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Stress Reduction Experiments in Daily Life: Scaling From the Lab to the World

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Paced breathing—longer exhalation than inhalation—can show short-term improvement of physiologic responses and affective well-being, though most studies have relied on narrow sample demographics, small samples, and control conditions that fail to address expectancy effects. We addressed these limitations through an app-based experiment where participants were randomly assigned to paced breathing or sham control (hand closure) conditions. We first validated the conditions in an online sample ($N = 201$; Study 1) and in a lab environment ($N = 72$; Study 2). In the primary app-based experiment, participants ($N = 3{,}277$; Study 3) completed 3 days of baseline assessments that included three check-ins each day in which we obtained heart rate and blood pressure responses using an optic sensor and assessed current stress and emotions. Participants were then randomly assigned to either the paced breathing or hand closure condition for the next 6 days. Relative to baseline days, both conditions were associated with increased positive emotions and perceived coping, and reduced blood pressure. Moreover, the increase in positive emotions and perceived coping was not evident among a comparison sample ($N = 2{,}600$) who completed check-ins but did not participate in either of the paced breathing or sham-control conditions. However, their blood pressure declined over time, suggesting that the continual monitoring of one's blood pressure may result in detectable decreases. Our results highlight the importance of designing experiments with appropriately matched control conditions and suggest that changes associated with techniques like paced breathing, in part, may stem from positive incidental features of the technique.

Public Significance Statement

Stress can lead to hypertension and cardiovascular disease, one of the leading causes of death worldwide. Strategies that might reduce acute stress and increase positive emotions while improving cardiovascular health are as important as ever given the deleterious effects of depression and hypertension that plague our society. Several studies have shown that paced breathing is effective at improving emotions and cardiovascular health though many studies have relied on small samples and have not appropriately accounted for expectancy effects. Addressing these limitations, we found that the sham-control condition of opening and closing one's hand was associated with increased positive emotions and reduced blood pressure just as strongly as paced breathing during naturalistic contexts throughout the day. These data provide novel insights into the role of appropriately matched control conditions in exercises designed to improve emotional well-being and cardiovascular health in daily life.

Keywords: paced breathing, stress, blood pressure, positive emotions, ecological momentary assessment

Supplemental materials: https://doi.org/10.1037/xge0001546.supp

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Strategies that putatively reduce stress and increase positive emotions have received considerable attention in recent years given that stress has been linked to physical and mental health problems, and positive emotions are thought to help combat the harmful effects of negative emotions (Boehm et al., 2020; Epel et al., 2018). Possible downstream consequences of stress are suggested to accumulate to diseases like essential hypertension and cardiovascular disease, the latter of which is one of the leading causes of death worldwide (Caldwell et al., 2019), accounting for more than 17 million deaths each year (Brenner et al., 2020). Strategies that might reduce stress and increase positive emotions have become increasingly important as psychological and emotional well-being is believed to have declined during the COVID-19 pandemic (Aknin et al., 2022).

To combat the deleterious effects of stress, researchers have considered stress reduction techniques that target physiological processes like paced breathing and muscle relaxation (Broadbent et al., 2012; Steffen et al., 2017). Theoretical accounts have posited that these activities could directly alter physiological responses associated with stress, such as decreased blood pressure and heart rate (HR) and increase heart rate variability (HRV), while also reducing psychological stress by increasing feelings of calm states (see Sevoz-Couche & Laborde, 2022, for a review). For instance, paced breathing could stimulate the parasympathetic nervous system and the vagus nerve by activating pulmonary stretch receptors, which could increase vascular relaxation and lower levels of stress chemicals in the brain (Gerritsen & Band, 2018; Herrero et al., 2018). As yet another possible mechanism, slow respiratory rates could influence the mechanoreceptors in the nose, which could send signals to the frontal cortex to lower inflammation (Zaccaro et al., 2018).

Research testing theories about physiological stress reducing techniques have shown promising signs of the effectiveness of paced breathing interventions, although some inconsistencies exist. According to a recent meta-analysis (Zaccaro et al., 2018), some paced breathing interventions increased certain positive affective states, such as ease, comfort, and relaxation (Edmonds et al., 2009; Lin et al., 2014; Van Diest et al., 2014), whereas other studies documented no significant changes in positive affect or negative affect (Critchley et al., 2015; Lin et al., 2014; Stark et al., 2000). In other research that examined physiological indicators of positive functioning, paced breathing interventions increased HRV (Laborde et al., 2019; Stark et al., 2000; Van Diest et al., 2014) and reduced blood pressure (Brenner et al., 2020; Elliott & Izzo, 2006).

The reason for inconsistent effects with paced breathing interventions could be attributed to several methodological limitations. Nearly all of these interventions have been conducted with small samples (typical *N*s range from 20 to 50; Zaccaro et al., 2018) which not only limit statistical power to detect effects that may exist but also preclude the examination of moderation analyses (e.g., Balban et al., 2023). Paced breathing exercises might be more or less effective among certain groups of people than others. Moreover, prior paced breathing interventions have almost exclusively used within-subjects designs in which the control condition involved spontaneous breathing by the participant. Thus, placebo effects may account for some of the reported effects. Other studies have used control conditions that make it difficult to determine whether the effect is driven by paced breathing or the control condition (e.g., using social media; Laborde et al., 2019). Additionally, many paced breathing interventions require participants to come to the lab and expose themselves to settings that may not generalize well to daily life. Finally, when control conditions are used, they tend to be poorly matched to the paced breathing condition, which often includes pleasant music, self-focused attention, and clear indicators that this approach is intended to help one relax. Expectancy effects along with pleasant cues that are typically paired with paced breathing present the potential problem that beneficial outcomes might be confounded with other incidental features of the paced breathing interventions.

Given the various limitations of past research, our goal was to provide a rigorous examination of the potential physiological and psychological benefits of a paced breathing exercise as a stress reduction technique. We designed a 3-week daily experience study to address several of the weaknesses of prior research. First, we analyzed data from a relatively large and diverse sample of participants, which allowed us to achieve higher levels of statistical power and examine potential moderating factors, such as demographic characteristics and beliefs in the effectiveness of the intervention. Second, we implemented a comparison condition that held constant the pleasant features, self-focus, and potential expectancy effects that often occur with paced breathing manipulations.

We employed a mixed factorial study that included (a) a within-subjects comparison between a baseline period and a treatment period and (b) a between-subjects comparison between a paced breathing exercise and a comparison exercise. Thus, we were able to determine the effectiveness of a paced breathing exercise relative to participants' own baseline levels and relative to a comparison group that included all the positive incidental features of paced breathing but did not alter respiration. Third, participants completed the stress intervention techniques and recorded their physiologic and psychological states during the course of their everyday lives in ecologically valid contexts. By using an ecological momentary assessment (EMA; Shiffman et al., 2008) method, we capitalized on several important advantages that EMA methods provide over traditional lab-based paradigms.

First, by asking participants to report on their current emotional experiences, EMA methods limit recall biases and heuristics that are present in long-term recall (Bradburn et al., 1987; Schwarz, 2012). Extended recollections of experiences or periods of time often overestimate levels of intensity in daily life (Conner & Barrett, 2012; Newman, Schwarz, & Stone, 2021; Wirtz et al., 2003). Second, repeated assessments allow researchers to generalize their findings across a variety of situations. They also provide more robust estimates of a person's daily experiences compared to a single assessment. Third, EMA methods capture people's experiences in naturalistic settings which often differ considerably from artificial settings in the lab (Newman et al., 2020). For instance, the types of emotional states experienced while lying under a scanner differ from everyday emotional experiences, the stressors people face in daily life vary considerably from stressors created in lab settings, and people's HR and blood pressure recorded in a doctor's office may not always converge with their physiologic states in daily life. In short, EMA methods allow researchers to study "life as it is lived" (Bolger et al., 2003).

Overview of Present Studies

Before presenting the results of our primary study, we first demonstrate the validity and effectiveness of our manipulation through two studies. In Study 1 (online), participants were randomly assigned to watch videos we used in the primary study that instructed participants to pace their breathing (experimental condition) or to open and close their hand (control condition). Both videos included pleasant music, an expanding and contracting orb, and indicated that the task might help reduce stress (videos of both conditions are available here: https://osf.io/46gqa/). Afterward, participants completed self-report manipulation check questions and questions about their stress, coping, and positive emotions.

To further validate the manipulation in Study 2 (laboratory), participants were randomly assigned to watch one of the two videos while sensors recorded their respiration rate, HR, and blood pressure. They also completed the same self-report questions as in Study 1. Finally, in our primary study (Study 3; EMA), a large and diverse sample of participants completed an app-based study in which they were randomly assigned to the two different conditions (paced breathing vs. matched control) and completed check-ins throughout the day over a 3-week period by recording their HR and blood pressure and answering questions about their stress, perceived coping, and positive emotions.

Transparency and Openness

None of the studies were preregistered. Deidentified data for all studies along with the materials and analytic scripts are available on Open Science Framework (OSF; https://osf.io/46gqa/).

Study 1: Online Study of Paced Breathing

Method

The study was approved by the Human Research Protection Program at the University of California, San Francisco (IRB: 19-27169). The study was posted on CloudResearch, an online crowdsourcing platform linked to Amazon's Mechanical Turk (Litman et al., 2017). CloudResearch is preferred over Mechanical Turk as the platform has screened participants based on their attentiveness in prior studies (Hauser et al., 2022). We utilized this feature by restricting our participants to those on CloudResearch's Approved Participants list. The study title was "video study" and was described as a study in which participants were asked to "watch a short (80 s) video and answer a few questions." The estimated length of time to complete the study was 5 min. They received $2.00 for their participation.

