A large-scale study of stress, emotions, and blood pressure in daily life using a digital platform

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Stress is often associated with pathophysiologic responses, like blood pressure (BP) reactivity, which when experienced repeatedly may be one pathway through which stress leads to poor physical health. Previous laboratory and field studies linking stress to physiological measures are limited by small samples, narrow demographics, and artificial stress manipulations, whereas large-scale studies often do not capture measures like BP reactivity in daily life. We examined perceived stress, emotions, heart rate, and BP during daily life using a 3-wk app-based study. We confirmed the validity of a smartphone-based optic sensor to measure BP and then analyzed data from more than 330,000 daily responses from over 20,000 people. Stress was conceptualized as the ratio of situational demands relative to individual resources to cope. We found that greater demands were associated with higher BP reactivity, but critically, the ratio of demands relative to resources improved prediction of BP changes. When demands were higher and resources were lower, there was higher BP reactivity. Additionally, older adults showed greater concordance between self-reported stress and physiologic responses than younger adults. We also observed that physiologic reactivity was associated with current emotional state, and both valence and arousal mattered. For example, BP increased with high-arousal negative emotions (e.g., anger) and decreased with low-arousal positive emotions (e.g., contentment). Taken together, this work underscores the potential for expanding stress science and public health data using handheld phones to reliably and validly measure physiologic responses linked to stress, emotion, and physical health.

stress | emotions | blood pressure | digital platforms | EMA

Life can be stressful. Financial, family, social, political, environmental, job, and healthcare stressors, to name a few, can create a constant feeling of a demanding and overwhelming life that, over time, can take a toll on physical and mental health. A large-scale annual report on stress in America found that, on average, while people viewed some stress to be beneficial, the average stress level of respondents was higher than what was perceived as healthy (1), and the COVID-19 pandemic substantially increased stress and its toll on physical and mental health (2). Decades of research have examined links between reported stress and physiological functioning like blood pressure (BP) changes (3–6). BP changes during stressful situations are important given they provide a possible mechanism into the development of hypertension (e.g., refs. 6, 7). However, previous studies examining the strength of the associations between perceived stress and direct changes in physiological reactivity often rely on artificial stressors in a laboratory or small sample field studies using student or patient samples that prevent robust exploration of possible moderating factors like age. Field studies with a large and diverse sample that included repeated assessments of how people respond to stressful situations to estimate the ways in which short- and long-term physiological fluctuations affect the body would provide much-needed evidence of how daily stress might affect health. Here, we present a large-scale study of perceived stress and BP responses in daily life that presents two important advances that extend previous work.

First, we examine how stress affects BP changes in daily life using a comprehensive framework that simultaneously considers how demanding a situation is along with perceived resources to cope (8). Consider a Chief Executive Officer (CEO) of a publicly traded company who has competing demands from shareholders, employees, customers, and legal and regulatory bodies along with personal demands of family, safety, and health. This CEO might report very high demands when responding to the question, "How stressful is your life?" However, this question ignores the personal and environmental resources that mitigate "stress" such as financial resources, family and work support, health insurance, safe and secure environments, and a large social network. These resources may alter the CEO's BP responses to stressors in their daily life, resulting in lower BP reactions to daily stress compared to individuals with similar "demands" but few, if any, resources.

Laboratory studies support this prediction. Decades of studies examining physiologic responses to acute stressors in the laboratory show that when situational demands are high and individuals perceive high or adequate resources to cope, they show more salutary physiologic response characterized by high heart rate (HR) and small to moderate BP increases. This physiologic pattern is labeled challenge responses. In contrast, situations that are high in demands but low in perceived resources result in high HR and greater BP increases—a pattern labeled threat responses (9, 10). In a related line of research, high demand when coupled with high perceived control was associated with decreased negative affect and lower cortisol during laboratory stressors compared to

Significance

Exaggerated blood pressure (BP) reactivity is associated with the development of hypertension and cardiovascular disease. Stress, and, to a lesser extent, emotions are suggested to be linked to BP reactivity, but this theorizing lacks robust evidence beyond small laboratory or field studies with narrow participant demographics. Using an app-based research study and analyzing more than 330,000 daily responses from over 20,000 people, we show that momentary stress, conceptualized as the perception of demands relative to resources, is associated with greater BP and heart rate reactivity. High-arousal negative emotions are associated with increased physiologic reactivity whereas low-arousal positive emotions are associated with decreased reactivity. These data point to daily stress experiences as likely candidates for improving physical health.

