup 12 h, perceived stress, and negative affect (study 1 [WDL] above the diagonal, study 2 [NTH] below the diagonal)

Variables	1	2	3	4	5	6	7
Within-Person							
1. Reactivity	1	–	.10	.08	.20**	.17**	.50***
2. Recovery	–	1	− .03	− .05	.09	− .17**	− .55***
3. Pileup: event	− .03	− .00	1	.33***	.46***	.14***	.13***
4. Pileup: response	− .05	.04	.57***	1	.70***	.09***	.40***
5. Pileup: event and response	.16***	.16***	.73***	.74***	1	.14***	.33***
6. Perceived stress	.28***	.01	.18***	.12***	.18***	1	.30***
7. Negative affect	.72***	− .12**	.12***	.20***	.23***	.50***	1
Between-Person							
1. Reactivity	1	.38***	.05	.29**	.36***	.19	.13
2. Recovery	.59***	1	.14	.13	.19	.21*	.22*
3. Pileup: event	− .04	− .04	1	.19	.43***	.49***	.39***
4. Pileup: response	.14*	.09	.52***	1	.85***	.17	.16
5. Pileup: event and response	.20**	.15*	.75***	.84***	1	.29**	.25*
6. Perceived stress	− .00	.01	.49***	.21**	.32***	1	.76***
7. Negative affect	.08	.07	.37***	.13*	.21**	.81***	1

Within-person correlations were computed with SAS PROC CORR on within-person centered variables. Between-person correlations were computed with SAS PROC CORR on person means of variables

***$p < .001$, **$p < .01$, *$p < .05$

Associations between everyday stress and physical activity

Table 4 shows the results from the mixed model analyses. Separate models were computed for each predictor variable and time window. In each model the within-person and between-person effect were computed. There were no within-person associations for stressor reactivity or for stressor recovery on subsequent physical activity. At the between-person level there was only one significant reactivity and recovery coefficient observed out of 12 estimated coefficients across the two datasets, an association between reactivity and activity counts averaged across the occasions the WDL dataset (b = − .65). This between-person association indicates that individuals who experienced greater average reactivity engaged in less physical activity 10 min after the beep compared to individuals with less stress reactivity.

In contrast, there was a clear pattern of results for stressor pileup. The pileup variables significantly predicted lower subsequent physical activity at the within-person levels and all of the coefficients were in the expected negative direction. These results were more consistent in Study 2 than Study 1. In both studies greater pileup of stress responses summed over the last 12 h predicted lower average activity counts in the next 1- and 2-h time windows (3 significant out of 4 observed estimates, *Betas* range from − .07 to − .26). In Study 2, there was also evidence indicating that greater pileup of stressor events and the combination of events and responses predicted lower subsequent activity counts across all of the time windows (*Betas* range from − .12 to − .14). A different pattern emerged at the between-person level in Study 2, where all

Table 4 B coefficients (SEs) of mixed models with reactivity, recovery, pileup, perceived stress, or negative affect as predictors and accelerometer activity counts (AC) as outcomes