Our primary goal was to validate the manipulation, and we expected to find large effects ($d = 0.80$). A power analysis indicated 52 participants were required to achieve 0.80 power. We opted to oversample. In total, 201 participants ($M_{\text{age}} = 38.24$, $SD = 11.04$; 61.69% male, 38.31% female; 72.14% non-Hispanic White) completed the study. A full description of their demographics is presented in Table S1 in the online supplemental materials. On average, participants took 4.61 min ($SD = 2.22$, $Mdn = 3.92$) to complete the study.

After reading a consent form, participants completed several demographic questions. Next, they completed three questions about their stress, perceived coping, and positive emotions as baseline measures. Stress was assessed with the item, "Right now, I feel stressed, anxious, overwhelmed." Perceived coping was assessed with the item, "Right now, I feel in control, coping well, on top of things." Positive emotions were assessed with the item, "Right now, I feel joyful, glad, happy." Responses to these questions were recorded on a 5-point scale (1 = *not at all*, 2 = *a little bit*, 3 = *somewhat*, 4 = *moderately*, 5 = *extremely*).

Participants were then randomly assigned to watch either the paced breathing video or the hand closure (control) video. To account for expectancy effects, before watching the video, everyone was instructed that the exercise they were about to complete could reduce feelings of stress, anxiety, and worry. They were instructed to be in a place where they can listen and concentrate. Additionally, they were asked to turn on their audio and be in a quiet place. Next, they watched the paced breathing or hand closure video for one minute and twenty seconds.

Both videos consisted of an orb that expanded to fill the screen for 6 s, with a 1-s pause, and then a 10-s contraction until only a small pin-sized point remained, and then a 2-s pause to reset. This cycle repeated four times. Pleasant calm music was played during the video. In the paced breathing condition, participants were instructed to inhale with the orb as it expanded, hold their breath at the peak, and then exhale as the orb deflated. The ratio of 6:10 s is a common paced breathing tempo that increases cardiac vagal activity (Laborde et al., 2022; Mather & Thayer, 2018). For the hand closure condition, participants were presented with the same visuals—an orb that expanded and contracted and the same music, but participants were instructed to open their hand when the orb expanded and to close their hand when the orb deflated. See Figure 1 for a visual depiction.

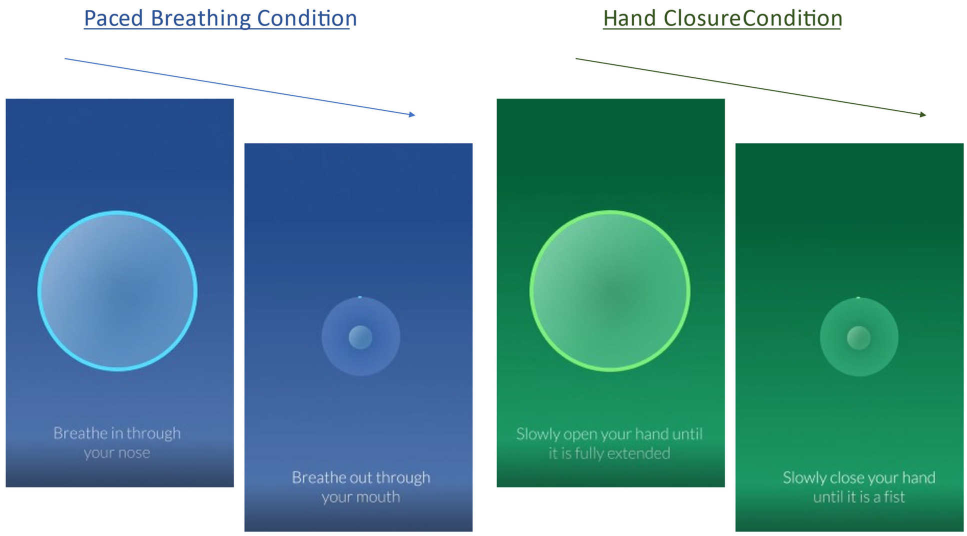
After the video ended, they were asked four questions about their experience during the video. First, they were asked, "Did you use audio when completing this task?" (1 = *not at all*, 2 = *yes, partially*, 3 = *yes, completely*). Next, they were asked, "How distracted were you while completing this task?" "How much did you like this task?" and "How much do you think this task reduced your stress?" Responses were recorded on the same 5-point scale as the questions about stress, perceived coping, and positive emotions except that the last category was either "greatly" or "a great deal." Next, they were asked the same three questions about their stress, perceived coping, and positive emotions that they completed prior to watching the video.

Following this, they answered six questions about their behaviors during the video. In the following order, participants indicated whether they paced their head motion, leg motion, mouth movement, hand motion, breathing, and eye movement with the video. We were specifically interested in their answers to the questions about their hand movement and breathing. The question concerning their hand motion was worded as follows: "During the task, I paced my hand motion with the video such that I opened my hand as the circle expanded and I closed my hand as the circle contracted." The question about breathing was worded as follows: "During the task, I paced my breathing with the video such that I breathed in as the circle expanded and I breathed out as the circle contracted." Responses were recorded on the same 5-point scale that was used for stress, perceived coping, and positive emotions.

Results

Our primary question concerned the differences in the manipulation check items across the two conditions. As expected, participants in the hand closure condition ($M = 4.44$, $SD = 1.02$) reported higher levels of hand movement than those in the paced breathing condition ($M = 1.53$, $SD = 1.14$), $t(199) = -19.01$, $M_{\text{diff}} = -2.91$, 95% CI [−3.21, −2.60], $p < .001$, $d = -2.68$. Participants in the paced

Figure 1
Visual Representation of Video Manipulations



Note. Participants watched videos of orbs that expanded and contracted and provided instructions as this cycle repeated four times. The color of the videos was counterbalanced across condition in Study 3. See the online article for the color version of this figure.

breathing condition ($M = 4.36$, $SD = 0.99$) reported higher levels of paced breathing than those in the hand closure condition ($M = 2.06$, $SD = 1.29$), $t(187.58) = 14.21$, $M_{diff} = 2.30$, 95% CI [1.98, 2.62], $p < .001$, $d = 2.00$.

Next, we were interested in whether the videos influenced levels of stress, perceived coping, and positive emotions. We ran mixed analyses of variance (ANOVAs) with a within-subjects factor (pre vs. post-manipulation) and a between-subjects factor (paced breathing condition vs. hand closure condition). We found significant within-subjects effects for stress, $F(1, 199) = 11.10$, $p = .001$, $\eta_p^2 = .053$; perceived coping, $F(1, 199) = 4.95$, $p = .027$, $\eta_p^2 = .024$; and positive emotions, $F(1, 199) = 18.09$, $p < .001$, $\eta_p^2 = .083$. As shown in Table 1, levels of stress decreased over time, and levels of coping and positive emotions increased over time. There were no significant between-subject effects ($p = .118$, $p = .534$, $p = .879$) or interactions ($p = .915$, $p = .465$, $p = .256$) for stress, perceived coping, or positive emotions, respectively. This indicates that the videos were equally associated with reduced perceived stress and increased perceived coping and positive emotions—paced breathing was not significantly different from the hand closure video. Though we believe the changes in emotions over time likely were due to the stress management videos, we cannot rule out the possibility that the changes in emotions may have occurred with the passage of time or there was selection bias of those who opted-in to a stress management study who showed regression to the mean in their self-reported emotion responses.

Study 2: Laboratory Experiment of Paced Breathing

To extend our validation beyond self-report measures and determine if the lack of differences between the experimental and control conditions might be due to the fact that people spontaneously alter their breathing even when not instructed in the hand closure condition, we sought to examine how the different video manipulations affected participants' respiration rate, HR, and blood pressure while watching the videos. We also included self-report validation questions along with measures of stress, perceived coping, and positive emotions similar to Study 1.

Method

Participants were recruited from the San Francisco Bay Area. They were deemed eligible to participate in the study if they were 18 to 65 years of age, fluent in English, and had a self-reported body mass index (BMI) of ≤35. Individuals who reported any of the following were excluded from the study: (a) pacemakers or other implanted cardiac devices, (b) a doctor's diagnosis of heart arrhythmia, hypertension, or other cardiovascular conditions, (c) prescribed medications for high blood pressure, and (d) a diagnosis of anxiety and/or depression without the use of prescribed medications. Additional exclusion criteria included any reported visual or auditory issues that would prevent them from following written instructions or listening to audio recordings during the lab visit. As in Study 1, our primary goal was to validate the manipulation, and a power analysis indicated a sample of 52 participants would result in 0.80 power to detect large effects ($d = 0.80$). We oversampled while also considering available resources. In total, 72 ($M_{age} = 25.24$, $SD = 9.36$; 23.61% male, 73.61% female; 40.28% non-Hispanic Asian, 27.78% non-Hispanic White) participants completed the study and received US$50.00 for their compensation (see Table S2 in the online supplemental materials for a full description of participant demographics).

After arriving at the lab, participants completed the informed consent form and were asked questions about their daily health and activity. Research assistants applied sensors to measure HR, respiration rate, and blood pressure (systolic blood pressure [SBP] and diastolic blood pressure [DBP]). We obtained electrocardiograph and impedance

Table 1
Mean Levels of Stress, Coping, and Positive Emotions Across Each Condition Before and After Completing the Stress Management Techniques

DV	Baseline			Post video		
	Paced breathing condition *M* (*SD*)	Hand closure condition *M* (*SD*)	Combined *M* (*SD*)	Paced breathing condition *M* (*SD*)	Hand closure condition *M* (*SD*)	Combined *M* (*SD*)
Stress	2.07 (1.17)	1.83 (1.16)	1.95[a] (1.17)	1.88 (1.10)	1.65 (1.05)	1.77[b] (1.08)
Perceived coping	3.56 (1.23)	3.62 (1.30)	3.59[a] (1.26)	3.64 (1.17)	3.78 (1.23)	3.71[b] (1.20)
Positive emotions	3.18 (1.31)	3.15 (1.31)	3.16[a] (1.31)	3.34 (1.31)	3.43 (1.34)	3.38[b] (1.32)

Note. Superscripts with different letters indicate significant differences across conditions. DV = dependent variable.

cardiograph signals with Biopac MP 150 (Electrocardiogram Amplifier and Noninvasive Cardiac Output modules) and edited and processed with Mindware (HRV 3.2.9) in 30-s time intervals to yield HR, respiration rate, and time-based HRV parameters, i.e., the root mean square of successive difference between normal heartbeats (RMSSD) and the standard deviation of the IBI of normal sinus beats (SDNN). Once applied, participants were instructed to rest quietly for 5 min to capture their resting, baseline physiology. At the end of the 5-min period, participants completed the same three questions about their stress, perceived coping, and positive emotions as in Study 1 as baseline measures.

