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A Pilot Study of Temporal Associations Between Psychological Stress and Cardiovascular Response

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Abstract— **Psychological stress (PS) in daily life can trigger acute changes in cardiovascular function and may lead to increased risk of cardiovascular problems. Prior laboratory-based studies provide little evidence on temporal changes in the associations between PS and cardiovascular responses in natural settings. We hypothesized that daily PS would be associated with higher heart rate (HR) and lower heart rate variability (HRV). Using smartphones, ten participants (four females, 21.1±1.1 years) completed ecological momentary assessment (EMA) 6 times a day for two weeks regarding their current affective state. Participants rated levels of PS, as well as 3 high-arousal negative affect (HNA: Anxious, Annoyed, and Upset), and 3 low-arousal negative affect (LNA: Sluggish, Bored, and Sad) states. They also wore a chest-mounted heart-rate monitor and a wrist accelerometer to monitor cardiovascular response and physical activity, respectively. HR and HRV variables in the time intervals (5, 30, 60 min) before and after EMA were used as indicators of cardiovascular response. Multilevel modeling was used to examine the association between affect and HR/HRV, controlling for physical activity. Higher HR and lower HRV were related to subsequent greater feelings of stress at the 5 and 30-min time intervals. No significant associations were observed between cardiovascular parameters and subsequent affective states, suggesting that the acute exaggerated cardiovascular responses occurred due to PS. Higher LNA was related to antecedent/subsequent lower HR or higher HRV within 2 hours, while HNA was unrelated to HR or HRV for all time intervals, suggesting that both high/low arousal NA were not related to exaggerated cardiovascular response. Understanding psychological feelings of stress and LNA may be helpful in the management of daily cardiovascular health.**

I. Introduction

Psychological stress (PS) is considered a risk factor for cardiovascular disease. PS in daily life causes acute increases in cardiovascular parameters such as heart rate (HR) and blood pressure [1]. Prior studies conducted in laboratory settings have revealed that repeated and prolonged exposure to daily stressors leads to an increased risk of development of cardiovascular disease [2]. However, in many of these studies, measures of PS (i.e., indicators of affective responses to stressors) and cardiovascular responses have been collected under controlled experimental environments over limited periods of time (e.g., 1-2 hours), which does not capture fluctuations and limits generalizability to real life [3].

Recent technological and methodological advances have been made in the assessment of ambulatory measures in daily life [4]. Self-reported behaviors and psychological states can be monitored real-time using electronic diaries, capturing fluctuations in daily experiences. Also, modern wearables can continuously monitor physiological responses such as physical activity and HR over periods of weeks or months. Although a few ambulatory studies using these methods have found exaggerated cardiovascular responses to PS [1], little is known about real-world temporal changes in their relationship. Also, these studies show mixed findings, which might be explained by them having examined temporal associations over relatively short study periods (e.g., 1-2 days at most).

Here, we investigate the temporal dynamics of the associations between cardiovascular responses and PS by simultaneously using ecological momentary assessment (EMA) [5] to assess affect, and wearables to conduct ambulatory assessment of cardiovascular functions over a longer study period (i.e., two weeks). We hypothesized that PS is associated with higher HR and lower heart rate variability (HRV). Understanding how cardiovascular function changes with PS in the everyday environment is expected to help generate strategies for timely management/intervention to prevent progression of cardiovascular disease.

II. Methods

A. Participants

The participants were students from Shizuoka University (Shizuoka, Japan) who were at least 18 years old and did not have medical issues or ongoing drug treatment. All participants signed an institutionally approved informed consent form after receiving a full explanation of the purposes and potential risks of the study given by well-trained staff. Of the 13 participants, three were excluded from the analyses because they did not complete the assessments of affective ratings by EMA (n=1) or cardiovascular functions by ambulatory assessment (n=2). Data from 10 participants (6 males/4 females, 21.1 ± 1.1 years of age) were analyzed in this study. Participants who completed the entire study were compensated with a 10k JPY (~100 USD) book gift card. The

