Brief breath awareness training yields poorer working memory performance in the context of acute stress

Simon B. Goldberg[1, 2*], Lisa Flook[1], Matthew J. Hirshberg[1], Richard J. Davidson[1,3,4], & Stacey M. Schaefer[1]

[1]Center for Healthy Minds, University of Wisconsin-Madison, Madison, WI, USA

[2]Department of Counseling Psychology, University of Wisconsin-Madison, Madison, WI, USA

[3]Department of Psychology, University of Wisconsin-Madison, Madison, WI, USA

[4]Department of Psychiatry, University of Wisconsin-Madison, Madison, WI, USA

*Corresponding author (sbgoldberg@wisc.edu)

Data Availability Statement

The data that support the findings of this study are openly available through the Open Science Framework at https://osf.io/hpcmk/

Recommended citation: Goldberg, S. B., Flook, L., Hirshberg, M. J., Davidson, R. J., & Schaefer, S. M. (in press). Brief breath awareness training yields poorer working memory performance in the context of acute stress. *Cognition and Emotion*.

Abstract

Mindfulness-based interventions that span multiple sessions over time appear to confer psychological benefits. However, the effects of brief periods of mindfulness meditation training are less clear, particularly on measures of cognitive functioning. This study assessed whether brief mindfulness practice (breath awareness) or training in two other contemplative practices – loving-kindness and gratitude – differentially impact working memory performance following acute physiological stress relative to an attentional control. Participants (*n* = 162) were randomly assigned to one of four training groups and completed the automated Operation Span (OSPAN) task pre-training and again after undergoing the cold pressor task. Three of the four groups improved in OSPAN performance, with loving-kindness, gratitude, and attentional control conditions showing increases in OSPAN relative to breath awareness. Changes in OSPAN were not correlated with changes in positive or negative affect. It appears that brief breath awareness training may not effectively buffer against acute stress in this predominantly meditation naïve sample and may in fact impair subsequent cognitive performance relative to a control or other contemplative practices. A granular approach is warranted to understand potentially distinct and contextually variable effects of different contemplative practices. Implications are discussed in light of the stress buffering hypothesis and Monitor and Acceptance Theory.

Keywords: mindfulness; gratitude; loving-kindness; working memory; stress

A growing body of evidence suggests that repeated meditation practice may confer a variety of psychological benefits (Sedlmeier et al., 2012). Mindfulness-based interventions (MBIs), such as mindfulness-based cognitive therapy, have shown effects superior to passive controls and on par with other active therapies across a range of populations, clinical conditions, and outcome measures (Goldberg et al., in press), including demonstrating beneficial effects on behavioral measures of executive function (Cásedas et al., 2020). Even brief periods of mindfulness meditation training (i.e., mindfulness inductions) may reduce negative affect (Schumer, Lindsay, & Creswell, 2018).

As the experimental literature examining mindfulness meditation grows, researchers have sought to clarify the precise contexts in which mindfulness may be most beneficial along with the mechanisms through which benefits may occur. The stress buffering hypothesis proposes that mindfulness training will be most efficacious in stressed populations (Creswell & Lindsay, 2014). Within the context of stress, mindfulness is proposed to promote both prefrontal regulatory processes as well as dampen central (e.g., amygdala) and peripheral (e.g., hypothalamic-pituitary-adrenal axis) reactivity pathways (Creswell & Lindsay, 2014). As indirect support of the stress buffering hypothesis, meta-analyses suggests that MBIs yield particularly large effects on measures of psychiatric symptoms within clinical samples and that mindfulness inductions produce larger effects in the context of experimentally induced stress (Goldberg et al., in press; Schumer et al., 2018). Monitor and Acceptance Theory (Lindsay & Creswell, 2017) proposes that the combination of attention to present-moment experience coupled with acceptance that is emphasized in mindfulness training form the key psychological mechanisms which circumvent affective reactivity. As the delivery of mindfulness training through mobile technology becomes increasingly ubiquitous, one can easily imagine the many stressful situations in which even brief mindfulness training could be deployed (e.g., prior to an exam or difficult conversation with a colleague).

While mindfulness meditation appears to be a promising stress reduction strategy, there are important gaps in the current literature regarding its stress buffering effects, particularly in the context of acute stress. For one, the vast majority of research on mindfulness has relied exclusively on self-report measures (Goldberg et al., in press), and evidence is lacking regarding the impact of mindfulness inductions on objective measures directly linked to daily life (e.g., working memory; Gill et al., 2020; Unsworth, Heitz, Schrock, & Engle, 2005). Moreover, mindfulness meditation is only one of a variety of practices based in contemplative traditions and positive psychology that may effectively buffer against stress (Dahl, Lutz, & Davidson, 2015). Indeed, it is entirely possible that common introductory mindfulness practices (e.g., breath awareness) may at first be depleting (e.g., require effortful attention control, result in monitoring without acceptance; Lindsay & Creswell, 2017; Hagger, Wood, Stiff, & Chatzisarantis, 2010; Mneimne et al., 2019). Kindness- (e.g., loving-kindness, compassion) and gratitude-based interventions have both demonstrated promising effects on wellbeing (Davis et al., 2016; Galante, Galante, Bekkers, & Gallacher, 2014) and may turn out to be more acceptable or more efficacious for some individuals and contexts than common forms of mindfulness meditation such as breath awareness (Salzberg, 2009). Neural evidence suggests that different meditation practices have distinct neural signatures (Fox et al., 2016), but experimental studies investigating the behavioral consequences of different types of contemplative practices in the context of acute stress are scarce.