Participants were then randomly assigned to either the paced breathing video or the hand closure (control) video. As in Study 1, before watching the video, they were told that one of the best ways to reduce feelings of stress, anxiety, and worry is to either change the way you breathe or activate the muscles in your hand. Next, they watched the paced breathing or hand closure video for one minute and twenty seconds. A 5-min physiological recovery period was recorded immediately following each condition while participants completed the same questions as in Study 1. After completing all parts, physiological sensors were removed, and the participant was compensated and debriefed about the study.

Results

Our first question concerned the differences in the self-report manipulation check items across the two conditions. Replicating the results from Study 1, participants in the hand closure condition ($M = 4.70$, $SD = 0.52$) reported higher levels of hand movement than those in the paced breathing condition ($M = 1.15$, $SD = 0.56$), $t(69) = 27.80$, $M_{diff} = 3.56$, 95% CI [3.30, 3.81], $p < .001$, $d = 6.61$. Participants in the paced breathing condition ($M = 4.82$, $SD = 0.52$) reported higher levels of paced breathing than those in the hand closure condition ($M = 2.59$, $SD = 1.30$), $t(48.05) = -9.62$, $M_{diff} = -2.23$, 95% CI [-2.69, -1.76], $p < .001$, $d = -2.25$.

Next, we were interested in whether respiration rates differed across conditions. We first assessed resting respiration rates during the final minute of the 5-min baseline period by aggregating their rates during the final two 30-s periods. We then aggregated their respiration rates during the next three 30-s periods to capture their respiration rates while they watched the videos. The average respiration rate during baseline in the paced breathing condition ($M = 14.83$, $SD = 2.60$) did not differ from the hand closure condition ($M = 14.84$, $SD = 2.51$), $t(70) = 0.02$, $M_{diff} = 0.01$, 95% CI [-1.19, 1.21], $p = .986$, $d = 0.004$. Consistent with lab-based physiological experiments (Blascovich et al., 2011), we created change scores by subtracting respiration rates during baseline from respiration rates during the video.[1]

We ran one-sample t tests for the change scores separately for each condition, and we also compared the change scores across conditions in a two-sample t test. Respiration rates decreased in the paced breathing condition by 2.66 breaths/min, whereas there was no significant difference in the hand closure condition. The respiration change was significantly different across conditions. See Table 2 and Figure 2 for details and Table S3 in the online supplemental materials for means and standard deviations across conditions.

We created change scores and executed the same analytic plan for blood pressure, HRV measures, and affective outcomes. None of the outcomes differed significantly during baseline (all $ps > .436$). SBP and DBP decreased in the paced breathing condition and increased in the hand closure condition (but neither change significantly different from zero). Differences across conditions were significant for SBP and DPB, $t(70) = 2.54$, $p = .013$, and $t(69) = 2.00$, $p = .049$, respectively. We found a similar pattern for SDNN, such that SDNN increased (significantly) in the paced breathing condition only, and the difference across conditions was also significant. We did not find significant differences across conditions for interbeat interval (IBI) or RMSSD.

When aggregated across conditions, stress decreased during the video relative to baseline, consistent with the results from Study 1. In contrast, we did not find the effects of either manipulation on changes in perceived coping or positive emotions. There were no differences across conditions for stress, perceived coping, or positive emotions suggesting that the incidental features of the tasks (e.g., music, focused attention, and expectancy effects) alone can reduce stress. In sum, we found the paced breathing manipulation was effective at reducing respiration rates compared to the hand closure condition (which did not change respiration from baseline). Paced breathing also lowered SBP, DBP, and increased SDNN. The exercise of watching either video was associated with reduced stress relative to baseline levels.

Study 3: Paced Breathing in Daily Life

Method

Participants and Procedure

Participants were volunteers who downloaded an app called MyBPLab (https://mybplab.com) from the Google Play Store on

[1] To be consistent with Studies 1 and 3, we also conducted traditional ANOVA analyses, which were more appropriate for those study designs. Substantive conclusions did not differ across approaches, and details of those analyses, including means across conditions, are presented in the online supplemental materials.

Table 2

Change Scores of Stress, Perceived Coping, Positive Emotions, and Physiologic States Across Each Condition Before and After Completing the Stress Management Techniques

Variable	Paced breathing			Hand closure			Comparison		Combined		
	Δ (*SD*)	*t* (*df*)	*p*	Δ (*SD*)	*t* (*df*)	*p*	*t* (*df*)	*p*	Δ (*SD*)	*t* (*df*)	*p*
Affective DV											
Stress	−0.11 (0.53)	−1.28 (34)	.211	−0.16 (0.55)	−1.78 (36)	.083	−0.37 (70)	.709	−0.14 (0.54)	−2.19 (71)	.032
Perceived coping	0.00 (0.34)	0.00 (34)	1.00	0.03 (0.37)	0.44 (36)	.661	0.32 (70)	.750	0.01 (0.36)	0.33 (71)	.741
Positive emotions	0.06 (0.54)	0.63 (34)	.535	0.05 (0.66)	0.49 (36)	.624	−0.02 (70)	.983	0.06 (0.60)	0.78 (71)	.437
Physiology DV											
Respiration rate	−2.66 (2.79)	−5.64 (34)	<.001	0.41 (2.31)	1.07 (36)	.292	5.09 (70)	<.001	−1.08 (2.97)	−3.10 (71)	.003
SBP	−2.06 (7.26)	−1.68 (34)	.103	2.51 (7.94)	1.93 (36)	.062	2.54 (70)	.013	.29 (7.91)	0.31 (71)	.755
DBP	−0.80 (4.44)	−1.07 (34)	.294	1.31 (4.43)	1.77 (35)	.086	2.00 (69)	.049	0.27 (4.53)	0.50 (70)	.620
IBI	−6.16 (47.34)	−0.77 (34)	.447	8.69 (37.09)	1.42 (36)	.163	1.49 (70)	.142	1.47 (42.74)	0.29 (71)	.771
SDNN	40.89 (22.53)	10.74 (34)	<.001	−1.61 (16.02)	−0.61 (36)	.544	−9.18 (61.11)	<.001	19.05 (28.82)	5.61 (71)	<.001
RMSSD	5.76 (26.32)	1.30 (34)	.204	−1.72 (16.63)	−0.63 (36)	.533	−1.43 (56.86)	.157	1.92 (22.05)	0.74 (71)	.463

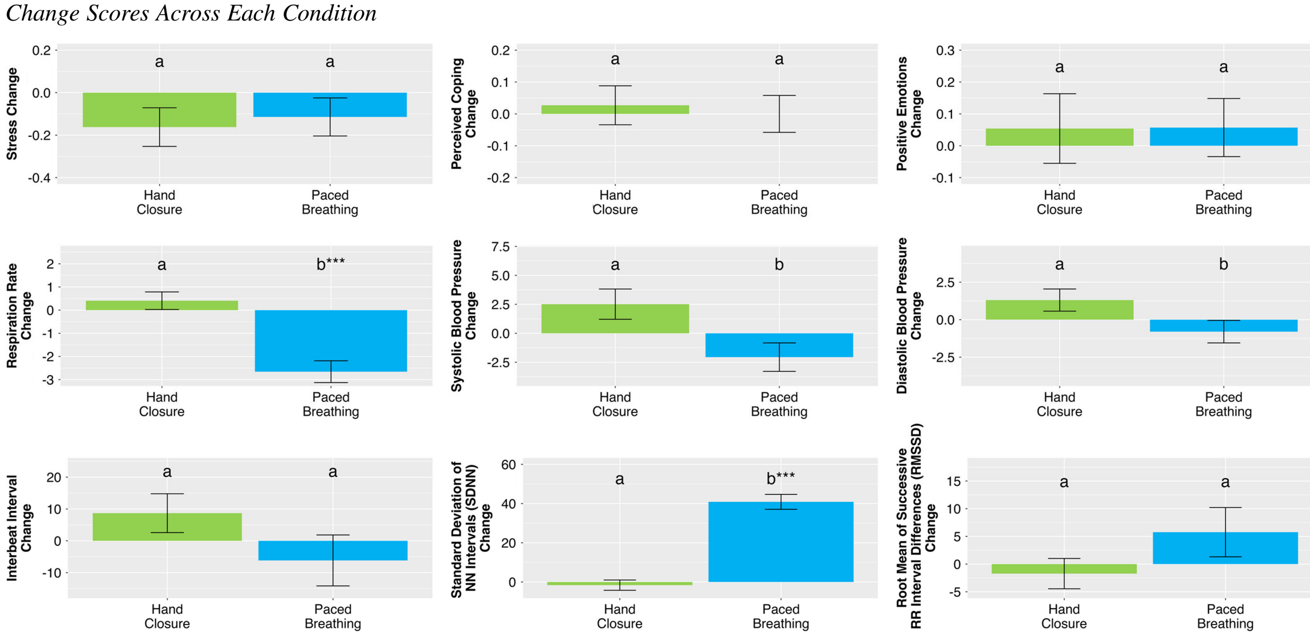
Note. The paced breathing and hand closure columns provide the results from the one-sample *t* tests for each condition. The comparison columns provide the two-sample *t* test results, and the combined columns provide the results from the one-sample *t* tests aggregated across conditions. Results from the log RMSSD yielded the same conclusions as the nontransformed RMSSD variable. DV = dependent variable; SBP = systolic blood pressure; DBP = diastolic blood pressure; IBI = interbeat interval; SDNN = standard deviation of the IBI of normal sinus beats; RMSSD = root mean square of successive difference between normal heartbeats.

their Samsung phone and agreed to participate in a 3-week study about people's stress, emotional experiences, HR, and blood pressure. These data from MyBPLab were collected as part of a larger project, and some additional papers that address distinct questions from the present study have been published previously (Don et al., 2023; Mak et al., 2023; Newman, Gordon, & Mendes, 2021; Newman et al., 2023; Park et al., 2023). As part of the study, they received notifications to complete three check-ins per day (once in the morning, afternoon, and evening). At each check-in, they were asked to place their finger over an optic sensor for approximately 30 s, which measured their HR (IBI) and estimated their blood pressure (see Gordon & Mendes, 2021, for validation studies). Following the measurement, participants answered a few questions about their day and how they were feeling.