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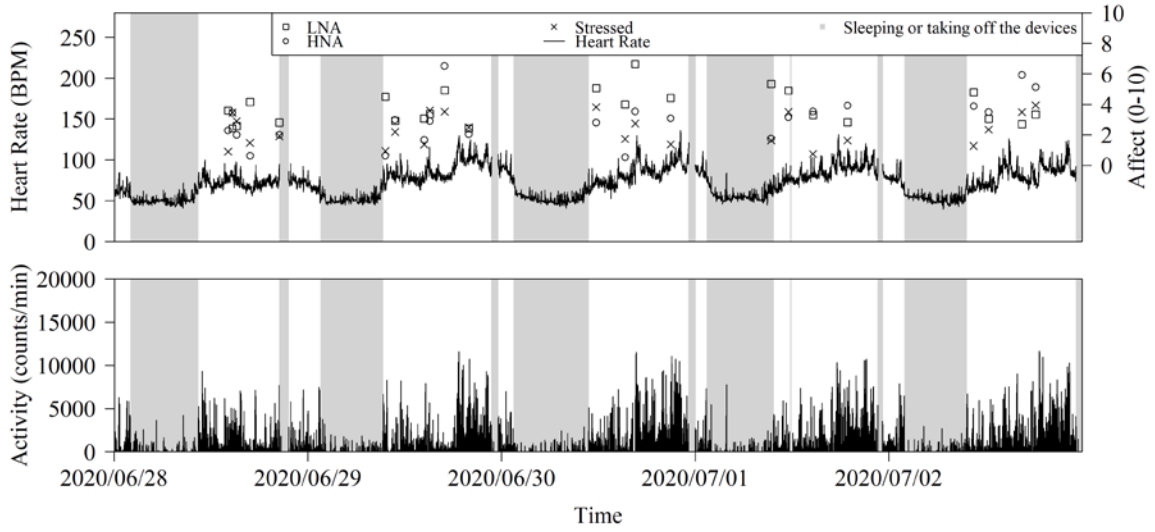

Fig. 1 Fluctuation in psychological stress and heart rate. Top: Example of a participant's perceived stress (i.e., "Stressed") and negative affect (NA) assessed by ecological momentary assessment (EMA) and simultaneously collected heart rate by a chest-strap wearable device for two weeks. Crosses indicate scores of Stressed. Squares and circles represent low-arousal NA and high-arousal NA, respectively. Heart rate is shown using a solid line. The periods shaded in gray are times during which the subject was sleeping or had taken off the device. **Bottom**: Physical activity is also simultaneously measured to adjust the confounding effects on the associations between Stressed/NA and heart rate (variability).

study was approved by the institutional review board at Shizuoka University.

B. Ecological Momentary Assessment of Psychological Stress

Using a smartphone application, participants were asked to complete PS assessments 6 times per day (Fig. 1). Assessments were signaled by a random beep alarm at approximately two-hour intervals between 9:30 to 20:30. Affect measurements were completed with a 7-item questionnaire (one item for Stress: Stressed and 6 items for negative affect (NA): Anxious, Annoyed, Upset, Sluggish, Bored, and Sad) about their current affective state rated on a Likert-type response scale ranging from 0 (Not at all) to 10 (Very much). Following previously used circumplex approaches [6], the 6 items for NA ratings were classified as high-arousal NA (HNA) or low-arousal NA (LNA). To estimate HNA, the items Anxious, Annoyed, and Upset were averaged. To estimate LNA, the items Sluggish, Bored, and Sad were averaged. Participants averaged 53.1 (SD=14.8, Range: 33-83) completed assessments over the two weeks.

C. Ambulatory Assessment of Cardiovascular Functions

Participants were asked to wear a Polar H10 device (Polar Electro Oy, Kempele, Finland) on their chest to monitor cardiovascular function. On their non-dominant wrists, participants also wore an activity monitor (wGT3X-BT, ActiGraph LLC, Pensacola, FL, USA) capable of automatically recording physical activity using a tri-axial accelerometer (see the data example from two devices in Fig. 1). The data obtained by the Polar H10 device were automatically saved in the activity monitor via Bluetooth. We simultaneously monitored cardiovascular parameters and physical activity due to the important confounding effects physical activity can have on cardiovascular response [7]. This approach allows us to clarify whether physical activity either attenuates or exaggerates the cardiovascular response to PS.