The Current Study

We sought to investigate the efficacy of brief, audio-guided mindfulness training (breath awareness)[1] relative to training in non-mindfulness-based contemplative practices (loving-kindness, gratitude), or an attentional control. We examined effects on an objective measure of executive functioning, in particular, working memory capacity – the automated Operation Span (OSPAN; Unsworth et al., 2005) task, within the context of a well-characterized physiological stressor – the cold pressor task (CPT; Lovallo, 1975). Based on the stress buffering hypothesis (Creswell & Lindsay, 2014) and evidence from prior studies testing brief mindfulness interventions (Schumer et al., 2018), we hypothesized that all three contemplative practices would reduce stressor-related declines in OSPAN (Shields, Sazma, & Yonelinas, 2016). Given the possibility that breath awareness may be at first depleting (Hagger et al., 2010), we hypothesized it would show effects inferior to loving-kindness and gratitude but superior to the attentional control. Further, we hypothesized that increases in negative affect would account for declines in OSPAN performance from pre- to post-stressor, suggesting a potential affective correlate underlying differential effects. The current study involves secondary analysis of a previously published RCT (Hirshberg et al., 2018).

Materials and Methods

All study procedures were approved by the Institutional Review Board at the University of Wisconsin – Madison. This study was pre-registered at ClinicalTrials.gov (NCT02214264).

---

[1] Although some forms of breath awareness meditation are more focused in orientation (e.g., *jhana* practice; Dahl et al., 2015), we used a guided practice that is very similar to that provided as a foundational technique in mindfulness-based interventions like mindfulness-based stress reduction. This practice involves some degree of open monitoring of experiences that occur in tandem with the breath (e.g., thoughts, emotions), although the individual is still encouraged to return to the breath as a central object when the mind has wandered. For a transcript of the practices, see Hirshberg et al. (2018).

Other measures collected have been reported in two previous studies (Goldberg et al., 2017; Hirshberg et al., 2018).

Participants and Procedure

We recruited 166 undergraduates from a large, Midwestern university in exchange for psychology course credit. Participants were required to be native English speakers and ≥18 years old. Four participants were excluded prior to randomization after indicating their first language was not English (Supplemental Materials Figure 1). Among the 162 randomized, the average age was 19.31 (*SD* = 0.75). The sample was predominantly female (63.58%) and non-Hispanic White (74.69%). The majority of participants (83.33%) reported not practicing meditation in the past month. The four groups did not differ on demographic characteristics at baseline (Supplemental Materials Table 1).

Participants were randomly assigned to study condition based on a randomly generated sequence (*n*s = 39, 37, 44, and 42, for attentional control, breath awareness, gratitude, and loving-kindness, respectively; Supplemental Materials Table 2). Experimenters were blind to study condition and hypotheses. Upon arriving in the laboratory, participants completed baseline measures (affect, OSPAN) prior to receiving their respective brief training. All four trainings involved 12 minutes of guided audio instruction (for additional details, see Hirshberg et al., 2018). Breath awareness training encouraged participants to maintain attention on the physical sensations of breathing, repeatedly returning to this object whenever their mind wandered (Salzberg, 2009). Loving-kindness meditation involved directing feelings of kindness towards oneself and others (close other, suffering other, neutral person) by repeating classical phrases (e.g., "May I/you be happy"; Salzberg, 2009). Gratitude practice involved first creating a list of events and people for whom the participant was grateful, followed by recollecting the specific experience of those things for which one is grateful, including someone acting kindly towards the participant (Watkins et al., 2003). The control condition in this study was an attentional control condition, and it was based on a similar control condition used in previous gratitude research (Watkins et al., 2003) and was designed to involve focusing attention in a way that was affectively neutral and lacked instruction on managing distraction. Participants in the attentional control condition wrote a description about the spatial details of their home after envisioning moving through it and then were instructed to visualize the various rooms in their home, including visualizing the contents of their favorite room. While participants were not explicitly instructed to use the various techniques introduced during the trainings while undergoing the CPT, all four recordings did end with encouragement to apply the techniques to daily activities.

Following the brief trainings, participants completed the CPT (Lovallo, 1975). Participants were asked to submerge their non-dominant hand in an ice bath up to the elbow for three minutes. Prior to initiating the task, research assistants confirmed that the water temperature was below 36° F. The average water temperature was 33.63° F ($SD = 0.87$) and did not differ by condition (condition-level means = 33.57 to 33.66, $p = .962$). In order to increase autonomic stress reactivity (Schwabe, Haddad, & Schachinger, 2010), participants were observed by an unexpressive research assistant who wore a white laboratory coat and recorded time. The CPT has been shown to impair performance on the OSPAN (Schoofs, Wolf, & Smeets, 2009). Following the CPT, participants completed affect ratings and the OSPAN again. The first OSPAN was administered approximately 20-25 minutes prior to the CPT and the second OSPAN approximately 15-20 minutes following the start of the CPT (i.e., within the period in which a physiological stress response would be expected to occur; Schwabe et al., 2010).

Measures

The 20-item Positive and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988) was used to assess current affect. Participants rated their experience of positive (e.g., interested) and negative (e.g., afraid) affect states in the current moment (1 = very slightly/not at all, 5 = extremely). Positive and negative affect subscale scores were computed, both showed high internal consistency (αs = .85-.95).

The automated OSPAN (Unsworth et al., 2005) was used to assess working memory. In this task, participants are asked to solve simple mathematical operations (e.g., (1*2) + 1 = ?) while simultaneously remembering a set of letters (for task details see Unsworth et al., 2005). Following practice trials that are used to determine the timing of stimuli presentation, participants recalled 75 letters and completed 75 math problems. Letters were presented in sets ranging from 3 to 7 letters. As has been recommended (Unsworth et al., 2005), a total score was calculated as the number of correctly recalled letters for those with >85% accuracy on the mathematical operations.