Predictors	Study	Within-person associations with post-EMA activity counts/min			Between-person associations with post-EMA activity counts/min		
		0–10 min window	0–60 min window	0–120 min window	0–10 min window	0–60 min window	0–120 min window
Reactivity	1	− 0.01 (0.15)	− 0.06 (0.22)	− 0.13 (0.17)	− 0.65 (0.29)*	− 0.15 (0.30)	− 0.07 (0.24)
	2	0.09 (0.13)	− 0.08 (0.11)	0.00 (0.09)	− 0.28 (0.21)	− 0.29 (0.17)	− 0.25 (0.16)
Recovery	1	− 0.26 (0.17)	0.14 (0.21)	0.16 (0.13)	1.48 (0.75)	0.24 (0.24)	0.05 (0.05)
	2	0.14 (0.17)	− 0.05 (0.13)	− 0.04 (0.11)	− 0.12 (0.24)	− 0.17 (0.18)	− 0.23 (0.17)
Pileup: event	1	− 0.03 (0.08)	− 0.08 (0.07)	− 0.09 (0.06)	− 0.10 (0.16)	− 0.04 (0.16)	0.02 (0.16)
	2	− 0.08 (0.03)**	− 0.07 (0.03)*	− 0.08 (0.03)*	0.16 (0.05)**	0.18 (0.05)***	0.19 (0.05)***
Pileup: response	1	− 0.18 (0.13)	− 0.22 (0.10)*	− 0.26 (0.09)**	− 0.04 (0.25)	− 0.08 (0.22)	− 0.18 (0.22)
	2	− 0.09 (0.03)**	− 0.07 (0.03)*	− 0.07 (0.04)	0.15 (0.05)**	0.13 (0.06)*	0.15 (0.06)**
Pileup: event and response	1	− 0.10 (0.21)	− 0.23 (0.16)	− 0.23 (0.15)	− 0.26 (0.37)	− 0.31 (0.33)	− 0.36 (0.33)
	2	− 0.12 (0.05)*	− 0.12 (0.05)*	− 0.14 (0.05)*	0.20 (0.09)*	0.20 (0.09)*	0.23 (0.09)*
Perceived stress	1	− 0.04 (0.06)	0.03 (0.05)	0.06 (0.04)	0.04 (0.12)	− 0.05 (0.11)	− 0.03 (0.11)
	2	0.07 (0.03)*	0.07 (0.02)**	0.07 (0.02)**	0.22 (0.07)**	0.20 (0.07)**	0.21 (0.07)**
NA overall[a,b]	1	− 0.08 (0.09)	− 0.17 (0.07)*	− 0.18 (0.06)**	0.15 (0.12)	0.00 (0.12)	0.00 (0.11)
	2	0.09 (0.06)	0.12 (0.06)*	0.09 (0.06)	0.23 (0.11)*	0.24 (0.10)*	0.25 (0.10)*
NA high activation[c]	2	0.11 (0.05)	0.14 (0.05)**	0.12 (0.05)*	0.27 (0.10)**	0.27 (0.10)**	0.28 (0.10)**
NA low activation[d]	2	0.00 (0.05)	0.01 (0.05)	− 0.01 (0.05)	0.08 (0.10)	0.10 (0.10)	0.10 (0.10)

The predictors are analyzed in separate models. Reactivity, Recovery, and Pileup are based on Overall NA. The baseline is person mean of resting + proximal baseline for all RRPs

Pileup aggregation is over 12 h (sum scores) and does not reset across days

Activity scores are standardized (subtracted by grand mean and then divided by SD of grand mean)

The fixed effect model was used in all WDL analyses due to failure to converge for the random effect model

[a]Tired and sad

[b]Tense, angry, nervous, hostile, depressed, and sad

[c]Tense, angry, nervous, and hostile

[d]Depressed and sad

[e]The random effects model failed to converge after 25 iterations. This result is from the fixed effect model

***$p < .001$, **$p < .01$, *$p < .05$

of the coefficients were positive and significant (*Betas* range from .20 to .23). People who, on average, reported higher pileup also exhibited higher activity counts. This association held for all three types of pileup (event, response and combined event and response). In Study 1, the between-person associations between pileup and activity counts were not significant, and the only significant within-person associations involved response pileup and PA in the 1- and 2-h time windows. We followed up on the associations between pileup and activity count by examining a clinically meaningful outcome: the odds of not engaging in at least 30 min of moderate-to-vigorous PA over the course of a day (which we could estimate in Study 1). On days when individuals had one more pileup event than their average, they had a significantly higher odds of failing to reach at least 30 min of moderate-to-vigorous PA, odds ratio (OR) = 1.552, 95% CI [1.02, 2.37]. The odds ratios were not significantly different from 1 for pileup response, OR = 1.03, 95% CI [0.57, 1.85], or pileup response and event, OR = 2.31, 95% CI [0.75, 7.15]. These day-level results should be interpreted with caution as there were only 38 days in which people reached at least 30 min of moderate-to-vigorous PA.

As a comparison to the findings on stress responses, the final rows of Table 4 show the association between NA or perceived stress and subsequent PA. In Study 2, greater perceived stress and high activation NA (Tense, Angry, Nervous, and Hostile) predicted higher activity counts in the next 2 h. In Study 1, low arousal NA (sad, tired) predicted lower activity counts in the next 2 h (Study 1 had no items representing high activation NA) and the association of perceived stressed on later physical activity was in the same direction as in Study 2, but was not statistically significant.