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high demand coupled with low perceived control (11–13). In the present work, we examine the simultaneous appraisals of demands and resources for a more precise measure of psychological stress and the association between these appraisals and BP reactivity.

The second advance of this work is the focus on stress experienced in daily life compared to an artificial laboratory-based study. While there are field studies that examine ambulatory BP responses, the samples tend to be small and are often patient samples with existing cardiovascular problems (e.g., ref. 14). This is likely due to the difficulty in obtaining valid BP measurements in daily life, given the reliance on inflatable upper arm cuffs (oscillatory BP monitors), which are inconvenient and potentially disruptive. As such, traditional methods of BP measurement have constrained research on BP in daily life to small samples and/or short-term studies (i.e., a few days), so there is limited knowledge of how daily stress experiences affect BP changes. In this work, we utilize BP measurement via a specialized optic sensor embedded in smartphones developed for the sole purpose of measuring BP. This technology allowed for the collection of tens of thousands of participants' BP responses and their concomitant stress experiences, capturing both situational demands and personal resources as they went about their daily lives.

We were also able to look beyond perceived stress and examine how emotions influence BP in daily life. While some work has considered how specific emotions like trait anger are related to resting BP levels (15) and theories from affective science suggest that emotions should influence physiologic responses like HR and BP (ref. 16, cf. ref. 17), there are not large-scale experience sampling studies that examine how a range of emotional experiences that differ in valence (positive and negative) and arousal (high and low) affect physiology. By including these different dimensions of emotion, the current work examines if negative emotions are associated with higher BP reactivity in daily life and if positive emotions are associated with lower BP reactivity, as well as how arousal interacts with valence to influence BP reactivity (18).

In addition to understanding how stress and emotions get under the skin to influence BP changes, it is also important to understand for whom stress and emotions are most likely to have these effects. Some people may be particularly vulnerable to stress, whereas others may be more resilient (19). Prior research has also shown that as individuals age there is an overall reduction in the perception of stress, including an affective bias toward more positive emotions (20), and less reactive physiologic responses to acute stressors (21). Moreover, in older age there may be stronger concordance between psychological states, like self-reported stress and emotion, and physiologic reactions due to increased wisdom, lower defensiveness, and enhanced understanding of self (22, 23).

Study Overview

In this work, we leveraged the use of a built-in optic sensor available on some smartphones and developed an app to conduct an experience momentary assessment study that measured participants' BP responses and HR along with their self-reported experiences three times a day for 21 d. During the first wave of data collection (March 2018 to June 2019), we gathered data from 91,892 participants who completed 460,023 BP measurements with accompanying emotional, psychosocial, and behavioral data. After exclusions (primarily people who did not complete three or more daily check-ins, reference *SI Appendix*, Fig. S2 for data cleaning procedures), we retained a final sample of 21,923 participants who completed 331,716 measurements. Participants were able to join the study if they had an eligible smartphone (i.e., a Samsung phone with a built-in optic sensor, which acted as a photoplethysmograph to estimate BP) and downloaded the MyBPLab app through the US Google Playstore. Participant demographics and sample sizes are shown in Table 1. Participants completed onboarding, which included an affirmation of eligibility (over 18), informed consent, demographics, and an initial calibration with an external BP monitor. For participants who did not calibrate with an external device, the app only displayed their percentage change in BP. In cases when calibration values were not provided, the algorithm to estimate BP used default values (for more on BP cleaning, see *Methods* and *SI Appendix, Main Study: Dating Cleaning Procedure*), and these BP values were stored in the database and only accessible to the researchers. After onboarding, participants received notifications three times a day (morning, afternoon, and evening) to complete a check-in, which included BP and HR measurements and a short survey. Survey questions rotated within and across days to minimize participant fatigue and maximize data collection. In the current analyses, we focus on questions about stress (demands and resources) that were collected every third morning and a different set of stress questions collected every afternoon (see *Methods* for more details). Questions about emotions were also collected during the same