Data Analysis

Analysis of variance (ANOVA) was used to compare groups at baseline. As a manipulation check, paired t-tests examined baseline to post-stressor changes in positive and negative affect. Paired t-tests also assessed within-group changes in OSPAN performance. Linear models equivalent to analysis of covariance (ANCOVA) were used to assess group effects on post-stressor OSPAN, while controlling for baseline OSPAN. Based on *a priori* hypotheses, linear models compared all three contemplative practice conditions with the attentional control and breath awareness with gratitude and loving-kindness. Finally, we examined associations between changes in affect and OSPAN. The primary linear models included all available data and a subsequent sensitivity analysis was restricted to those who completed the CPT (i.e., kept their hand submerged for the full three minutes). A second sensitivity analysis used all available data across all study variables (i.e., OSPAN, affect, demographics, CPT completion) in a multiple imputation model (10 imputed data sets) to account for missing data (see Supplemental Materials Table 3 for multiple imputation R code). All analyses were conducted in R. As noted in Hirshberg et al. (2018), we aimed to recruit a sample of 350 participants to allow 80% power to detect a small to moderate moderation effect by group (Cohen's $d = 0.30$). The study was terminated early for logistical reasons (study coordinator leaving for graduate school), yielding the reduced sample size reported here.

Results

At baseline, groups did not differ in OSPAN performance ($p = .871$), positive affect ($p = .296$), or negative affect ($p = .331$; Table 1). As reported by Hirshberg et al. (2018), participants in the contemplative practice conditions were marginally more likely to complete the CPT than controls (odd ratio = 3.08, $p = .054$, CPT non-completer *n*s = 2, 2, 6, and 8, for the breath awareness, loving-kindness, gratitude, and control conditions, respectively; Supplemental Materials Figure 1). The sample overall showed a large increase in negative affect ($d = 0.80$, $p < .001$) and a small decrease in positive affect ($d = 0.27$, $p = .018$) from baseline to post-stressor. Contrary to expectations, three out of the four conditions improved in OSPAN performance from baseline to post-stressor (*d*s = 0.29 to 0.38, *p*s < .050; Table 1). Only the breath awareness condition did not improve, but instead showed a non-significant decline in performance (*d* = -0.30, *p* = .638). Linear models examined post-stressor OSPAN controlling for baseline OSPAN. In these models, loving-kindness and gratitude did not differ from controls in change in OSPAN (*B*s = 0.92, 95% confidence interval [CI] [-2.94, 4.78] and 0.19, [-3.70, 4.08], *p*s = .638 and .925, respectively), while breath awareness showed worsening performance relative to controls (*b* = -4.08, [-8.11, -0.06], *p* = .047; Figure 1, Supplemental Materials Table 4). Similarly, breath awareness showed worsening performance relative to both loving-kindness and gratitude (*B*s = 5.00, [0.77, 9.24], and 4.27, [0.002, 8.54], *p*s = .021 and .050, respectively; Supplemental Materials Table 5). Significance tests from linear models were unchanged when restricted to those who completed the CPT and when using multiple imputation (Supplemental Materials Tables 6 to 9). Changes in OSPAN performance were not correlated with changes in positive or negative affect (*r*s = .04 and -.01, *p*s = .950 and .603, respectively).

Discussion

The current study sought to determine the impact of brief training in one of three contemplative practices on working memory capacity within the context of acute stress. Contrary to our hypotheses, there was no evidence that any of the three contemplative practices yielded superior working memory performance post-stressor than an attentional control. In partial support of our hypotheses, breath awareness training, a foundational practice in mindfulness meditation (Salzberg, 2009), produced poorer working memory performance following acute stress relative to both alternative contemplative practices. Breath awareness was also associated with significantly poorer working memory performance post-stressor relative to the control condition. Furthermore, it did not appear that changes in working memory performance were linked with changes in either positive or negative affect.

Importantly, the absence of a control condition that did not receive a brief training (i.e., passive control condition), the acute stressor, or the baseline OSPAN administration makes it impossible to determine whether changes in OSPAN performance were due to benefits produced by brief training (i.e., that would have been observed without the stressor), the interaction between training and the stressor (i.e., stress buffering), or an interaction between training and repeated OSPAN administrations (i.e., practice effects). Nonetheless, the experimental design did demonstrate that, at the very least, breath awareness does not yield improved working memory performance in the context of acute stress relative to an attentional control condition.

It is helpful to interpret our findings in light of the broader literature on short- and longer-term training in contemplative practices. A large body of experimental evidence suggests that longer-term training in mindfulness meditation (i.e., mindfulness-based interventions) indeed reduces stress and yield small to moderate improvements in working memory (Cásedas et al., 2020; Goldberg et al., in press). However, the evidence supporting short-term mindfulness training is much less clear. Schumer et al.'s (2018) meta-analysis, while detecting a modest overall effect of mindfulness inductions on negative affect (d = 0.21), was not robust to publication bias. Gill et al.'s (2020) meta-analysis also found a modest overall effect of mindfulness on cognitive function (g = 0.18), but this effect was very small and non-significant when restricted to measures of memory (g = 0.10, 95% CI [-0.10, 0.30]). Thus, the lack of evidence that breath awareness improved working memory performance within the context of acute stress (e.g., relative to the control) is largely consistent with the available literature.