Once the app was downloaded and the participants consented to the study, they were offered the option to participate in a "stress management" study. If they opted-in to the stress management study, they completed 3 days with baseline check-ins. During the following 6 days, participants were randomly assigned to the same videos described above, either the paced breathing video (experimental

Figure 2

Change Scores Across Each Condition



Note. Differences in letters indicate a significant difference across conditions ($p < .05$). Asterisks indicate a significant reactivity score for that particular condition ($p < .001$). Error bars represent one standard error. See the online article for the color version of this figure.

condition) or the hand closure video (control condition). See Figure 3 for a flow of the study design.

After the video, participants provided a sensor recording and answered questions about their stress and emotions. To not overburden participants, during these 6 days, participants received either the paced breathing or hand closure video during two of the three check-ins of the day, and they received one check-in each day without any video. After 6 days of completing treatment check-ins, participants completed 3 days of check-ins without any videos (Days 10–12), which served as a postexperimental period (i.e., a washout period) to examine possible lingering effects of the manipulation. During the next 6 days (Days 13–18), the pattern reversed such that the participants completed either the paced breathing or hand closure videos that they did not complete earlier (i.e., an AB/BA design). This was followed by a final postexperimental 3-day period on days 19–21 in which participants completed check-ins without any videos. Of the 3,277 participants who completed at least one baseline check-in and one check-in during the first treatment period, 1,411 (43.06%) participants completed at least one check-in during the second treatment period. Thus, the full study was designed as a 21-day study. However, because 1,866 (56.94%) participants did not remain in the study for the second 6-day treatment period, we focused our analyses on the first 12 days of the study (i.e., baseline, first treatment period, first washout period) to maximize statistical power.

Participants were volunteers; thus, we collected data from as many participants as possible. A post hoc power analysis indicated we achieved 0.80 power to detect effects as small as $d = 0.06$. Our primary pool of participants consisted of 3,277 ($M_{age} = 44.17$; $SD = 12.45$; 68.96% male) people who completed at least one baseline check-in and one treatment check-in. Participants were fairly well educated and mostly from the United States, though the study was global. There were more males than females, consistent with the demographics of people who have android phones. A full description of the demographic characteristics of the participants is presented in Table 3.

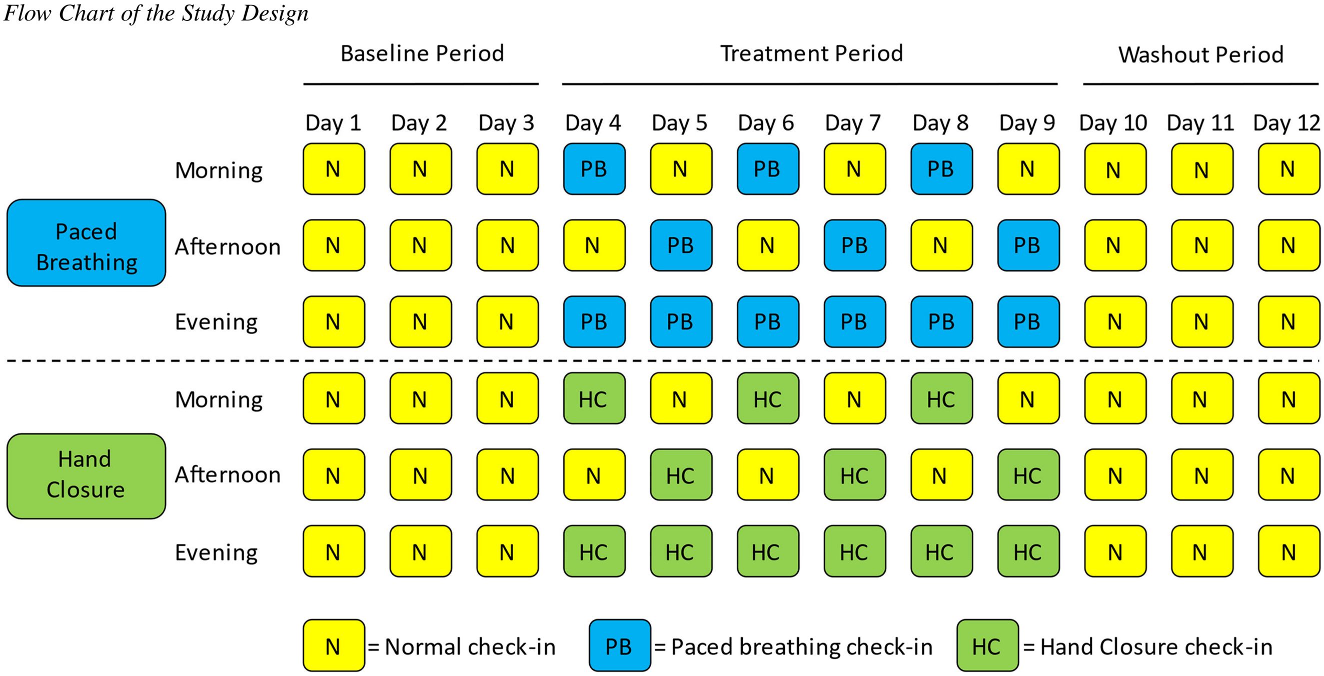
Physiologic Measures

At each check-in, participants were instructed to place their finger over the optic sensor for 30 s. The optic sensor (photoplethysmography) estimates HR and applies an algorithm that requires calibrated blood pressure responses to calculate SBP and DBP. In a prior validation study, participants provided multiple blood pressure measurements in two lab visits and in their daily lives for a week (Gordon & Mendes, 2021). Blood pressure measurements were obtained simultaneously using both the optic sensor and an FDA-approved blood pressure cuff. Correlations between the two devices for SBP, DBP, and HR were $r = .78$, $r = .82$, and $r = .96$, respectively. These correlations were similar to observed correlations between two separate FDA-approved devices. This study also found no variation in the reliability of the measurement over the 7-day period.

When participants joined the study, they were encouraged to calibrate their blood pressure with an external source. We recommended the FDA-approved A&D BP device for calibration, but we allowed any BP device to be used or BP values obtained from a health visit. To encourage calibration, which increased accuracy of blood pressure estimates, only participants who provided calibration values were presented with blood pressure values (others viewed the percentage increase or decrease from the previous check-in). In the present analyses, we include only calibrated blood pressure scores.

We also allowed for new calibration values to be entered at any time for more precise calculations of BP. The average (mean) number of calibrations was 2.01 ($SD = 1.72$, $Mdn = 1$, minimum = 1, maximum = 30). We standardized the measurement of BP by providing a video of how to properly collect a BP response, namely

Figure 3
Flow Chart of the Study Design



Note. See the online article for the color version of this figure.

Table 3
Study 3: Participant Demographics

Variable	Paced breathing condition		Hand closure condition	
	N	%	*N*	%
Gender				
Male	1,110	68.99	1,136	68.93
Female	482	29.96	482	29.25
Another gender	17	1.06	30	1.82
Age				
18–29 years old	188	11.73	205	12.51
30–39 years old	405	25.27	392	23.92
40–49 years old	507	31.63	495	30.20
50–64 years old	402	25.08	441	26.91
65+ years old	101	6.30	106	6.47
Country				
United States	1,034	64.91	1,080	66.26
United Kingdom	158	9.92	141	8.65
Australia	135	8.47	155	9.51
Canada	92	5.78	100	6.13
Another country	174	10.92	154	9.45
Education				
Elementary school (no high school)	35	2.24	37	2.32
High school or GED	179	11.45	217	13.60
Some college	369	23.61	373	23.37
2-year degree	163	10.43	179	11.22
4-year degree	416	26.62	414	25.94
Graduate school	401	25.66	376	23.56
Race/ethnicity				
Non-Hispanic White	957	59.81	989	60.6
Non-Hispanic Black	95	5.94	93	5.70
Non-Hispanic Asian	139	8.69	144	8.82
Hispanic/Latinx	194	12.12	184	11.27
Multiple races	55	3.44	53	3.25
Another race/ethnicity	160	10.00	169	10.36
Hypertension present	463	29.32	468	28.96
Hypertension absent	1,116	70.68	1,148	71.04

Note. There were no significant demographic differences across conditions (all $ps > .07$). GED = general educational development.

by sitting down with both feet on the floor, holding the phone at heart height, and completely covering the sensor with the finger. Too much motion would result in a failed reading, so participants were motivated to complete the sensor reading properly so as to not receive a failed measurement. See Gordon and Mendes (2021) for additional details of the validation studies.

Psychological Measures

After recording their HR and blood pressure, participants were asked, "Have you experienced any particularly stressful event since your last check-in?" (yes/no). If they selected "yes," acute stress was assessed with the question, "How stressful was it?" If they selected "no," they answered questions about stress, perceived coping, and positive emotions in the same manner as in Studies 1–2. In the majority of check-ins (>84%), people selected "no," so consistent with previous papers, our analyses focused on the latter questions (Mak et al., 2023; Newman et al., 2023; Park et al., 2023).