Table 1. Sample demographics

Sample demographics	Final sample		Final sample calibrated†		
Participant *N*	21,923		SBP	DBP	HR
Male	17,281	78.8%	128.77	80.74	75.17
Female	4,487	20.5%	125.40	78.84	77.9
Another gender identity	57	0.3%	126.92	78.38	75.44
Age*					
18 to 29	5,609	25.6%	124.39	77.74	78.56
30 to 49	12,306	56.1%	128.08	81.49	77.25
50 to 64	3,296	15.0%	129.04	80.29	73.38
65+	630	2.9%	129.83	76.09	69.29
Identified as:					
White	14,598	66.6%	128.26	79.99	75.18
Asian or Pacific Islander	3,583	16.3%	125.65	80.99	77.34
Black or African American	1,604	7.3%	131.99	82.33	77.79
American Indian or Alaskan Native	278	1.3%	130.79	82.31	76.91
Another race	2,336	10.7%	126.76	80.81	77.05
Education					
Elementary school	272	1.2%	129.33	81.60	72.39
High school	3,762	17.2%	129.24	81.24	75.75
Some college	5,452	24.9%	129.66	80.77	77.39
Two-year degree	2,192	10.0%	127.27	80.42	76.78
Four-year degree	5,035	23.0%	127.35	79.96	75.24
Graduate school	4,528	20.7%	127.01	79.66	74.4
Self-reported health					
Poor	709	3.2%	133.41	83.88	80.16
Fair	4,493	20.5%	131.22	82.38	78.64
Good	10,089	46.0%	128.41	80.84	76.34
Very good	5,134	23.4%	125.24	78.07	73.00
Excellent	1,215	5.5%	124.18	77.42	70.96
Regularly exercise (3x/wk)					
Yes	8,528	38.9%	127.00	79.11	72.67
No	13,095	59.7%	128.87	81.26	78.07
BMI*					
Underweight (<18.5)	368	1.7%	118.67	75.38	78.65
Normal weight (18.5 to 24.9)	6,077	27.6%	122.59	77.4	73.96
Overweight (25 to 29.9)	7,442	33.8%	128.28	80.58	74.98
Obese I (30 to 34.9)	3,910	17.8%	130.55	81.48	76.38
Obese II and III (35+)	3,493	15.9%	133.17	83.03	79.06

Note: Ethnicity was select all that apply; some variables have missing data; for BP and HR: All *N*s = 323,914 to 331,716 from 21,923 Ps; for calibrated: *N*s = 182,976 to 187,852 from 11,650 participants.

*Age filtered to <91, BMI filtered to >14.99 and <60.

†Removing 29,142 check-ins in which P exercised within 30 min of physio measurement.

check-in every afternoon (reference *SI Appendix*, Table S9 for sample sizes). Before we describe the results of the main study, we present the assessment of the reliability and validity of the optic sensor to measure BP and HR.

Results

Assessing the Reliability and Validity of the Optic Sensor. We assessed the optic sensor's reliability and validity by recruiting 123 participants to take part in a multimethod study that required frequent BP measurements in the laboratory and field using both the phone-based optic sensor and a Food and Drug Administration-approved BP cuff (A&D UA-651BLE monitor). We assessed BP measurements from the two devices near simultaneously on opposite arm and hand to allow for temporal precision. Sample characteristics, detailed procedures, and additional analyses are available as supplemental materials (*SI Appendix*). Data, syntax, and supplemental material are available online https://osf.io/dbve5/.

Across both the laboratory and field, there was moderate to strong agreement between the optic sensor and the cuff. Distributions, descriptive values, and correlations for the primary BP measurement are shown in Fig. 1 and additional descriptive and correlational analyses are in *SI Appendix*, Fig. S1 and Tables S1–S7.

Given the novelty of our methodology, along with the fact that BP measurements tend not to be perfectly correlated, even when comparing estimates from gold-standard measurements (e.g., two doctors using the auscultatory method), we collected additional data using two different FDA-approved oscillatory-based external cuffs measured simultaneously on separate arms. The optic sensor performed as well in estimating BP as when comparing two different external cuffs to each other (reference *SI Appendix*, Table S8).

Having established the phone-based optic sensor provides acceptable reliable and valid BP responses similar to those obtained by FDA-approved arm-based external cuffs, we used it to explore the ways in which daily experiences of stress and emotions influence BP and HR reactivity in daily life.

Data Analytic Plan. Given that check-ins were nested within individuals, we utilized multilevel modeling (i.e., mixed-effects models; lme4 package in RStudio 1.2.5019 and mixed models in SPSS version 27, further details in *SI Appendix*) in which check-ins were nested within participants. To assess physiological reactivity, we subtracted a "baseline" measure from every estimate. Baseline was determined by identifying the check-in during which participants exhibited the lowest HR (suggesting a relaxed state) and subtracting it from all of their measurements. For example, to calculate systolic BP (SBP) reactivity, we first found the minimum HR for an individual across all their check-ins and then took the SBP value from that check-in to subtract from each of the SBP values.