The inclusion of three contemplative practices, including two far less studied approaches (loving-kindness, gratitude), extends the brief training literature and may point to ways in which contemplative practices may differ in their short-term effects. Our omnibus conclusion – that breath awareness training specifically was not associated with improved working memory performance – raises the possibility that this practice in particular may have unintended consequences, at least when coupled with stress in a predominantly meditation naïve sample (see also Hirshberg et al., 2018). One possibility is the focused attention required for breath awareness practice may, at least in the short term, deplete self-regulatory resources (Hagger et al., 2010) such as the attentional and memory control required for working memory capacity.[2] This effect may be magnified in the context of an acute stressor that itself requires self-regulation (i.e., resisting removing one's arm from the ice bath). In contrast to loving-kindness and gratitude practice, breath awareness training did not involve intentional cultivation of positive affective states. It may be that naïve participants were attempting to monitor their experience while breathing, but were doing so without warmth or acceptance (Lindsay & Creswell, 2017). Consistent with this possibility, data from the current trial reported in Hirshberg et al. (2018) found breath awareness produced declines in positive affect from baseline to immediately post-training relative to gratitude. It would be valuable to more closely assess participants' application of the meditation instructions in a future study to determine the degree to which they may have been monitoring in the absence of acceptance, as well as the degree to which the meditation

[2] A reviewer raised the intriguing possibility that reduced working memory performance may be adaptive within the context of an acute stressor in which initiation of behavior (i.e., action) may be preferred to internal processing (i.e., cognition). Thus, increased working memory seen for the loving-kindness, gratitude, and control condition may inhibit adaptive responding to an external threat. It would be worthwhile investigating the differential effects of brief training on measures designed to index other potentially adaptive responses to acute stress (e.g., inhibitory control, set shifting).

practice is perceived to be mentally exhausting, both initially and over time. Another possibility is that the focus on physical sensations during the breath awareness training sensitized these individuals to the physical stress effects of the CPT. An objective assessment of physiological stress would have been helpful for investigating this possibility.

The equivalence between loving-kindness, gratitude, and the control condition was unexpected and somewhat ambiguous in the absence of a fully passive control condition. While the attentional control was not intended to generate feelings of loving-kindness or gratitude, it is possible that participants may have experienced these states when thinking about the spatial layout of their favorite room. Again, future research more closely assessing the subjective experience *during* the brief training, not only the cognitive and affective consequences of this training, can help characterize mechanisms that may be operant. In addition, the loving-kindness, gratitude, and the control condition all involved focusing attention on externally related information (i.e., picturing one's home, thinking of individuals for whom one is grateful or to whom one is sending wishes of kindness) while the breath awareness practice focused on internal stimuli (i.e., physical sensation of breathing). It is conceivable that this internal focus may have inhibited OSPAN performance, which involves attention to external stimuli (i.e., numbers and letters). Again, a passive control condition would have allowed assessment of the degree to which the internal focus of breath awareness negatively impacted OSPAN performance.

Finally, also important to note was our finding of an overall increase seen in OSPAN performance across all groups except breath awareness. The impact of acute stress on working memory is well-established, albeit often demonstrated through between-group designs that lack a pre-post assessment of working memory (Schoof et al., 2009; Shields et al., 2016). The most parsimonious explanation for this increase is a practice effect. Another tenable possibility is that acute stress is less impactful for practiced versus non-practiced executive function tasks. Thus, the practice afforded during the pre-test OSPAN administration may itself have buffered against stress-induced declines in performance, at least for all but the breath awareness group.

Limitations and Future Directions

This study has several important limitations. The sample size was relatively modest and smaller than initially planned (Hirshberg et al., 2018), which limited statistical power. The trainings were quite brief, which may have limited their efficacy and/or produced unintended consequences (e.g., exhaustion of self-regulatory resources) that may not occur in repeated training sessions. We used a convenience sample of predominantly White, female undergraduates which limits generalizability (e.g., to racial/ethnic minorities). We did not measure training-related state variables beyond affect and specifically did not assess participants' experience during the trainings themselves (e.g., degree to which they were monitoring without acceptance). Similarly, we did not include a physiological measure of stress. Although negative affect increased from baseline to post-stressor and some individuals found the task sufficiently aversive that they removed their hands early, we cannot definitively claim that the task was physiologically stressful for all participants.

As noted, an additional important limitation was the lack of a passive control condition. All of the groups in our design received a brief training and the CPT. Therefore, we are unable to determine the degree to which changes in OSPAN performance were related to practice effects, the brief trainings themselves, the CPT, or some combination of these factors. Based on the extensive literature documenting decrements in working memory within the context of acute stress (including the CPT; Shields et al., 2016), it seems safe to assume that in the absence of brief trainings and practice effects, the CPT would have yielded decreased OSPAN performance relative to a no stressor control. We likewise can also not rule out the possibility that breath awareness buffered against the CPT, although we do know it did so less than the other trainings. Whether the brief trainings would have yielded improvements (or differential improvements) outside the context of the CPT is unclear, but worthy of future investigation.

These limitations notwithstanding, the current study is one of a small number investigating the behavioral consequences of different types of contemplative practice. Given the stress buffering hypothesis (Creswell & Lindsay, 2014), it would be valuable to conduct future studies in clinical samples. Based on the possibility that some types of training may be less efficacious or even harmful (Hirshberg, Goldberg, Rosenkranz, & Davidson, 2020), it will be important to attend to potential adverse effects in future work. While using a standardized stressor allowed greater experimental control, it would be worthwhile to test the impact of various brief trainings within ecologically valid contexts (e.g., before an exam). Based on the possibility of gathering large samples due to shorter intervention periods, future brief training studies can assess baseline characteristics that may moderate response to interventions to inform efforts to match individuals with maximally effective practice strategies. Brief trainings targeted based on individual differences at baseline could work towards realizing the potential of personalized behavioral medicine (i.e., "steering patients to the right drug at the right dose at the right time," Hamburg & Collins, 2010, p. 301).