The per minute HR and RR intervals (ms) were used as indicators of cardiovascular function. The RR intervals were first processed for extra or missing beats using the automatic artifact correction algorithm provided by the HRV analysis software Kubios HRV Standard [8]. The intervals identified as abnormal by the processing algorithm were then manually inspected and corrected by the insertion/omission of missing/extra beats [9]. The time-domain HRV measurements were computed from RR intervals. The following variables were used to quantify the HRV every minute: standard deviation of RR intervals (SDRR) and root mean square of successive differences (RMSSD) between heartbeats [10]. Activity counts accumulated every minute were used as physical activity.

D. Analytic Plan

To examine how affective indicators of PS (i.e., Stress, LNA, and HNA) predicted subsequent HR/HRV and vice versa, we used HR and HRV for various time intervals before or after the affect rating (i.e., each EMA beep). HR, SDNN, and RMSSD per minute were averaged for each time interval. Activity counts per minute were also averaged for each time interval: short (5 minutes), medium (30 minutes), and long (1 hour) time intervals before/after each EMA to reflect momentary to sustained effects. For example, because the epoch size of HR is one minute, HR using a 30-minute time interval was calculated from 30 data points. The data for each time interval were excluded from the analysis when the HR, HRV or activity counts were missing (i.e., suggesting the devices had been removed) or defined as sleep judging by the accelerometer data.

To deal with the hierarchically structured data set in this study, we employed a multilevel modeling approach [11] using SAS PROC MIXED (SAS 9.4, SAS Institute Inc.,

Cary, NC). Separate multilevel models were estimated for i) PS (i.e., Stress, LNA, or HNA) as a predictor of subsequent HR or HRV outcome variables and ii) vice versa. All models were estimated with 2-levels (i.e., beep and person) in which the EMA for PS and the corresponding time intervals of averaged HR, HRV, and activity counts were nested within persons. Multilevel models with random intercepts and fixed predictors were used. Person-mean centered predictors were used to test the within-person variability in each model. The person-mean was also included in the model as a predictor to adjust for between-person differences. Physical activity (i.e., mean activity counts over each time interval) was included as a covariate in each model to control for confounding effects on the associations between PS and cardiovascular functions. A $p<0.05$ was considered significant.

III. Results

A. Recording Profiles

The mean±SD ratings across participants of Stress, LNA, and HNA over the two weeks were 2.6±2.1, 1.8±1.1, and 1.9±1.4, respectively. Descriptive statistics for cardiovascular function and physical activity are shown in Table I.

B. Psychological Stress Predicting Subsequent Cardiovascular Functions

Table II shows the association between affective state and subsequent HR or HRV (i.e., SDRR and RMSSD) after controlling for physical activity in 5, 30, and 60 minutes time intervals. Participants had higher HR after instances when they reported greater LNA than their person-mean LNA (i.e., higher relative to their usual ratings in all time intervals: 5-minute (B=-1.51, SE=0.46, $p<0.01$), 30-minute (B=-1.42, SE=0.41, $p<0.01$) or 60-minute time interval (B=-1.25, SE=0.41, $p<0.01$). Meanwhile, Stress and HNA ratings were not associated with subsequent HR at any time interval. Current LNA was positively associated with SDRR or RMSSD during the next hour (see Table II). Neither Stress nor HNA ratings were related to subsequent SDRR and RMSSD in any time intervals. The controlled for variable 'activity counts' was positively significantly associated with HR, SDRR, and RMSSD (results not shown).