In this study, our focus was on within-person variation. That is, we wanted to test the extent to which people exhibited a change in their BP and HR from baseline when experiencing changes in their stress and emotions relative to how they typically feel. To do this, we utilized a contextual model in which we controlled for between-person differences by entering person-level aggregates for each of our main predictors. This approach unconfounds within- and between-person effects while maintaining the original scaling (reference *SI Appendix* for more details). All random effects were modeled, including covariances between random effects. Below are sample equations for our main stress analyses (syntax for all key analyses are available at: https://osf.io/dbve5/):

Main effects of demands and resources (PM = person mean):

$$\begin{aligned}\text{SBP Reactivity}_{ti} = {} & (\beta_{00} + u_{0i}) + (\beta_{10} + u_{1i})\text{DEMANDS}_{ti} + \\ & (\beta_{20} + u_{2i})\text{RESOURCES}_{ti} + \\ & \beta_{01}\text{DEMANDS\_PM}_i + \beta_{02}\text{RESOURCES\_PM}_i + e_{ti}\end{aligned}$$

Main effect of demands/resources ratio:

$$\begin{gathered}\text{SBP Reactivity}_{ti} = (\beta_{00} + u_{0i}) + (\beta_{10} + u_{1i}) \\ \text{DEMANDS\_RESOURCES\_RATIO}_{ti} + \\ \beta_{01}\text{DEMANDS\_RESOURCES\_RATIO\_PM}_i + e_{ti}\end{gathered}$$

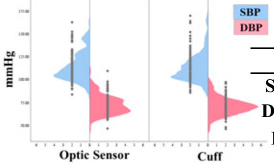
Moderation of demands/resources ratio by age:

$$\begin{gathered}\text{SBP Reactivity}_{ti} = (\beta_{00} + u_{0i}) + (\beta_{10} + u_{1i}) \\ \text{DEMANDS\_RESOURCES\_RATIO}_{ti} \\ \beta_{01}\text{DEMANDS\_RESOURCES\_RATIO\_PM}_i + \beta_{02}\text{AGE}_i + \\ \beta_{11}\text{DEMANDS\_RESOURCES\_RATIO}_{ti} * \text{AGE}_i + \\ \beta_{02}\text{DEMANDS\_RESOURCES\_RATIO\_PM}_i * \text{AGE}_i + e_{ti}\end{gathered}$$

Descriptive Analyses. The right side of Table 1 depicts BP and HR estimates by demographic group. BP and HR estimates from the optic sensor tracked with epidemiological trends. For example, females had lower estimated BP and higher HR than males, BP was higher and HR was lower among older ages, and both BP and HR were higher as Body Mass Index (BMI) increased and self-reported health decreased. Reference *SI Appendix*, Table S9 for descriptive values of our primary variables.

Main Results.

Daily stress and physiological reactivity. In order to determine the associations between demands and resources and physiological reactivity in daily life, we followed prior research (24, 25) and conducted two different sets of analyses. In our first model we entered demands and resources as simultaneous predictors of BP and HR to determine whether they uniquely contributed to helping explain changes in physiology from baseline. Then, in a separate model, we entered the ratio of demands and resources as a single predictor. As shown in Fig. 2 (and *SI Appendix*, Tables S10 and S11 and Fig. S3), in line with prior work on challenge and threat responses to stress, we found consistent evidence across two separate measures of demands and resources (assessed in the morning and



	Optic Sensor	Cuff	Bias	Precision	Correlation
	Mean (SD)	*Mean (SD)*	*Mean Diff*	*SD of Diff*	*r*
SBP	114.05 (15.37)	113.23 (15.40)	0.82	10.27	0.78
DBP	72.59 (10.37)	71.09 (9.32)	1.49	5.96	0.82
HR	72.66 (10.85)	70.31 (10.83)	2.36	2.95	0.96

Fig. 1. Violin plots depicting SBP and DBP distributions and descriptive information of primary measurements from the laboratory assessment of reliability and validity of the optic sensor.

