The Effects of Mindfulness-Based Stress Reduction on the Association Between Autonomic Interoceptive Signals and Emotion Regulation Selection

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ABSTRACT

Objective: The ability to select the most adaptive regulatory strategy as a function of the emotional context plays a pivotal role in psychological health. Recently, we showed that mindfulness-based interventions (MBIs) can improve the sensitivity of regulatory strategy selection to emotional intensity. However, the mechanisms underlying this improvement are unclear. In this study, we tested the hypothesis that MBIs support adaptive regulatory selection by increasing sensitivity to interoceptive signals associated with the emotional stimuli.

Methods: Participants (n = 84, mean [standard deviation {SD}] age = 30.9 [8.3] years; 54% women) were randomized to either a mindfulness-based stress reduction (MBSR) program or a wait-list control condition. Before and after the MBSR program, physiological measures for autonomic nervous system activity were obtained, and participants performed a task examining emotion regulation selections (reappraisal versus distraction) when confronted with low or high negative intensity images. They also completed a battery of mindfulness, interoception, and well-being self-report measures. A cross-classified model was used for the main analyses.

Results: The participants assigned to the MBSR were overall more likely to choose reappraisal than distraction (b = 0.26, posterior SD = 0.13, 95confidence interval = 0.02–0.52) after the program. Interoceptive signals in response to negative images were associated with subsequent regulatory selections (b = 0.02, posterior SD = 0.01, 95% confidence interval = 0.01–0.03) in the MBSR group. Specifically, lower cardiac reactivity was associated with the choice to reappraise, whereas higher cardiac reactivity was related to the choice to distract. Greater differences in cardiac reactivity between states that prompt reappraisal and states that prompt distraction were associated with higher well-being (Satisfaction With Life Scale, Pearson r (29) = 0.527, p = .003).

Conclusions: Mindfulness seems to increase the sensitivity of regulatory selections to interoceptive signals, and this is associated with subjective well-being. This may be a central pathway through which MBIs exert their positive effects on mental health and resilience.

Key words: mindfulness, regulatory flexibility, regulatory choices, regulatory decisions, regulatory selections, emotion regulation choice, emotion regulation, interoception, interoceptive signals, cardiac, cardiovascular, heart rate, electrocardiography, electrodermal activity, autonomic signals.

INTRODUCTION

Emotion regulation processes are key contributors to mental health (1,2). Recent developments in the field are indicative of a shift from a simplistic "good/bad" categorization of certain emotion regulation strategies (henceforth "regulatory strategies") as inherently adaptive or maladaptive to a more complex view (3,4) where the characteristics of different regulatory strategies result in a differential cost-benefit trade-off in terms of affective modulation level, cognitive resource expenditure, and long-term motivational costs. This suggests that the adaptive value of regulatory strategies depends on the specific emotional context and the situational demands (3). For example, during hurtful and intense emotional situations, it is more adaptive to withdraw and disengage to enable stronger short-term modulation of affect and minimal cognitive resource expenditure, which may permit reengagement later on (e.g., (5,6)). In contrast, in less intense and challenging situations, engaging with a difficult situation is advantageous. The negative influences of reencountered emotions that have been processed and altered can gradually subside and lead to long-term benefits (5,7). Selecting a regulatory strategy (henceforth "regulatory selection") according to the specific emotional context (e.g., emotional intensity) is considered more adaptive (henceforth "adaptive regulatory selection") and has been linked to better mental health and well-being (2,4,8–18).

An individuals' ability to identify the demands and opportunities arising in different emotion-triggering situations and then to select and implement the most adaptive regulatory strategy requires skill. It requires deliberate executive control that can override automatic emotional responses, high sensitivity to emotional

ECG = electrocardiography, **EDA** = electrodermal activity, **EMG** = electromyography, **ERC** = emotion regulation choice, **HR** = heart rate, **MBI** = mindfulness-based interventions, **MBSR** = mindfulness-based stress reduction, **WLC** = wait-list control

SDC Supplemental Digital Content

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context, high responsiveness to emotional feedback (e.g., internal information about one's own emotions), and the availability of a diverse repertoire of regulatory strategies to select from (10,17,19). Because of individuals differ in these abilities, it is important to identify interventions that can foster adaptive regulatory selection skills. Recently, we suggested that mindfulness-based interventions (MBIs) could serve this purpose (20).