In conclusion, the current study, while lacking clear evidence supporting any of the three brief contemplative practices tested, highlights the possibility that different practices yield different effects. Future work continuing to characterize precisely when and for whom these effects occur can aid in realizing the potential contribution of contemplative practices for supporting psychological health and functioning and reduce any potential negative impacts.

References

Cásedas, L., Pirruccio, V., Vadillo, M. A., & Lupiáñez, J. (2020). Does mindfulness meditation training enhance executive control? A systematic review and meta-analysis of randomized controlled trials in adults. *Mindfulness*, 1-14.

Creswell, J. D., & Lindsay, E. K. (2014). How does mindfulness training affect health? A mindfulness stress buffering account. *Current Directions in Psychological Science, 23*(6), 401-407.

Dahl, C.J., Lutz, A., & Davidson, R.J .(2015). Reconstructing and deconstructing the self: Cognitive mechanisms in meditation practice. *Trends in Cognitive Sciences, 19*(9), 515-523. doi:10.1016/j.tics.2015.07.001

Davis, D. E., Choe, E., Meyers, J., Wade, N., Varjas, K., Gifford, A., ... & Worthington Jr, E. L. (2016). Thankful for the little things: A meta-analysis of gratitude interventions. *Journal of Counseling Psychology, 63*(1), 20-31.

Fox, K.C.R., Dixon, M.L., Nijeboer, S., Girn, M., Floman, J.L., Lifshitz, M.,...Christoff, K. (2016). Functional neuroanatomy of meditation: A review and meta-analysis of 78 functional neuroimaging investigations. *Neuroscience and Biobehavioral Reviews, 65*, 208-228. doi: 10.1016/j.neubiorev.2016.03.021

Galante, J., Galante, I., Bekkers, M. J., & Gallacher, J. (2014). Effect of kindness-based meditation on health and well-being: a systematic review and meta-analysis. *Journal of Consulting and Clinical Psychology, 82*(6), 1101-1114. .doi: 10.1037/a0037249

Gill, L. N., Renault, R., Campbell, E., Rainville, P., & Khoury, B. (2020). Mindfulness induction and cognition: A systematic review and meta-analysis. *Consciousness and Cognition, 84*, 102991.

Goldberg, S. B., Riordan, K., Sun, S., & Davidson, R. J. (in press). The empirical status of mindfulness-based interventions: A systematic review of 44 meta-analyses of randomized controlled trials. *Perspectives on Psychological Science*.

Goldberg, S. B., Flook, L., Hirshberg, M. J., Findley, D., Kesebir, P., Schaefer, S. M., & Davidson, R. J. (2017). Getting a grip on the handgrip task: Handgrip duration correlates with neuroticism but not conscientiousness. *Frontiers in Psychology, 8*, 1367. doi: 10.3389/fpsyg.2017.01367

Hamburg, M. A., & Collins, F. S. (2010). The path to personalized medicine. *New England Journal of Medicine, 363*(4), 301-304.

Hirshberg, M. J., Goldberg, S. B., Rosenkranz, M., & Davidson, R. J. (in press). Prevalence of harm in mindfulness-based stress reduction. *Psychological Medicine*. doi: 10.1017/S0033291720002834

Hirshberg, M.J., Goldberg, S.B., Schaefer, S.M., Flook, L., Findley, D., & Davidson, R.J. (2018). Divergent effects of brief contemplative practices in response to an acute stressor: A randomized controlled trial of brief breath awareness, loving- kindness, gratitude or an attention control practice. *PLOS ONE 13*(12): e0207765. doi: 10.1371/journal.pone.0207765

Lindsay, E. K., & Creswell, J. D. (2017). Mechanisms of mindfulness training: Monitor and Acceptance Theory (MAT). *Clinical Psychology Review, 51*, 48-59.

Lovallo, W. (1975). The cold pressor test and autonomic function: A review and integration. *Psychophysiology, 12*(3), 268-282.

Mneimne, M., Dashineau, S., & Yoon, K. L. (2019). Mindfulness and negative affectivity in real time: A within-person process model. *Cognition and Emotion, 33*(8), 1687-1701.

Salzberg S. (2009). *Guided meditations for love and wisdom: 14 essential practices*. [CD]. Louisville, CO: Sounds True.

Schoofs, D., Wolf, O.T., & Smeets, T. (2009). Cold pressor stress impairs performance on working memory tasks requiring executive functions in healthy young men. *Behavioral Neuroscience, 123*(5), 1066-1075. doi: 10.1037/a0016980

Schumer, M. C., Lindsay, E. K., & Creswell, J. D. (2018). Brief mindfulness training for negative affectivity: A systematic review and meta-analysis. *Journal of Consulting and Clinical Psychology, 86*(7), 569-583.

Schwabe, L., Haddad, L., & Schachinger, H. (2010). HPA axis activation by a socially evaluated cold-pressor test. *Psychoneuroendocrinology, 33*, 890-895. doi:10.1016/j.psyneuen.2008.03.001

Sedlmeier, P., Eberth, J., Schwarz, M., Zimmermann, D., Haarig, F., Jaeger, S., & Kunze, S. (2012). The psychological effects of meditation: A meta-analysis. *Psychological Bulletin, 138*(6), 1139–1171. doi: 10.1037/a0028168

Shields, G. S., Sazma, M. A., & Yonelinas, A. P. (2016). The effects of acute stress on core executive functions: A meta-analysis and comparison with cortisol. *Neuroscience &*

Biobehavioral Reviews, 68, 651-668.

Unsworth, N., Heitz, R., Schrock, J., Engle, R. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*, (3), 498-505.

Watkins, P. C., Woodward, K., Stone, T., & Kolts, R. L. (2003). Gratitude and happiness: Development of a measure of gratitude, and relationships with subjective well-being. *Social Behavior and Personality, 31*(5), 431-451.