afternoon [presented in *SI Appendix*, Fig. S3]) that both demands and resources were associated with BP reactivity, as was the ratio of demands to resources. The associations between demands and resources with HR reactivity were weaker, which is consistent with previous studies (10, 25). Taken together, these results suggest that during moments when people are experiencing higher demands (what people perceive as "stress"), both SBP and diastolic BP (DBP) are significantly higher relative to a relaxed baseline. In addition, the more resources people report having in that moment, the lower their SBP and DBP. However, when considering their relative contributions, the ratio of demands to resources better predicts BP than demands alone (reference *SI Appendix*, Tables S10 and S11). Comparisons of model fit (Akaike information criteron/Bayesian information criterion) between models with only demands and those with demands and resources (as separate predictors and as a ratio) showed that model fit was meaningfully improved when including resources ($\Delta > -500$). The increased model fit from demands alone to the ratio of demands to resources, also a single predictor, suggests that the benefits of resources are not simply due to including a second predictor in the model.

Age as a moderator of the association between daily stress and physiological reactivity. In addition to significant associations between stress and BP, we also found heterogeneity in this association (reference *SI Appendix*, Fig. S4). One potential source of this heterogeneity is age. We examined whether the association between the ratio of demands to resources and physiological reactivity was moderated by age, given prior work showing age-related changes in the link between perceived stress and physiological reactivity (21). Results revealed a moderating effect of age for both SBP and DBP (interaction effect sizes: *r's* = 0.07 to 0.08; reference *SI Appendix*, Tables S12 and S13 and Fig. S5 for full analyses and graphs). When demands were high and resources were low (threat ratio was higher), younger and older adults showed higher BP and HR reactivity. However, when the threat ratio was lower (demands were lower and resources were higher), age moderated physiologic responses, with older adults showing lower BP reactivity than younger adults at similar levels of threat appraisals. Stated another way, older individuals had a steeper slope, showing stronger HR, SBP, and DBP reactivity as demands outweighed resources. These effects remained significant when controlling for other relevant demographic variables (sex, self-reported health, and education; reference *SI Appendix*, Tables S14 and S15). In sum, while younger adults reacted more strongly overall to stressful experiences, even stressful experiences that were less threatening, older adults were more attuned to fluctuating experiences of stress and showed greater concordance between their self-reported stress and BP changes.

Emotions and physiological reactivity. We also examined how emotions tracked BP reactivity. To measure emotions, we presented an emotion grid with two dimensions: valence (negative and positive) and arousal (low and high). Participants selected one of the quadrants that best represented their current feelings and then reported on the intensity of that emotional state. All quadrants were selected at some point, but positive emotions were selected more often than negative emotions: low-arousal positive, 47%; high-arousal positive, 30%; high-arousal negative, 12%; and low-arousal negative, 11%.

Fig. 3 illustrates the associations between the intensity of these four emotion dimensions and BP and HR reactivity (reference *SI Appendix*, Table S16; also reference *SI Appendix*, Tables S17 and S18 and Fig. S6 for moderations by age). When people reported more intense high-arousal negative emotions (like anger and fear; relative to when they had less intense experiences of these emotions), they showed significantly greater BP and HR reactivity. The intensity of people's experiences of low-arousal negative emotions (like sadness and disgust) were not associated with changes in BP but were associated with greater HR reactivity. In contrast, when people experienced more intense low-arousal positive emotions (like calmness and serenity), they showed significantly lower BP reactivity but little change in HR. Finally, when people reported more intense high-arousal positive emotions (like excitement and happiness), there was no significant change in SBP but lower DBP and greater HR reactivity. These results suggest that both valence and arousal are important when considering how emotions are associated with physiological reactivity, particularly when examining across multiple physiological signals (e.g., BP and HR).

Our emotion analyses focused on within-person differences in emotion intensity for each of the four quadrants of emotions, removing concerns about between-person differences driving our effects. Nonetheless, we examined whether there were individual differences in emotional experience (reference *SI Appendix*, Table S19) and found some descriptive evidence for demographic differences. For example, younger participants (ages 18 to 29) made up a larger subset of participants who reported low-arousal negative emotions compared to their representation in other emotion quadrants, and older adults (ages 50 to 64 and 65+) made up a larger subset of people reporting positive emotions compared to their representation for negative emotions. Rerunning our emotion analyses with only the 1,502 participants who selected all four emotion quadrants during the study (72,855 check-ins) returned the same pattern of results as with the full sample (*SI Appendix*, Table S20).