Discussion

The overarching goal of this study was to understand which temporal components of stress impede physical activity. A coordinated analysis using two EMA studies with intensive assessments of stress every 45 to 120 min and device-monitored physical activity yielded four main findings: (a) Pileup of stress is more predictive of subsequent activity than reactivity or recovery responses; (b) The effects of everyday stress pile-up differ from the effects of perceived stress on physical activity; (c) Associations are more likely to be observed after longer periods relative to shorter periods; (d) Within-person associations differ from between-person associations.

One aim of this paper was to provide an example of the everyday stress approach (Smyth et al., 2018) applied to the prediction of physical activity. This approach delineated the temporal components of stress (reactivity, recovery and pileup) and assessed within-person links of these components to subsequent PA. Other research on stress and PA has relied primarily on static and general reports of stress (Stults-Kolehmainen & Sinha, 2014), but the everyday stress approach views stress as a process with distinct temporal components. Our initial results provided evidence for face validity of this approach in both studies. Compared to prior non-stressor moments (baseline), participants reported increases in NA during stressor moments (reactivity), followed by decreases in NA following stress moments (recovery), and accumulation of stress events and responses over time (pileup). The relatively large means in Study 2 might be due to the shorter assessment intervals compared to Study 1 (45 min vs. 120 min). There was also a relatively large degree of within-person variation in these components across the day. That is, the level of individual stress responses differed at different points across the day. We used this variation to predict subsequent physical activity across very short (0–10 min) to longer time intervals (0–60 and 0–120 min).

Everyday stress and PA: temporal components matter

One novel component of everyday stress, stress pileup, was associated with lower subsequent PA. In study 2, the accumulation of stress events and responses significantly predicted decreases in PA across most of the time intervals. Response pileup was the most consistent predictor, with significant associations observed with physical activity in each of the two studies. On occasions when participants accumulated stress responses over the past 12 h, they exhibited less physical activity in the subsequent 1 to 2 h. Our follow-up analysis indicated that on days when individuals experienced one more pile-up stressor than typical, the odds of failing to meet the recommended 30 min of moderate-to-vigorous PA were 55% greater than the odds of succeeding. Note that we were only able to test this in one study and urge reapplication of this finding. Overall, the accumulation of stress responses appears to limit the volume of physical activity. Note that most field studies of daily stress rely on checklists to determine overall stressor exposure (e.g., Almeida, 2005) and thus are not able to determine pile up of stress responses.

Stress reactivity and recovery were not associated with PA, but the pattern of results was in the expected direction. The lack of significant findings may reflect relatively small amounts of change in stress responses. In order for these responses to affect PA they may need to be more extreme. Small and acute perturbations in stress responses may not carry enough signal to disrupt PA. Although we did have variation in the responses, we did not have enough sampling occasions to test more extreme stress responses. This effect can be seen in the response pileup results where the accumulation of a relatively high response (1.5 SD greater than a persons' average) predicted PA in both studies.

The overall pattern of results suggests that pileup of everyday stress may be particularly pernicious for disrupting PA and may be a good target for intervention. Next steps are to understand potential mechanisms for this association. For example, does pile-up disrupt the translation of intention into action (Rhodes & Dickau, 2012)? Or does pile-up interfere with plans for physical activity (Schwarzer, 2008)? Pileup could also alter the priority that individuals place on or the effort they invest in pursuing physical activity goals amidst competing adaptational challenges. As everyday stress piles up, individuals may have less time to be physically active as they manage the challenges of their stress. On these pile up occasions, they may also have less motivation and less energy to be physically active.

These results differ from findings for perceived stress. Respondents' general feeling of stress was either unrelated to PA (Study 1) or positively related to PA (Study 2). In contrast to the temporal components of stress that were measured in the present study, global perceived measures of stress often ask participants how stressed they felt and/or the extent to which they feel they could control important things in their lives (Cohen et al., 1983). Our findings point to the importance of how stress can be measured and the different assumptions that may accompany each method. In other words, a person's report on the temporal components of stress reflects different information than global assessments, such as how negatively the person experienced that stress, or how stressed and out of control she or he felt at that time. Although speculative, it is possible that people who are reporting feeling out of control because of stress may attempt to reassert control by scheduling and engaging in physical activity (Berger, 1994; Pierceall & Keim, 2007). Future work should continue to explore different ways of assessing stress and how these different measures might relate to physical activity, given that physical activity can be both a planned activity that can be derailed due to stress as well as a coping strategy to deal with stress.