After watching the paced breathing or hand closure video and prior to recording their HR and blood pressure, participants were asked whether they believed the video reduced their stress. Specifically, they were asked, "How much do you think this task reduced your stress?" Responses were recorded on a 5-point scale (1 = *not at all*, 2 = *a little bit*, 3 = *somewhat*, 4 = *moderately*, 5 = *a great deal*).

Analytic Plan

As in the prior studies, the primary question of interest was whether the stress interventions influenced people's HR, blood pressure, stress, perceived coping, and positive emotions relative to preintervention check-ins and if the conditions differed from each other. We examined these questions with several different models. First, we compared people's first treatment check-in with a corresponding baseline check-in to determine whether people's first treatment experience had an effect relative to their baseline level. Next, we examined all available check-ins from the baseline period and all available treatment check-ins during Days 4 through 9 (i.e., the treatment period) among people who completed at least two check-ins during baseline and two treatment check-ins. We also ran sensitivity analyses with participants who provided at least one and at least three check-ins during each period (presented in the online supplemental materials).

Next, we considered how the changes from the baseline period to the treatment period were moderated by several demographic and baseline variables. Following this, we tested lasting effects of the interventions in two different manners. First, we tested whether the completion of a treatment check-in influenced people's physiologic and psychological outcomes during the next check-in that did not include a treatment video. Second, we examined whether the effects from the baseline period (Days 1–3) to the treatment period (Days 4–9) remained during the next 3 days (washout period; Days 10–12) when participants completed normal check-ins without any stress management videos. Finally, we compared changes over time among participants in the study with a different group of participants who opted out of participating in the stress intervention study but still completed normal check-ins during the same general period of time as those who participated in the "stress management" study.

We conducted two different types of analyses, depending on the research question and structure of the data. To answer the first question that compared participants' first baseline check-in with their first experimental or control check-in, we conducted mixed ANOVAs with a within-subjects factor (baseline period vs. treatment period) and a between-subjects factor (paced breathing condition vs. hand closure condition). In all other analyses, we ran multilevel models to accommodate all available data without having to average scores across time periods for each participant as would have been the case with mixed ANOVAs. In the multilevel modeling approach, we nested check-ins within participants. We created separate models to test the within-subjects effects, the between-subjects effects, and interactions. We acknowledge either mixed ANOVAs or multilevel models could be considered reasonable approaches to analyze these data, so we, therefore, present additional results using mixed ANOVAs with aggregated check-in data in the online supplemental materials for the purpose of transparency. The substantive conclusions were the same across the two analytic approaches. All analyses were conducted in R and can be found on OSF (https://osf.io/46gqa/) along with the materials and data.

Results

Comparisons Involving First Check-Ins

The primary research question addressed whether people's HR, blood pressure, stress, perceived coping, and positive emotions were influenced by either the paced breathing or hand closure exercises relative to their baseline levels. To provide a reasonable comparison of check-ins, we identified the first baseline check-in that matched the time of day (morning, afternoon, or evening) of the first completed treatment check-in. This was possible for 84.83% of the participants. For the remaining 15.17%, we identified their first baseline check-in. The means across conditions are presented in Table 4 and are depicted visually in Figure 4.

First, there were several within-subjects changes over time such that HR increased, $F(1, 3026) = 5.86$, $p = .016$, $\eta_p^2 = .002$; SBP decreased, $F(1, 1720) = 4.76$, $p = .029$, $\eta_p^2 = .003$; DBP decreased, $F(1, 1720) = 12.47$, $p < .001$, $\eta_p^2 = .007$; perceived coping increased, $F(1, 2105) = 13.18$, $p < .001$, $\eta_p^2 = .006$; and positive emotions increased, $F(1, 2105) = 17.62$, $p < .001$, $\eta_p^2 = .008$, from baseline to the first treatment check-in. Daily stress did not differ significantly across time, $F(1, 2105) = .29$, $p = .593$, $\eta_p^2 = .000$. Interestingly, there were no significant between-subjects condition effects or interactions (all $ps > .180$; A complete list of all tests is found in Table S5 in the online supplemental materials). In sum, the paced breathing videos and hand closure videos were both associated with changes in people's physiologic and psychological states.

Comparisons Involving Multiple Check-Ins

To address the robustness of the results, we replicated the analyses with all available data from participants who provided at least two baseline check-ins and two treatment check-ins. We conducted multilevel models with check-ins nested within persons. We ran three separate models to test the within-subjects effects, the between-subjects effects, and the interaction effects. Because all parameters are estimated simultaneously in multilevel modeling, we relied on a tradition in multilevel modeling of beginning with the simplest models before adding new predictors (Nezlek, 2012, pp. 68–70). In the within-subjects effects (Model 1), we entered a dummy-coded time period variable (0 = *baseline period*, 1 = *treatment period*) uncentered at level 1. In the between-subjects effects (Model 2), we entered a dummy-coded condition variable (0 = *hand closure condition*, 1 = *paced breathing condition*) uncentered at Level 2. Finally, the interaction effects (Model 3) included both Levels 1 and 2 predictors together in the same model (see Models 1–3 in the online supplemental materials).

The results were similar to the first set of analyses. Positive emotions increased ($b = .06$, $t = 3.97$, $p < .001$, $\eta_p^2 = .007$), SBP decreased ($b = -0.59$, $t = -3.18$, $p = .002$, $\eta_p^2 = .007$), and DBP decreased ($b = -0.59$, $t = -4.09$, $p < .001$, $\eta_p^2 = .011$) over time. When considering more check-ins, we did not observe HR ($b = -0.01$, $t = -0.06$, $p = .950$, $\eta_p^2 = .000$) or perceived coping ($b = 0.02$, $t = 1.60$, $p = .111$, $\eta_p^2 = .001$) differences over time. Similar to analyses examining just the first check-in, daily stress ($b = 0.02$, $t = 1.36$, $p = .175$, $\eta_p^2 = .001$) did not differ over time. There were no significant between-condition or interaction effects (all $ps > .052$). Table 5 depicts the means across conditions, and Table S10 in the online supplemental materials shows the complete set of results.

We also conducted the analyses with different cutoff values. Participants who completed at least one check-in and at least three check-ins during baseline and treatment periods were included in separate analyses that are presented in the online supplemental materials. We also present a forest plot of all within-subjects changes over time across different cutoff values in Figure 5. These results largely mirrored those reported with two check-ins as a criterion score with the notable exception that perceived coping increased over time in the analyses with at least one check-in as a cutoff but did not increase over time in the analyses with at least three check-ins as a cutoff. Across all sets of analyses, the robust and replicable effects showed that blood pressure decreased over time and positive emotions increased over time. There was some additional mixed evidence that perceived coping increased over time.

Moderation of Within-Subjects Changes Over Time

The prior analyses documented several within-subject changes from baseline period check-ins to treatment period check-ins across both conditions. These within-subjects changes over time may be moderated by demographic characteristics (age, gender, income, and education), participants' perceptions that the stress management manipulations reduced their stress, and baseline levels of emotions and physiology. To examine these possibilities, we included covariates in the first analyses (conducted with ANOVAs) that included their first baseline check-in and their first treatment check-in. We also included the person-level moderators in the within-subjects multilevel models (Model 1) that included all data from participants who provided at least two baseline check-ins and two treatment check-ins.

In the first analyses, we found that perceptions of stress reduction moderated the within-subjects change in positive emotions,

Table 4

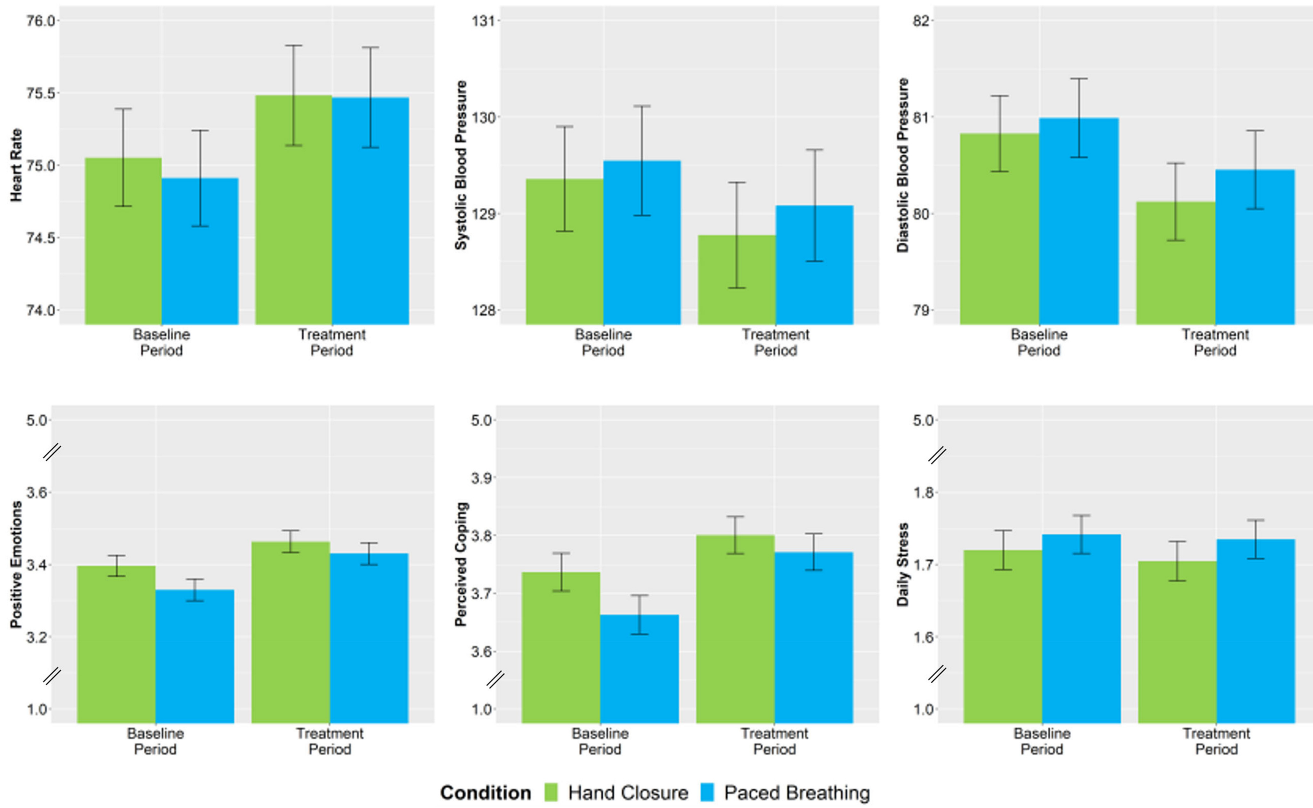
Means of First Treatment Check-In and Corresponding First Baseline Check-In