Discussion

Experiences of stress and emotion can alter physiologic responses like BP and HR, but large-scale studies examining these changes in daily life and across a broad age range are rare. We examined the validity of an optic sensor embedded in phones and found acceptable validity when compared to FDA-approved BP monitors and then developed an app-based research study in which we assessed stress, emotion, and BP multiple times a day. This study

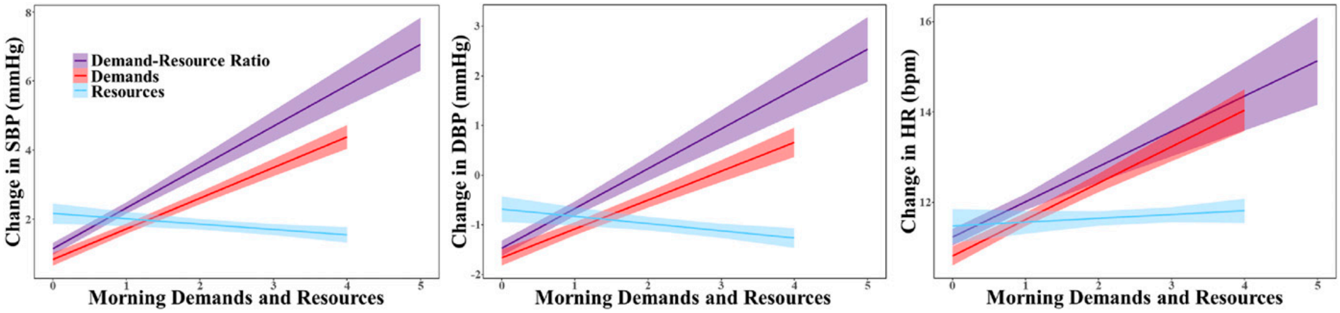


Fig. 2. Regression estimates and 95% confidence bands for main effects in Study 2. Overlay of morning demands and resources from model 1 and morning ratio of demands to resources from model 2 for changes in SBP, DBP, and HR.

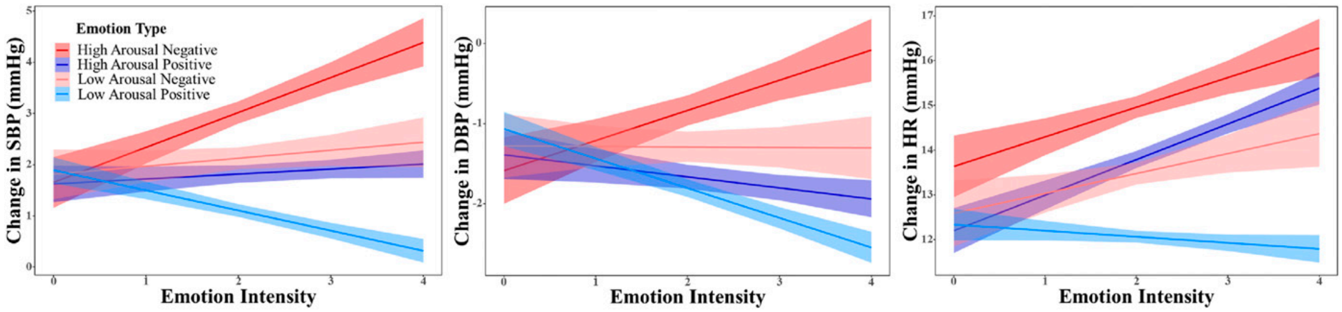


Fig. 3. Regression estimates and 95% confidence bands for emotions predicting BP and HR reactivity. Regression lines are shown separately for four emotion types: high-arousal negative emotion; high-arousal positive emotion; low-arousal negative emotion; and low-arousal positive emotion.

approach allowed us to develop a database to examine within-person changes in stress, emotions, and physiology.

There are three primary messages from the analyses presented here. First, we find that not all stress reports are created equal. Self-reported appraisals of situational demands are related to higher BP reactivity, as expected, but critically individuals' resource appraisals were associated with lower BP responses, and models which include both demands and resources were more reliably associated with BP reactivity than models with demands alone. Returning to the analogy, a CEO might report a demanding life, but their assessed resources are likely to be a strong buffer to BP reactivity that would unlikely be observed among individuals with fewer personal, psychological, and financial resources.