Different findings for between-person results

The pattern of findings was different at the between person level. In study 2, people who experienced greater everyday stress pileup exhibited more physical activity compared to people who experienced less pileup. This finding is in the opposite direction of the within-person findings in study 2. Between-person associations do not reflect within person processes. That is, reasons for people to vary from one another in their levels of stress and physical activity may be unrelated to reasons that contribute to people being less physically active following occasions when they are stressed. In addition, between-person differences do not specify the temporal sequence underlying the association. Physically active people might be adding their physical activity goals to other goal pursuits in an already busy day, resulting in greater stress on average. Our everyday stress approach emphasizes within-person predictions where we can specify the direction of effect from stress to PA. The between-person associations between stress and PA could also be due to stable third variables (age, personality). For example, prior research has shown that younger adults experience more stress (Almeida & Horn, 2004) and are more physically active (Caspersen et al., 2000). Another advantage of the within-person approach holds all stable third variables constant thereby eliminating the risk of this type of stable third variable confounding. (Almeida, 2005).

Limitations and future directions

Although this paper presents some initial and important findings on the use of an everyday stress approach to physical activity, a number of limitations need to be noted. First, there were a limited number of days in both studies to assess within-person linkages. This resulted in fewer stress episodes than optimal to assess the effects of reactivity and recovery and decreased power to establish significant associations. Future research should strongly consider longer monitoring periods. More stress episodes would also increase the opportunity to assess more extreme stress responses that might be more likely to drive health behaviors. More sampling days would also allow better discrimination between pile-up, time of day, and day of week effects. In addition the EMA design might introduce some reporting bias due to the intensive nature of data collection. The burden of providing multiple assessments across the day may result in less accurate reporting due to habituation or fatigue.

This study did not assess the intensity, frequency, or duration of physical activity. These dosing parameters may be particularly important in assessing if components of every stress responses specifically disrupt the ability to meet recommended levels of moderate-to-vigorous intensity physical activity. Previous EMA research failed to find evidence of perceived stress and subsequent intensity of activity (Jones et al., 2017). Incorporating intensity information would provide valuable information on the role of everyday stress in disrupting physical activity and could help to explain the low prevalence of U.S adults meeting recommended levels (Troiano et al., 2008).

Even in light of these limitations we believe that this preliminary research lays the ground work for assessing everyday stress intensely within the day and across multiple days but also for developing interventions that target the components of everyday stress. The preliminary work suggest that the best target to increase PA would be to focus on stress pileup. One rationale for targeting pileup is that physical activity is often not something that is done multiple times per day and often does not occur daily for most people. Thus, measures of reactivity and recovery may actually be too fine-grained temporally to detect lower activity levels that are due to stress. Additionally, an advantage for targeting pileup is the potential to act proactively rather than reactively. In other words, pileup is something that occurs over the course of the day, with a certain level of pileup possibly needed to disrupt physical activity. As such, it may be possible to monitor individuals in real-time and prophylactically act when a certain pileup score is reached. For example, if an individual reports their second stressor of the day, they could be instructed to engage in controlled breathing or mindfulness meditation as a way to calm down and reset. Such an intervention approach may then limit the likelihood of additional stress occurrences, or less emotional reactivity in a subsequent stress occurrence, which could raise pileup to the critical threshold level that derails physical activity. Future work should continue to assess what level of pileup is most detrimental to engaging in physical activity so as to calibrate the timing of intervention delivery.

Conclusion

Having frequent and recurrent stress responses—i.e., the pileup of everyday stress—consistently predicted subsequent decreases in short-term physical activity in two separate EMA studies. In contrast, there were no significant effects for indicators of acute stress reactivity or recovery. By assessing everyday stress as it unfolds within individuals over time, delineating stress into temporally distinct components, and focusing on within-person prediction we hope that these findings encourage others to take an everyday stress approach to understanding physical activity and potentially other health behaviors.

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Compliance with ethical standards

Conflict of interest David M. Almeida, David Marcusson-Clavertz, David E. Conroy, Jinhyuk Kim, Matthew J. Zawadzki, Martin J. Sliwinski, and Joshua M. Smyth declare that they have no conflict of interest.

Human and animal rights and Informed consent All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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