	Baseline period (Days 1–3)						Treatment period (Days 4–9)					
	Paced breathing condition		Hand closure condition		Combined		Paced breathing condition		Hand closure condition		Combined	
Dependent variable	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)
Heart rate	1,493	74.91 (12.80)	1,535	75.05 (13.19)	3,028	74.98^{a} (13.00)	1,493	75.47 (13.29)	1,535	75.48 (13.55)	3,028	75.48^{b} (13.42)
Systolic blood pressure	850	129.55 (16.47)	872	129.36 (16.00)	1,722	129.45^{a} (16.23)	850	129.08 (16.75)	872	128.78 (16.21)	1,722	128.93^{b} (16.48)
Diastolic blood pressure	850	80.99 (11.89)	872	80.83 (11.58)	1,722	80.91^{a} (11.73)	850	80.45 (11.73)	872	80.12 (11.79)	1,722	80.29^{b} (11.76)
Daily stress	1,044	1.74 (0.85)	1,063	1.72 (0.88)	2,107	1.73^{a} (0.86)	1,044	1.73 (0.85)	1,063	1.70 (0.89)	2,107	1.72^{a} (0.87)
Perceived coping	1,044	3.66 (1.07)	1,063	3.74 (1.07)	2,107	3.70^{a} (1.07)	1,044	3.77 (1.01)	1,063	3.80 (1.03)	2,107	3.79^{b} (1.02)
Positive emotions	1,044	3.33 (0.97)	1,063	3.40 (0.96)	2,107	3.36^{a} (0.96)	1,044	3.43 (0.97)	1,063	3.46 (0.97)	2,107	3.45^{b} (0.97)

Note. Means with different subscript letters indicate differences at $p < .05$.

Figure 4

Bar Graphs Depicting the Distributions During Baseline and Treatment Check-In Periods Across the Two Conditions



Note. See the online article for the color version of this figure.

$F(1, 950) = 8.48$, $p = .004$, $\eta_p^2 = .009$, such that the increase in positive emotions was greater among those who more strongly believed the videos reduced their stress. Age moderated the within-subjects change in DBP, $F(1, 1698) = 5.11$, $p = .024$, $\eta_p^2 = .003$, such that the decrease in DBP was greater among older than younger participants. Income moderated the within-subjects change in SBP, $F(1, 1538) = 4.02$, $p = .045$, $\eta_p^2 = .003$, such that the decrease in SBP was stronger among those with higher incomes than those with lower incomes. Finally, gender (comparing males to females) moderated the within-subjects change in perceived coping, $F(1, 2065) = 4.87$, $p = .028$, $\eta_p^2 = .002$, such that the increase in coping was greater among females than males.

Those with higher blood pressure at baseline were more likely to have lower blood pressure over time. Those with higher HR at baseline decreased in their HR, whereas those with lower HR at baseline increased. Those with lower positive emotions and perceived coping at baseline increased the most in positive emotions and perceived coping, respectively. Those with higher baseline levels of stress decreased in stress over time, whereas those with lower baseline stress increased over time. This observation could be due to several factors like regression to the mean, law of initial values (Wilder,

Table 5

Means of All Check-Ins Among Participants With at Least Two Check-Ins During Each Period

	Baseline period (Days 1–3)						Treatment period (Days 4–9)					
	Paced breathing condition		Hand closure condition		Combined		Paced breathing condition		Hand closure condition		Combined	
Dependent variable	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)	*N*	*M* (*SD*)
Heart rate	887	74.90 (11.02)	973	75.08 (11.13)	1,860	74.99[a] (11.08)	887	75.05 (11.39)	973	75.05 (11.37)	1,860	75.05[a] (11.38)
Systolic blood pressure	646	129.31 (16.06)	698	129.45 (15.93)	1,344	129.38[a] (15.99)	646	128.91 (16.39)	698	128.70 (15.50)	1,344	128.8[b] (15.93)
Diastolic blood pressure	646	80.70 (11.48)	698	80.34 (11.07)	1,344	80.52[a] (11.27)	646	80.13 (11.43)	698	79.74 (11.09)	1,344	79.93[b] (11.25)
Daily stress	823	1.76 (0.67)	902	1.72 (0.68)	1,725	1.74[a] (0.67)	823	1.78 (0.76)	902	1.73 (0.77)	1,725	1.75[a] (0.77)
Perceived coping	823	3.74 (0.80)	902	3.81 (0.82)	1,725	3.78[a] (0.81)	823	3.76 (0.90)	902	3.83 (0.90)	1,725	3.79[a] (0.90)
Positive emotions	823	3.35 (0.81)	902	3.41 (0.81)	1,725	3.38[a] (0.81)	823	3.40 (0.87)	902	3.47 (0.88)	1,725	3.44[b] (0.88)

Note. Means with different subscript letters indicate differences at $p < .05$.

1962), or the fact that the stress reduction techniques were most beneficial to those who needed it the most.

Taken together, the results from these analyses suggest that the increases in positive emotions (and to some degree perceived coping) were stronger if people believed they worked in reducing stress. Observed reductions in blood pressure with time were most pronounced among older adults. In general, decreases in blood pressure were moderated by baseline levels such that the decreases were stronger among those with higher blood pressure. Similarly, the increases in positive emotions and perceived coping were stronger among those with lower baseline levels of positive emotions and perceived coping, respectively. That is, observed changes over time from the paced breathing and hand closure exercises were most pronounced among unhealthy and unhappy individuals.

Lasting Changes Associated With the Interventions

The prior results demonstrated that the paced breathing and hand closure exercises were associated with changes in the outcome measures immediately after completion of the stress intervention videos. To examine the lingering changes associated with the exercises, we conducted two sets of analyses. The first considered whether the stress reduction exercises influenced the participants during the very next check-in that did not include a stress reduction exercise. The second analysis considered whether the change in outcomes from the baseline period (Days 1–3) to treatment period (Days 4–9) remained during the washout period (Days 10–12) that did not include any treatment check-ins among participants who completed at least two check-ins per period.

To address the first question, we created multilevel models that included a dummy-coded variable representing whether the check-in was a treatment check-in or a subsequent normal check-in (0 = *treatment check-in*, 1 = *subsequent normal check-in*). The intercept provides an estimate of the outcome variable during the treatment check-ins, and the Level 1 coefficient provides an estimate of the difference between the treatment check-in and the subsequent normal check-in (see Model 4 in the online supplemental materials).

The results of these models showed that daily stress levels decreased ($b = -0.03$, $t = -2.08$, $p = .038$, $\eta_p^2 = .004$) from treatment check-ins until the next normal check-in. All other within-subjects main effects and interactions were not significant.

The second question was addressed with a similar model that included separate dummy-coded variables representing the treatment period and the washout period. The intercept in the model represented the level of the outcome measure during the baseline period. The coefficients from the two dummy-coded variables provide estimates of the differences between those respective time periods and the baseline period. We were interested in whether the washout period levels differed significantly from baseline levels (see Model 5 in the online supplemental materials).

The results from Model 5 showed that increases in perceived coping and positive emotions and decreases in blood pressure remained during the washout period. More specifically, results from Model 5 showed that the differences between baseline and washout were significantly different for perceived coping ($b = 0.05$, $t = 2.51$, $p = .012$), positive emotions ($b = 0.09$, $t = 4.21$, $p < .001$), SBP ($b = -1.10$, $t = -4.01$, $p < .001$), and DBP ($b = -0.88$, $t = -3.94$, $p < .001$). See the left side of Table 6 for a summary of the means across time periods.

Comparing Time Trends Between Opt-In and Opt-Out Participants

Although it could be inferred that the changes in physiologic and psychological outcomes over time were due to the stress management exercises, it is possible that the trends merely reflected a natural process of changes over time due to the repeated assessments of these measures. To address this possibility, we examined whether the changes in physiologic and psychological outcomes over time from participants in our stress management study differed from participants who completed check-ins without participating in the experiment (those who opted out).