Second, although we found strong main associations between stress and BP, we also found heterogeneity in these responses, with not all participants showing the same relationship between stress and BP. In line with this evidence that not everyone responds to stress in the same way, we find that there is greater concordance (agreement) between self-reported stress and BP in older adults compared to younger adults as indicated by stronger correlations between self-reports and physiology among older adults. It may be the case that older adults, more than younger adults, used the information from the sensor reporting on their BP and HR reactivity to guide their self-reported affective responses. Though speculative, this general idea would be consistent with the observation that older adults have poorer interoception (ability to sense internal states) and may rely more on external information to assess feeling states (26).

Finally, we observed significant relationships between emotions and physiology. Extending past work with smaller samples, high-arousal negative emotions (e.g., anger) are associated with increased BP reactivity. We also found that low-arousal positive emotions (e.g., calmness, serenity) were associated with decreased BP reactivity. Positive emotions are less studied than negative emotions in the context of physiologic responses and physical health, and when they are examined it is typically via the lens of trait-like positive emotions—optimism, gratitude. This finding may be particularly fruitful given that, when asked to select their current affective state, participants were more likely to report experiencing low-arousal positive emotions than the other valence/arousal combinations. Identifying daily level associations of in-the-moment low-arousal positive emotion linked to lower BP is a critical observation for those interested in developing positive emotion interventions aimed at reducing BP reactivity.

Constraints on Generality. While this work boasts a large sample size for an experience sampling study with physiologic responses, there are critical constraints on generality that are important to contextualize the findings. First, there are issues related to sample characteristics. The app was available on Google Playstore, so we had no control over who joined the study other than excluding people under the age of 18. It might be the case that individuals who selected to be in this study might be more concerned with their health given the primary distinguishing factor was the ability to measure BP, which might result in an overall healthier sample than the general population. The demographics were skewed toward younger white males with a particular smartphone (Samsung), which is consistent with the customer demographics of this phone brand. We did test for moderation by sex and did not observe any meaningful interactions, but the relatively larger male than female sample might be exaggerating some BP reactivity differences given males tend to have both higher BP and greater BP reactivity. Relatedly, while our sample did not exclude older adults, the majority of the sample was midlife (30 to 49) and less than 3% was 65 and older. This younger sample likely is healthier, so these data are limited in how well then can characterize how stress and emotion affect BP reactivity in the very old (80 and older).

There are also technological constraints with the use of on-demand measures. When notified for a "check-in," participants had to be able to stop and take a BP measurement, and it is likely that when stress was especially high, participants could not stop what they were doing to complete the check-in. Wearables that allow for continued measurement will be able to overcome this barrier, at least as it relates to a sensor measure, but this is a clear limitation with phone-based sensors.

We have limited control over the quality of measurement. BP is sensitive to body position and movement—body position, sensor location relative to the heart. In the validation study, we were able to give instructions directly to our participants and train them face-to-face. All of this instruction was moved to videos and written instructions within the app, which limited our control over the measurement quality. Without question, there is measurement error in our study that likely leads us to underestimate effect sizes. As technological advances develop that include geospatial awareness and movement minimization, we will increase our ability to obtain greater precision in BP measurement.

Finally, we focused on changes in BP reactivity in daily life and how stress appraisals and emotions were associated with those changes. However, most research examining how BP is related to morbidity and mortality focuses on baseline/resting BP levels rather than BP reactivity (ref. 27, cf. ref. 6; 7). Indeed, BP increases upon exposure to acute stressful tasks can indicate engagement and approach motivation (28, 29). This noted, exaggerated and/or sustained BP reactivity has been linked to the development of hypertension and cardiovascular disease, so it remains an important question to pursue the relative contribution of resting BP levels and BP reactivity to the development of physical diseases.

In conclusion, we find that optic sensors embedded in smartphones can reliably and accurately measure BP. Furthermore, we find with tens of thousands of people using hundreds of thousands of check-ins that while "stress" increases BP in the moment, stress is not a unitary construct. Instead, stress is best understood in its relation to the resources that individuals have. Similarly, the associations between emotions and physiological changes are better captured when considering both valence and arousal.

Methods

Participants. Individuals who downloaded the app, MyBPLab, through the US Google Playstore between March 15, 2018 and June 30, 2019 ($N = 91{,}892$) were considered for the analyses presented here.* As incentive, participants received feedback about their BP, and those who completed at least 21 check-ins within 3 wk were entered into a lottery to win 1 of 20 new Samsung smartphones. Sample characteristics for both the initial sample and final sample are shown in Table 1. The only exclusions to participating in this study were that participants had to be at least 18 y of age, fluent in English (because we did not offer the app in other languages), and have a compatible phone with the embedded optic sensor (Samsung S9 or Note 9). For the current analyses, additional exclusions included the following: participants who completed less than three check-ins (because we were calculating individual reactivity scores using one of the check-ins as a baseline measurement) and check-ins in which participants indicated they had exercised in the past 30 min because exercise acutely increases BP levels. For more details on the data analytic plan and data cleaning procedures, reference *SI Appendix*. These decisions resulted in a final sample of 21,923 participants who completed 331,716 measurements.