Watson, D., Clark, L., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54*(6), 1063-1070.

Acknowledgements

We thank Rachel Koszalinski for her help in managing the study and all of the undergraduate research assistants involved in data collection. We thank David Findley for his contributions to conceptualizing this study and overseeing the project management. Research reported in this publication was supported by the National Center for Complementary & Integrative Health of the National Institutes of Health under Award Number K23AT010879 (S. B. Goldberg) and P01AT004952 (R. J. Davidson).

Declaration of Interest

R. J. Davidson is the founder, president, and serves on the board of directors for the nonprofit organization Healthy Minds Innovations, Inc. The remaining authors declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

Table 1. Operation span (OSPAN) and affect ratings at baseline and post-stressor

	OSPAN				Negative Affect		Positive Affect	
Condition	Pre	Post	*d*	*p*	Pre	Post	Pre	Post
Control	60.13 (12.25)	64.06 (10.01)	0.32	.028*	1.37 (0.37)	1.59 (0.55)	2.65 (0.73)	2.56 (0.82)
Breath Awareness	60.51 (8.49)	57.97 (13.59)	-0.30	.638	1.35 (0.32)	1.68 (0.56)	2.84 (0.76)	2.38 (1.01)
Loving-kindness	58.95 (11.19)	63.24 (12.08)	0.38	.001**	1.26 (0.23)	1.63 (0.6)	2.80 (0.71)	2.48 (0.82)
Gratitude	58.7 (12.17)	62.24 (10.65)	0.29	.028*	1.29 (0.31)	1.92 (0.71)	2.58 (0.64)	2.58 (0.87)

Note: Pre = baseline (i.e., pre-training and pre-stressor) means and standard deviations; Post = post-stressor means and standard deviations. *d* = Pre-post Cohen's *d* computed as pre-post change divided by pre-test standard deviation. *p* = *p*-value from pre-post, within-group paired t-test. Estimates based on the full sample (i.e., not restricted to cold pressor test completers). Baseline sample sizes were 39, 37, 42, and 44, for control, breath awareness, loving-kindness, and gratitude, respectively (see Supplemental Materials Table 2 for sample sizes at each time point).

*$p < .050$, **$p < .010$, ***$p < .001$

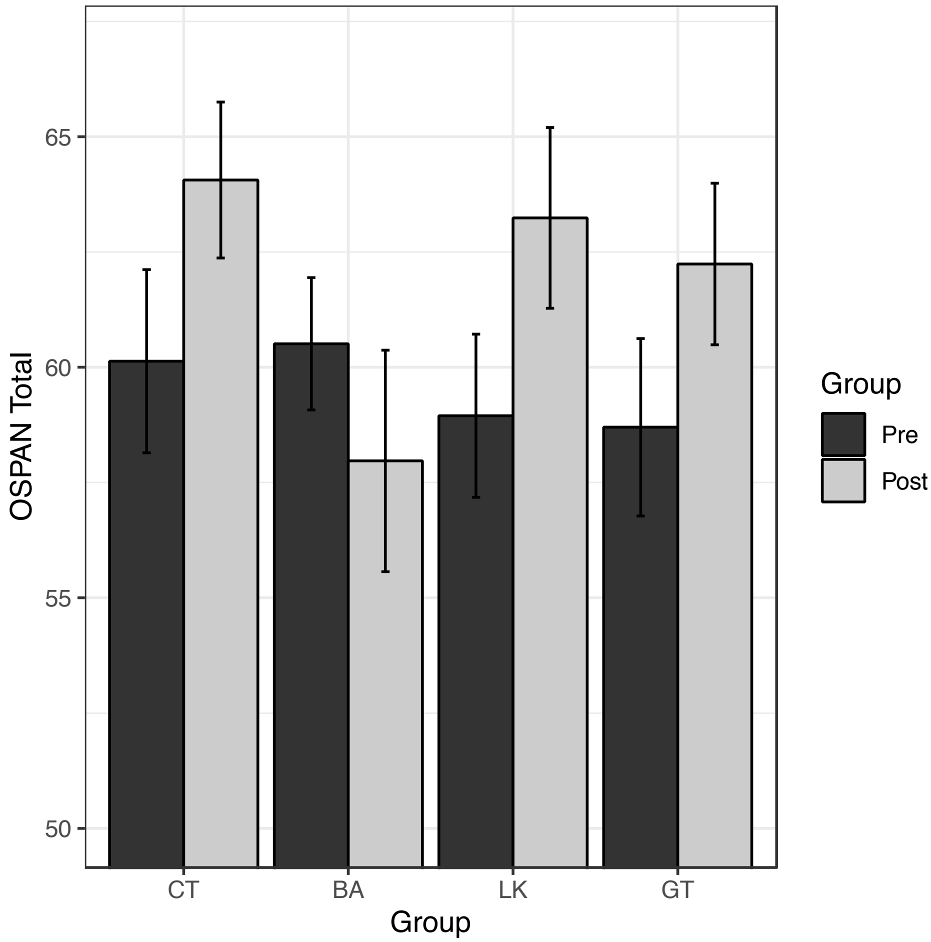


Figure 1. Operation Span (OSPAN) performance at baseline (pre-training and pre-stressor [cold pressor test]) and post-stressor. CT = attentional control; BA = breath awareness; LK = loving-kindness; GT = gratitude; error bars = one standard error. Control, loving-kindness, and gratitude conditions showed significant pre-post increases in OSPAN and increases relative to breath awareness (*p*s < .050). Breath awareness did not change significantly (*p* > .050).