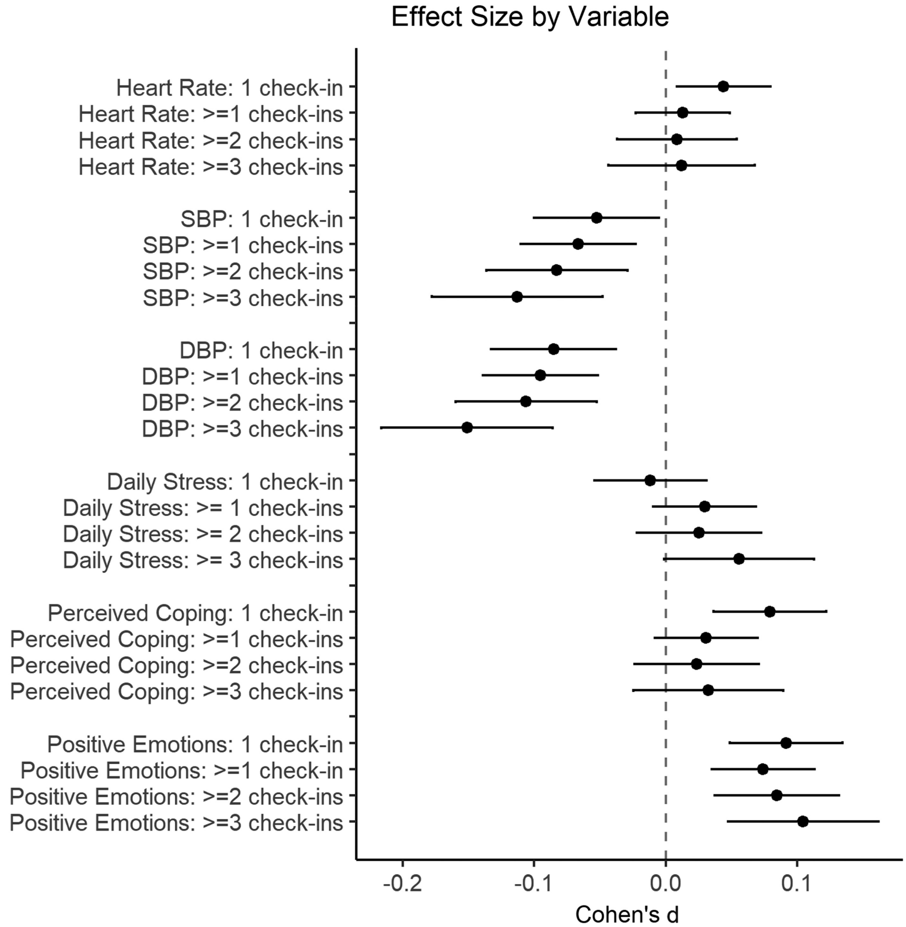
We examined the data from 2,600 “opt-out” participants ($M_{age} = 50.08$, $SD = 12.91$, 69.71% male) who provided at least two check-ins during the baseline period (Days 1–3), at least two check-ins during Days 4 through 9, and at least two check-ins during the washout period (Days 10–12). For all the check-ins during the 12-day period, they answered questions about their emotions and recorded their HR and blood pressure without watching any videos. To compare the linear trends in the outcome measures over time across the two different groups, we created a time variable that represented the three time periods (1 = *baseline*, 2 = *Days 4 through 9*, 3 = *washout*). This variable was centered around each individual’s mean and entered at Level 1, and an uncentered dummy-coded variable representing the two groups of participants (0 = *nonexperimenters*, 1 = *experimenters [combined conditions, given no condition differences]*) was entered at Level 2. The coefficient from the Level 2 predictor provides an estimate of the differences in the slopes across the two groups. Because participants were not randomly assigned to participate or not participate in the experiment, we additionally controlled for several demographic characteristics (age, gender, education, income, BMI, hypertension, race, and ethnicity).

The results showed that the increases in perceived coping and positive emotions over time were significantly stronger among those who participated in the stress reduction study compared to those who did not participate ($b = 0.04$, $t = 2.91$, $p = .004$; and, $b = 0.06$, $t = 4.29$, $p < .001$, respectively). The means presented at the right side of Table 6 show there were functionally no changes in perceived coping and positive emotions over time among those who did not participate, whereas there was an increase among those who did participate in the study.

Interestingly, although we did not observe any significant reductions in daily stress among those who participated, there was an increase in daily stress among those who did not participate. The difference between these slopes was significant ($b = -0.04$, $t = -2.84$, $p = .005$). This suggests that although the stress reduction exercises may not have been associated with lower daily stress over time, they may have helped prevent an increase in daily stress over time. Finally, levels of SBP and DBP decreased over time among those who participated in the study and among those who did not participate. The decreases over time appeared stronger among those who participated in the stress reduction study, but the differences in the slopes for SBP and DBP were not significant ($b = -0.17$, $t = -0.91$, $p = .365$; and, $b = -0.28$, $t = -1.94$, $p = .053$, respectively). These results show that the

Figure 5

Cohen's d *Effect Sizes for the Within-Subjects Changes Over Time From Baseline to Treatment Period Combined Across Conditions for Each Cutoff Criterion for Each Dependent Variable*



Note. The dots represent effect size estimates, and the lines represent 95% confidence intervals. To aid with comparisons across each criterion, we used Cohen's *d* from ANOVA analyses as an effect size estimate even though the latter three comparisons were conducted with multilevel models. Positive values (>0) indicate an increase from baseline to intervention period, whereas negative values (<0) indicate a decrease from baseline to intervention period. ANOVA = analysis of variance; SBP = systolic blood pressure; DBP = diastolic blood pressure.

act of repeated assessments in daily life may lower people's blood pressure.

Discussion

Summary

With increasing levels of stressors in today's society ranging from the COVID-19 pandemic to political conflicts and climate change, understanding ways to minimize stress and increase positive emotions in daily life is ever more important. The current set of studies provides a critical examination of a paced breathing condition, delivered effortlessly on people's phones and requiring little time and investment from participants. We examined the effectiveness of paced breathing on changes in psychological and physiological processes in ecologically valid contexts across a large sample of participants while implementing a comparison condition that controlled for expectations and relaxing features that often accompany paced breathing interventions. One key consistent finding across the different methods and studies was that the paced breathing and hand closure conditions were equally associated with increased perceived coping and positive emotions. Thus, the act of paced breathing may not be necessary to increase positive emotions but rather the positive incidental features that often accompany paced breathing interventions like focusing on a target, soothing music, and the suggestion that the intervention could help reduce stress might be sufficient.

Reconciling Discrepant Findings Across Methods

In addition to the key findings that replicated across methods, several interesting results emerged from distinct but complementary

Table 6
Means of All Check-Ins Among Participants With at Least Two Check-Ins During Each Period, Including Washout

		Opt-in participants				Opt-out participants		
Dependent variable	*N*	Baseline period (Days 1–3) *M* (*SD*)	Treatment period (Days 4–9) *M* (*SD*)	Washout period (Days 10–12) *M* (*SD*)	*N*	Baseline period (Days 1–3) *M* (*SD*)	Treatment period (Days 4–9) *M* (*SD*)	Washout period (Days 10–12) *M* (*SD*)
Heart rate	981	74.26[a] (11.05)	74.06[a] (11.11)	74.57[a] (11.43)	2,571	74.59[a] (10.98)	74.58[a] (10.80)	74.49[a] (11.33)
Systolic blood pressure	712	129.39[a] (16.03)	128.54[b] (15.73)	128.23[b] (15.32)	2,079	129.41[a] (15.12)	128.86[b] (14.49)	128.72[b] (14.83)
Diastolic blood pressure	712	80.06[a] (11.30)	79.23[b] (11.09)	79.14[b] (11.00)	2,079	79.64[a] (10.48)	79.22[b] (10.11)	79.17[b] (10.43)
Daily stress	900	1.70[a] (.64)	1.70[a] (0.73)	1.69[a] (.75)	1,984	1.62[a] (0.63)	1.61[a] (0.65)	1.66[b] (0.77)
Perceived coping	900	3.83[a] (.80)	3.88[b] (0.87)	3.87[b] (.90)	1,984	3.80[a] (0.86)	3.83[a] (0.88)	3.79[a] (0.95)
Positive emotions	900	3.41[a] (.79)	3.49[b] (0.85)	3.50[b] (0.89)	1,984	3.44[a] (0.84)	3.46[a] (0.88)	3.44[a] (0.94)

Note. Note that means are aggregated across conditions in this table. Within each sample of participants, differences across time points are indicated with different superscript letters.

methods. Before describing these results, we acknowledge that the devices used to measure physiology differed from the lab to daily life. Not surprisingly, the equipment in the lab allowed us to measure physiology with greater precision than the devices on people's phones. Some of the differences across studies may be attributed to these differences. Nevertheless, we highlight some of the differences that emerged across studies.

In the online and laboratory experiments (Studies 1–2), stress levels decreased after participants completed the paced breathing and hand closure exercises relative to their baseline levels, whereas there was no significant decrease in stress in the app-based EMA study (Study 3). This could be attributed to the fact that laboratory environments are tightly controlled, whereas there are many confounds and factors in the real world that cannot be controlled (Brunswik, 1956; McGrath, 1982). This factor might be especially important for physiological measures, which are collected by experts in a lab with expensive equipment with carefully controlled baseline assessments compared to an app-based approach that leverages an optic sensor as part of the many features on a phone with no oversight on the quality of the measurement. Additionally, it is worth reiterating that stress levels increased in the app-based study among those who completed normal check-ins without participating in the stress management study, whereas stress levels did not increase among those who participated in either the paced breathing or hand closure conditions. Thus, the stress management videos may be effective at reducing stress immediately in a tightly controlled lab setting, and they may be effective at preventing increases in stress levels in everyday life.

Another interesting difference between studies was that blood pressure levels decreased in the lab experiment after participants completed the paced breathing exercise relative to their baseline levels, but no difference emerged in the hand closure condition (Study 2). In contrast, blood pressure levels decreased over time in the app-based EMA study, but there were no differences across conditions (Study 3). These findings show that paced breathing is effective at immediately reducing blood pressure, but the effects may not linger over time. Another difference between the methods that could explain this discrepancy is that blood pressure levels were recorded during an initial 3-day baseline period, but these levels of blood pressure might differ from their blood pressure level immediately preceding the stress management videos. Finally, it is important to note that the differences observed might be due to person-level effects such that people who sign up to come to a psychology lab for an hour-long study for monetary compensation tend to be younger and likely different than those who download an app to monitor their blood pressure.