Procedure. After downloading the app, participants confirmed their age and English fluency by taking a short comprehension quiz. They completed the consent form and basic demographics and received email authorization to participate. Participants then completed an initial BP measurement to calibrate the optic sensor on the phone. Participants were encouraged to calibrate using an external cuff. If they did not have a BP monitor to calibrate the sensor, they were able to use the app and we collected their raw BP estimates, but participants only saw percent changes in BP relative to their initial measurement instead of actual BP levels. They could recalibrate against a cuff at any time during the study. Once enrolled in the study, participants could complete up to three daily check-ins during set time windows (morning: 7 AM to 10 AM; afternoon: 10 AM to 4 PM; and evening: 8 PM to 11 PM), which included BP and HR measurements and survey questions. Participants could also take on-demand BP measurements at any time. The app included an optional section where participants could complete surveys assessing individual differences. The app was designed to be a 21-d study, although participants could continue participating after 21 d. The study was approved by the Human Research Protection Program at the University of California, San Francisco (International Review Board No. 17-24159).

Daily Check-In Measures. Each check-in included a BP measurement, ~30 seconds, and then questions assessing participant's location, who they were with, and whether they had exercised vigorously in the past 30 min. The other survey questions varied across check-ins to minimize fatigue, with three different sets of rotating morning check-in questions, one set of afternoon check-in questions, and seven sets of rotating evening check-in questions.

To test our questions regarding stress in daily life, and specifically how demands and resources collectively are associated with BP, we focused on the questions most relevant to our interests, which were measured during one of the mornings and every afternoon. The morning items for demands and resources (assessed every 3 d) were as follows: "I feel stressed, anxious, overwhelmed" and "I feel in control, coping well, on top of things" (0 = Not at all, 1 = A little bit, 2 = Somewhat, 3 = Moderately, and 4 = Very much). The afternoon item assessing demand was, "Do you feel like things are overwhelming right now?" The item assessing resources was, "Do you feel like things are unpredictable right now?" Both items were measured on a five-point scale (resources were reverse scored; higher numbers are more predictability; 0 = No, not at all; 1 = Not really; 2 = Neutral; 3 = A little bit; and 4 = Yes, a great deal). In order to calculate the ratio of demands to resources, we added 1 to each variable to avoid having 0 as part of the division, then divided demands by resources following previous research (24, 28). We analyzed these two measures of stress separately, treating the afternoon data as an attempt to conceptually replicate morning responses given there was no reason to expect morning appraisals would be different from afternoon appraisals.

To test our questions regarding emotions in daily life, participants completed two steps: First, they selected which one of four quadrants of an emotion grid best represented their current emotional state (high-arousal negative emotions, low-arousal negative emotions, high-arousal positive emotions, or low-arousal positive emotions). They then completed a follow-up question ascertaining the intensity of those feelings (0 = Not at all, 1 = A little bit, 2 = Moderately, 3 = A lot, or 4 = Extremely). We focused on the association between emotion intensity and physiological reactivity, examining intensity separately for each emotion quadrant (*SI Appendix*, Table S9). These questions were asked in the afternoon during the same check-in as the afternoon stress questions.

Within-person reactivity. For daily level analyses, we looked at change from a baseline value for both BP and HR. Baseline for both BP and HR was set as the measurement with the lowest HR value for each person. The corresponding SBP, DBP, and HR values from that measurement (adjusted for the calibration offset for BP) were subtracted from each check-in measurement to create a reactivity score. These reactivity scores serve as our main dependent variables.

Data Availability. Anonymized data files have been deposited in OSF (https://osf.io/63pf5/?view_only=f1d8dee8607b470c8455b84f3e7edbc6). Data, syntax, and supplemental material are all available online https://osf.io/dbve5/. All other study data are included in the article and/or *SI Appendix*.

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*Although the app was only available on the US Google Playstore, data from the Playstore suggests that participants in a number of other countries ended up accessing and downloading the app, either when visiting the United States or through side loading the app.

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