Appendices

Supplemental Materials Table 1. Sample demographic characteristics

Variable	Full Sample	Control	Breath Awareness	Loving-kindness	Gratitude	*p*
Race/Ethnicity (%)						
Asian	5.56	5.13	8.11	7.14	2.27	
Black	4.32	5.13	2.70	4.76	4.55	
Latinx	4.32	2.56	2.70	2.38	9.09	
Multiracial	5.56	7.69	0.00	7.14	6.82	
Not reported	5.56	5.13	2.70	4.76	9.09	
White	74.69	74.36	83.78	73.81	68.18	.460
Gender (%)						
Male	36.42	35.9	37.84	28.57	43.18	
Female	63.58	64.1	62.16	71.43	56.82	.574
Meditation (%)						
No	83.33	87.18	83.78	80.95	81.82	
Yes	16.67	12.82	16.22	19.05	18.18	.884
Age (mean [SD])	19.31 (0.75)	19.20 (0.72)	19.39 (0.77)	19.36 (0.77)	19.30 (0.75)	.690

Note: Meditation = practiced meditation in the past month; *p* = *p*-values from one-way analysis of variance comparing groups at baseline.

Supplemental Materials Table 2. Missing data accounting

	Control (n = 39)	Breath Awareness (n = 37)	Loving-kindness (n = 42)	Gratitude (n = 44)
Missing pre-test OSPAN	1	2	2	4
Missing pre-test OSPAN reason	Accuracy <85% (n = 1)	Accuracy <85% (n = 2)	Accuracy <85% (n = 2)	Fell asleep during task (n = 1), Accuracy <85% (n = 3)
Did not complete CPT	8	2	2	6
Missing post-test OSPAN	4	5	4	7
Missing post-test OSPAN reason	Accuracy <85% (n = 4)	Adverse reaction to CPT (n = 3), Accuracy <85% (n = 2)	Accuracy <85% (n = 4)	Fell asleep at baseline (n = 1), Adverse reaction to CPT (n = 2), Accuracy <85% (n = 4)

Note: OSPAN = Operation Span task; CPT = cold pressor test; Accuracy = accuracy solving mathematical operations in OSPAN. Typical adverse reaction to CPT was becoming “dizzy,” with one participant fainting.

Supplemental Materials Table 3. Syntax for multiple imputation model

```
library(jomo)
library(mitools)
library(mice)

imp10<-jomo1(df[,c("Ospan1Total","Ospan2Total","CPT_complete",
                "PANAS.neg.1","PANAS.neg.3",
                "PANAS.pos.1","PANAS.pos.3",
                  "gender","age.years","white","med.recent",
                "Condition")],
            nimp=10)
outjomo<-subset(imp10,Imputation>0)
mi_list <- imputationList(split(outjomo, outjomo$Imputation))
mi_results <- with(mi_list, lm(Ospan2Total ~ Ospan1Total + Condition))
summary(pool(as.mira(mi_results)))

outjomo<-subset(imp10,Imputation>0 & !Condition=="CT")
mi_list <- imputationList(split(outjomo, outjomo$Imputation))
mi_results <- with(mi_list, lm(Ospan2Total ~ Ospan1Total + Condition))
summary(pool(as.mira(mi_results)))
```

Supplemental Materials Table 4. Linear model predicting post-stressor OSPAN in the full sample with control as reference group

Variable	*B*	SE	*t*	*p*
(Intercept)	23.72	4.11	5.77	< .001***
Baseline OSPAN	0.66	0.06	10.44	< .001***
Breath Awareness	-4.08	2.04	-2.01	.047*
Loving-kindness	0.92	1.95	0.47	.638
Gratitude	0.19	1.97	0.09	.925

Note: *B* = unstandardized coefficient; SE = standard error; *t* = *t*-value; *p* = *p*-value; OSPAN = Operation Span.
**p* < .050, ***p* < .010, ****p* < .001

Supplemental Materials Table 5. Linear model predicting post-stressor OSPAN in the full sample with breath awareness as reference group

Variable	*B*	SE	*t*	*p*
(Intercept)	19.68	4.95	3.97	< .001***
Baseline OSPAN	0.66	0.08	8.46	< .001***
Loving-kindness	5.00	2.14	2.34	.021*
Gratitude	4.27	2.15	1.98	.050*

Note: *B* = unstandardized coefficient; SE = standard error; *t* = *t*-value; *p* = *p*-value; OSPAN = Operation Span. Control group omitted from model.
*$p < .050$, **$p < .010$, ***$p < .001$

Supplemental Materials Table 6. Linear model predicting post-stressor OSPAN in cold pressor test completers with control as reference group

Variable	*B*	SE	*t*	*p*
(Intercept)	27.52	4.62	5.95	< .001***
Baseline OSPAN	0.61	0.07	8.62	< .001***
Breath Awareness	-5.16	2.2	-2.35	.020*
Loving-kindness	0.09	2.13	0.04	.967
Gratitude	-0.69	2.19	-0.32	.752

Note: *B* = unstandardized coefficient; SE = standard error; *t* = *t*-value; *p* = *p*-value; OSPAN = Operation Span.
*$p < .050$, **$p < .010$, ***$p < .001$

Supplemental Materials Table 7. Linear model predicting post-stressor OSPAN in cold pressor test completers with breath awareness as reference group

Variable	*B*	SE	*t*	*p*
(Intercept)	22.86	5.46	4.18	< .001***
Baseline OSPAN	0.61	0.09	6.99	< .001***
Loving-kindness	5.25	2.17	2.41	.018*
Gratitude	4.46	2.24	1.99	.049*

Note: *B* = unstandardized coefficient; SE = standard error; *t* = *t*-value; *p* = *p*-value; OSPAN = Operation Span. Control group omitted from model.
*$p < .050$, **$p < .010$, ***$p < .001$