TABLE I. DESCRIPTIVE STATISTICS OF CARDIOVASCULAR FUNCTION AND PHYSICAL ACTIVITY

	Heart rate	SDRR (ms)	RMSSD (ms)	Activity counts
Time intervals *before* affect				
Prior 5 min	78.5±8.4	62.3±14.2	39.9±12.3	1743.6±423.9
Prior 30 min	79.1±8.8	61.1±13.5	39.5±12.4	1839.8±637.8
Prior 60 min	79.4±9.1	60.2±13.0	39.0±12.4	1855.6±664.1
Time intervals *after* affect				
Next 5 min	78.0±8.9	64.8±14.7	40.8±12.6	1966.1±490.0
Next 30 min	78.3±9.6	61.5±13.6	40.3±13.1	1898.5±524.4
Next 60 min	78.6±9.8	60.5±13.5	39.7±12.6	1873.7±573.5

Note. The values represent person mean and standard deviation (i.e., Mean±SD) for heart rate, heart rate variability, and activity counts per minute averaged during each time interval before and after affect ratings. SDRR: SD of the RR intervals. RMSSD: root mean square of successive differences between heartbeats.

TABLE II. MULTILEVEL MODEL PREDICTING SUBSEQUENT CARDIOVASCULAR FUNCTIONS FROM CURRENT PSYCHOLOGICAL STRESS

	Cardiovascular functions		
	Next 5 min	Next 30 min	Next 60 min
Affect -> Heart rate			
Person-mean centered stressed	0.46 (0.23)	0.05 (0.23)	0.17 (0.23)
Person-mean centered LNA	-1.51 (0.46)**	-1.42 (0.41)**	-1.25 (0.41)**
Person-mean centered HNA	0.28 (0.32)	-0.20 (0.29)	-0.18 (0.30)
Affect -> SDRR			
Person-mean centered stressed	0.77 (0.96)	0.43 (0.33)	-0.08 (0.29)
Person-mean centered LNA	2.20 (1.58)	1.73 (0.61)**	1.28 (0.55)*
Person-mean centered HNA	0.25 (1.10)	0.69 (0.43)	0.66 (0.40)
Affect -> RMSSD			
Person-mean centered stressed	0.04 (0.43)	0.18 (0.31)	-0.07 (0.31)
Person-mean centered LNA	1.83 (0.73)*	1.84 (0.53)**	1.62 (0.53)**
Person-mean centered HNA	0.16 (0.51)	0.61 (0.38)	0.45 (0.38)

Note. B coefficients (and standard errors) of multilevel models which indicate the within-person associations between person-mean centered affect ratings and subsequent cardiovascular responses are shown. All coefficients are estimated in a separate multilevel model after controlling person-mean of affect ratings and activity counts as a covariate. Heart rate and heart rate variability per minute are calculated from each time interval: 1-5, 1-30, or 1-60 minutes *after* affect ratings. SDRR: standard deviation of the RR intervals. RMSSD: root mean square of successive differences between heartbeats. ** $p<0.01$, * $p<0.05$.

C. Cardiovascular Function Predicting Subsequent Psychological Stress

Stress, LNA, and HNA ratings regressed on HR, SDRR, or RMSSD in the preceding 5, 30, and, 60-minute time intervals are shown in Table III. Higher HR during the preceding 5 minutes (B=2.27, SE=0.88, $p=0.01$) or 30 minutes (B=2.35, SE=1.06, $p=0.03$) was observed before instances when participants were more stressed than usual; this did not extend to the prior 60 minutes. In addition, lower SDRR was related to higher PS in the previous 30 minutes (B=-1.59, SE=0.80, $p=0.05$) and 60-minute time interval (B=-1.82, SE=0.95, $p=0.06$; marginally significant). LNA was associated with prior HR, SDRR, or RMSSD in all time intervals (see details in Table III). We did not find any significant associations between HNA and either measure of cardiovascular function at any time intervals. Activity counts were significantly associated with HR, SDRR, and RMSSD (results not shown).