Advantages of a Large EMA Study

One advantage of conducting a large mobile-based experiment in people's daily lives was that we were able to recruit a large sample allowing us to examine key moderators of the variables that evidenced changes over time across both conditions. First, participants who believed the exercise was effective at reducing their stress showed a greater increase in perceived coping and positive emotions. Although these individuals did not show a greater decrease in their stress, the results suggest that a belief in the effectiveness of the intervention appeared to provide a boost to their positive emotions relative to baseline levels. This pattern is consistent with research on expectancy beliefs and placebo effects (Geers et al., 2021).

Second, we were able to examine demographic moderators, and we found that the reductions in blood pressure and increases in perceived coping (to some extent) over time were stronger among older than younger adults. Though the changes over time were relative to baseline levels as opposed to a true control condition, these results suggest that the paced breathing and hand closure exercises both might be associated with better outcomes among older adults who have higher levels of blood pressure (Lakatta et al., 1987; Sutton-Tyrrell et al., 2001).

Third, many of the within-subjects changes over time were moderated by baseline levels of emotions and physiology, such that the changes over time across both conditions were stronger among those with higher baseline levels of stress, HR, and blood pressure, and lower baseline levels of perceived coping and positive emotions. In other words, the increases in positive emotions and perceived coping and the decreases in stress and blood pressure over time were stronger among unhealthy and unhappy individuals, whereas there were essentially no changes over time among healthy and happy people. This can be viewed as an encouraging finding because it suggests that the interventions were associated with the greatest changes over time among people who are in the greatest need of improving their emotions, HR, and blood pressure levels. Moreover, it qualifies some of the very small effect sizes. Although the effect sizes of the exercises are very small on average, they are slightly larger among those who would benefit the most from the exercises.

Another key advantage of conducting a mobile-based EMA study over the course of several days is that we were able to examine changes in emotions, HR, and blood pressure over time. We found that blood pressure levels decreased over time across both conditions, but this decrease over time was also evident in a sample of participants who completed check-ins without taking part in the exercises. This suggests that the continual monitoring of one's blood pressure can result in detectable decreases over time. We acknowledge it is possible that over time people learn strategies to measure their blood pressure that result in lower values—analogous to weighing yourself in the morning versus after a big meal. For example, measuring blood pressure after running up a couple of flights of stairs is likely to result in higher than typical values, whereas measuring blood pressure while sitting and relaxing is likely to be associated with values that are lower than typical. These general trends in lower BP over time might reflect these learned associations. Thus, the stress management exercises may not have a unique sustained long-term effect of reducing blood pressure beyond that of repeated measurement. In contrast, our results showed that levels of perceived coping and positive emotions remained elevated over time across both conditions. This pattern was not replicated among the other group of participants who completed check-ins without completing the exercises. Thus, the exercises seem to be associated with lasting positive increases in people's perceived coping and positive emotions, but they were not associated with reducing stress.

Implications

Our results across studies highlight two key implications. First, because both exercises were equally associated with increased perceived coping and positive emotions (and decreased general stress in Study 1), it suggests that there may be nothing unique or special about the act of paced breathing. Instead, watching a video that forces the viewer to slow down while distracting them from the hassles and busyness of everyday life may be sufficient. This finding appears to conflict with theoretical accounts of the physiological benefits of paced breathing as well as prior research which has found paced breathing to have beneficial emotional effects relative to control conditions (Edmonds et al., 2009; Lin et al., 2014; Van Diest et al., 2014). However, we note that the control conditions in prior research may not have accounted for expectancy effects in the manner that our control condition did. The control condition was designed to isolate the effect of paced breathing by appropriately matching other features that might also be relaxing (e.g., music playing, expanding and contracting orb). Participants in control conditions in prior studies may not have expected anything positive to happen to them, whereas those in the paced breathing condition likely expected positive benefits. In our study, participants likely expected benefits in both conditions because the videos helped participants slow down and the instructions explicitly mentioned that the strategies were intended to reduce stress. Consistent with this, we found that the increases in positive emotions were strongest among people who believed the exercises were beneficial. Thus, our results emphasize the importance of considering expectancy effects and appropriately matched control conditions in stress reduction experiments.

Second, although the paced breathing exercise was effective at reducing blood pressure immediately following the exercise relative to the hand closure condition when assessed in the lab, the reduction in blood pressure due specifically to paced breathing was not evident over time in daily life. This means that any particular beneficial effects of paced breathing on blood pressure may be short-lived. Prior research conducted in laboratory settings without continual monitoring over time has not been able to examine these questions.

Constraints on Generality

Although our final sample was larger than many lab-based studies, this was not a representative sample and there are likely selection effects to consider. Specifically, people presumably decided to participate in the study because they were interested in monitoring their HR and blood pressure and reducing their stress. Relative to those who completed normal check-ins without participating in the experiment, those who elected to participate in the study had higher levels of stress. Future research could examine how effective paced breathing and stress reduction techniques are among those who have less interest in them. In general, we expect our findings to generalize to fairly diverse populations that are similar to the demographic characteristics of our samples.

Additional Limitations and Future Directions

In addition to our constraints on generality, we note a few areas of limitations and future directions. First, the significant results we detected in the EMA study were very small in magnitude. This likely reflects the fact that daily life includes many confounds that cannot be controlled. Given the noise in the measurement of physiology and emotions in daily life, we suspect the reported effect sizes are underestimates of the true effect sizes. However, we cannot firmly conclude this, so we urge readers to interpret our small effect sizes with caution. Nevertheless, small effects when carried out in magnitude can yield important and beneficial consequences to society at large (Milkman, Gromet, et al., 2021; Milkman, Patel, et al., 2021; Milkman et al., 2022; Newman et al., 2019, 2022).

However, it is difficult to determine whether the small effect sizes associated with changes in emotions and blood pressure from our data represent practically meaningful changes. One approach to calibrate these findings is to benchmark or compare the size of the effects with other relationships from our data that have known practical significance (Bourassa et al., 2017; Sechrest et al., 1996). Age and education are two variables that have received considerable attention in public policy and public health, and their relationships with blood pressure and positive emotions can be used as a comparison. In our data, age was weakly related to SBP ($r = .10$), DBP ($r = -.03$), and positive emotions ($r = .14$). Education was also weakly related to SBP ($r = -.03$), DBP ($r = -.02$), and positive emotions ($r = .03$). These effect sizes are similar to the within-subjects effect sizes of the experimental conditions from the baseline period to the washout period. To make this more concrete, the increase in positive emotions from baseline to the washout period (0.09) is the same as the difference in positive emotions from someone who does not have a high school diploma to someone who has a 4-year college degree (0.09). As yet another example, the reduction of blood pressure of 1.16 mmHg in our study was comparable to the difference in blood pressure from someone between the ages of 35 and 40 to someone between the ages 45 and 50 (1.45 mmHg). Thus, in more colloquial terms, engaging in one of the stress reduction techniques was associated with decreases in SBP and increases in positive emotions over time that are similar to taking 10 years off one's age or obtaining high school and college degrees, respectively.

Though these comparisons suggest the effect sizes we observed are similar in magnitude to other meaningful effect sizes, whether these effects amount to clinically meaningful differences over longer periods of time remains an open research question. An alternative perspective to the benchmarking approach we have outlined is to conclude that it is extremely difficult to produce meaningful changes in physiologic and psychological states through simple behavioral interventions. This may highlight the need for researchers to rethink the activities and behaviors designed to improve people's health and well-being.

We also acknowledge that our moderation analyses included many models, and we may have capitalized on chance. Thus, additional research replicating our moderation analyses is needed before strong conclusions can be drawn about when, and for whom, these intervention strategies may be most effective.

Second, the exact mechanism explaining why and how the paced breathing and hand closure exercises influenced people's emotions remains unclear. One reason for this lack of clarity is because we did not include a control condition that lacked expectancy effects. We attempted to remedy this issue by comparing the paced breathing and hand closure conditions with participants who opted out of the study and provided reports of emotions and physiology, but participants were not randomly assigned to this condition. Thus, we cannot make any firm causal claims about the effectiveness of the paced breathing and hand closure exercises.

Nevertheless, the key takeaway from our studies was that the paced breathing and hand closure exercises did not differ from each other in their changes over time relative to baseline levels. In particular, the changes in emotions over time in the paced breathing condition replicate prior research which has used control conditions that did not include expectancy effects. With this broader context in mind, we speculate that some of the detected changes over time could behave in a similar manner to certain mindfulness and meditation exercises that have calming effects (Grossman et al., 2004). Another possibility is that the paced breathing and hand closure exercises are effective emotion regulation strategies because of the incidental features like soothing music, a calm voice, a target to focus on, and the expectation that the task might be helpful to reduce stress. For instance, they may help interrupt ruminative and suppressive thoughts and feelings. These possibilities remain fruitful avenues for future research.

Third, the extent to which we can generalize the findings of our paced breathing exercise to other paced breathing exercises may be limited to a degree. Though we relied on a common practice by having participants watch an orb that contracted and expanded at a ratio of 6:10, other researchers have used slight variations of this paced breathing exercise, such as cyclic sighing, or box breathing (e.g., Balban et al., 2023). The rates at which people pace their breathing could influence their emotions and physiology in ways we could not detect. It may be useful to examine the effectiveness of alternative paced breathing exercises with appropriately matched control conditions in future research.

Conclusion

Across three studies in different settings, we determined that a paced breathing exercise might be associated with increases in positive emotions over time in a similar manner to a hand closure control exercise. The changes over time associated with these exercises could likely be attributed to expectancy effects and/or the shared incidental features of the exercises like hearing calm music, a soothing voice, and pacing bodily changes with a target. Moreover, blood pressure levels decreased over time for those who opted in and who opted out of the stress management study, which suggests that continual monitoring might contribute to blood pressure declines. These results point to important implications for stress reduction strategies and expectancy effects.

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