Supplemental Materials Table 8. Linear model predicting post-stressor OSPAN in full sample with missing data replaced using multiple imputation with control as reference group

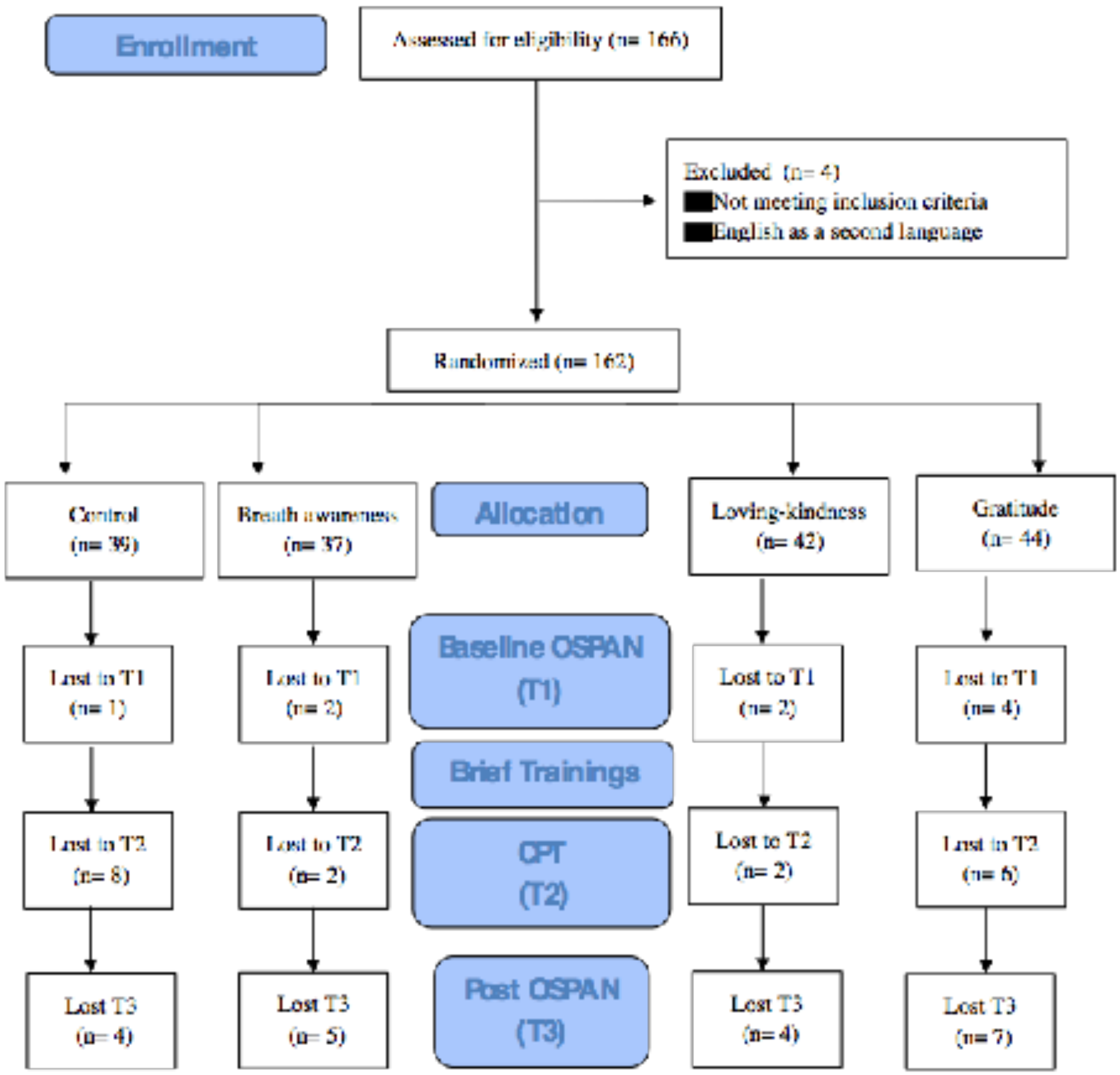
Variable	*B*	SE	*t*	*p*
(Intercept)	22.27	4.25	5.24	< .001***
Baseline OSPAN	0.69	0.06	10.61	< .001***
Breath Awareness	-4.78	2.07	-2.31	.023*
Loving-kindness	0.73	2	0.37	.715
Gratitude	-0.16	2.03	-0.08	.936

Note: *B* = unstandardized coefficient; SE = standard error; *t* = *t*-value; *p* = *p*-value; OSPAN = Operation Span.
**p* < .050, ***p* < .010, ****p* < .001

Supplemental Materials Table 9. Linear model predicting post-stressor OSPAN in full sample with missing data replaced using multiple imputation with control as reference group

Variable	*B*	SE	*t*	*p*
(Intercept)	16.72	4.77	3.50	.001**
Baseline OSPAN	0.70	0.08	9.11	< .001***
Loving-kindness	5.52	2.15	2.57	.012*
Gratitude	4.63	2.14	2.17	.033*

Note: *B* = unstandardized coefficient; SE = standard error; *t* = *t*-value; *p* = *p*-value; OSPAN = Operation Span. Control group omitted from model.
*$p < .050$, **$p < .010$, ***$p < .001$



Supplemental Materials Figure 1. CONSORT flow diagram. Note that primary models included all participants will available pre- and post-stressor Operation Span (OSPAN) data, regardless of cold pressor test (CPT) completion. Analyzed sample sizes for primary linear models were 35, 31, 37, and 36 for control, breath awareness, loving-kindness, and gratitude respectively. See Supplemental Materials Table 2 for additional details regarding the cause of missing data.