IV. Discussion

The associations between PS and acute cardiovascular response in daily life are not fully understood. We observed that PS was related to cardiovascular responses such as HR and HRV after controlling for physical activity. Participants had higher HR in the 30 minutes before they reported feeling more 'Stressed' than usual, showing acute exaggerated cardiovascular responses to PS. Also, higher PS was reported after HRV (i.e., SDRR) was observed to be blunted in the preceding 30-60 minutes. These measures, 'high HR' and

TABLE III. MULTILEVEL MODEL PREDICTING SUBSEQUENT CURRENT PSYCHOLOGICAL STRESS FROM PREVIOUS CARDIOVASCULAR FUNCTIONS

	Affect		
	Prior 5 min	Prior 30 min	Prior 60 min
HR(V) -> Stressed			
Person-mean centered HR	2.27 (0.88)*	2.35 (1.06)*	1.49 (1.20)
Person-mean centered SDRR	0.05 (0.54)	-1.59 (0.80)*	-1.82 (0.95)
Person-mean centered RMSSD	-0.82 (0.68)	-1.02 (0.80)	-0.88 (0.89)
HR(V) -> LNA			
Person-mean centered HR	-1.64 (0.49)**	-2.26 (0.58)**	-2.67 (0.66)**
Person-mean centered SDRR	1.01 (0.30)**	1.43 (0.44)**	1.74 (0.53)**
Person-mean centered RMSSD	1.10 (0.38)**	1.12 (0.44)*	1.37 (0.50)**
HR(V) -> HNA			
Person-mean centered HR	0.41 (0.65)	0.07 (0.78)	-0.85 (0.86)
Person-mean centered SDRR	0.49 (0.40)	0.32 (0.59)	0.63 (0.68)
Person-mean centered RMSSD	0.08 (0.50)	0.00 (0.59)	0.59 (0.64)

Note. B coefficients (and standard errors [SEs]) of the multilevel models which indicate the within-person associations between person-mean centered cardiovascular functions and subsequent affect ratings are shown. All coefficients are estimated in a separate multilevel model after controlling person-mean of cardiovascular functions and activity counts as a covariate. Heart rate and heart rate variability per minute are calculated from each time interval: 1-5, 1-30, or 1-60 minutes *before* affect ratings. SDRR: standard deviation of the RR intervals. RMSSD: root mean square of successive differences between heartbeats. Coefficients and SEs are multiplied by 100 to make the table easier to read. ** $p<0.01$, * $p<0.05$.

'low HRV' can be physiological risk factors for cardiovascular disease.

High LNA moments were bidirectionally related to lower HR and higher HRV from short (5 minute) to long (60 minute) time intervals, while HNA was unrelated to HR and HRV at all time intervals. Prior findings have widely reported risks of NA on cardiovascular health [12], but this study did not support negative effects of NA on cardiovascular functions (i.e., reversed associations of LNA and no associations of HNA with cardiovascular functions) which is consistent with other prior studies [13, 14]. Although the effects of NA on cardiovascular response are not fully explained in this pilot study, one study [13, 14] suggests that "suppression of emotions (e.g., perceived social norms, corporate culture, or personal coping strategies)" might lead to these unclear and mixed associations. Further clarification regarding high- and low- arousal NA may shed some light on these mixed findings. It should be noted that this pilot study used limited cardiovascular variables (i.e., HR and time-domain HRV) and a small sample (n=10; young undergraduate and graduate students who are free from cardiovascular disease), thus it is important to conduct further studies using robust cardiovascular measures and in larger and more diverse samples (e.g., age, occupation, fitness, etc.). Once these findings are confirmed in larger samples, they can be used to inform the design of real-time interventions for stress relief when detecting prolonged high stress. For example, short interventions such as forms of light physical activity (e.g., short walks to interrupt sedentary behavior), relaxation activities (e.g., deep breathing, muscle relaxation), meditation, cognitive therapies (e.g., reframing, reappraisal), encouraging positive feelings and pleasant activities, and self-regulation (e.g., goal setting, action planning) can be delivered [15].

In conclusion, better understanding and awareness of feeling stressed and low-arousal NA might contribute to better management of cardiovascular health in everyday life. Using ambulatory sensors to monitor cardiovascular functions and affective state with high granularity allowed the examination of those associations. This approach also enabled processing and analysis of the data in near real time, suggesting the potential to apply these findings towards timing interventions for when stressed people have exaggerated or blunted cardiovascular responses.

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