MBIs are secular adaptations of contemplative Buddhist practices developed to reduce suffering and increase well-being (21). They typically use a range of practices intended to cultivate an attentional stance characterized by curiosity, openness, and acceptance, and are oriented toward present-moment bodily and mental experiences (22). Growing evidence suggests that MBIs have a wide range of positive psychological and health-related outcomes (e.g., (23–30)).

Such mindfulness practices may tap the capacities that are likely to underlie individual differences in the ability to use adaptive regulatory selection strategies (20). For example, MBIs are believed to increase deliberate executive control, enhance sensitivity to body-related emotional information, and cultivate the ability to attend to broader aspects of difficult situations, which may thus facilitate their appraisal in novel ways (10,17,21,26,31–42). The contemplative practices used in MBIs enable the enhanced implementation of different regulatory strategies (such as skillful engagement with an emotional experience or distracting from it by turning one's attention to the breath) (20,37,43,44). This is assumed to improve an individual's ability to evaluate the emotional context, detect the need to implement (or adjust) regulation strategies, and enable the selection and switching between different regulatory strategies rather than automatically defaulting to specific strategies (e.g., (37,39,45–47)). In addition, MBIs may stimulate the capacity to positively reappraise adverse events. For example, the mindfulness-to-meaning model introduced by Garland and colleagues (33) posits that by modifying how one attends to the cognitive, affective, and interoceptive sequelae of emotion provocation, MBIs may introduce greater flexibility in the ability to generate cognitive appraisals, even during stressful events (48). Until recently, however, there has been no direct empirical evidence that MBIs indeed enhance regulatory selection abilities.

To address this call for more research, we recently used a well-validated behavioral paradigm developed by Sheppes and colleagues (15,16) to measure how MBIs affect regulatory selection at varying emotional intensities. We investigated whether selection patterns differed between wait-list controls (WLCs) and participants who completed a mindfulness-based stress reduction (MBSR) workshop (49), an 8-week program considered the criterion standard for MBIs (50). In this behavioral paradigm, the emotional context is operationalized as different intensities of negative images (low versus high intensities, based on normative ratings), and the participants are asked to select between two strategies: cognitive reappraisal or distraction, to regulate their emotions. The benefits of early attentional disengagement (distraction) are known to include stronger affective modulation and lesser expenditure of cognitive resources. By contrast, attentional engagement and appraisal of emotional information (cognitive reappraisal) are considered to have the longer-term benefits of being able to reconfigure negative situations and their influence when reencountering them (3). Thus, reappraisal is considered more adaptive and more supportive of well-being in the case of low negative emotional intensities, whereas distraction is preferable when emotional intensities are high (15,16). Our main finding was that, relative to controls, participants who completed the MBSR training program were more likely to reappraise low-intensity images (20).

These findings lend weight to our claim that MBIs can affect regulatory selection patterns. However, whether this is indeed related to well-being and the mechanisms that underlie this relationship remains unclear. One of the central components of MBIs is enhancing attention to bodily processes (51,52), which are known to be strongly linked to emotion and emotion regulation processes. Thus, we hypothesized that MBIs affect regulatory selection by enhancing sensitivity to the internal physiological responses (also known as interoceptive signals) associated with emotional stimuli.

Interoception refers to the (conscious and subconscious) sense of the physiological condition of the body and includes physical sensations related to internal organ functions such as heartbeat and respiration, as well as autonomic nervous system activity related to emotions (53–56). It is considered to underlie individual differences in a wide range of emotional, cognitive, perceptual, and decision-making processes, and thus has major implications for psychopathology and health (57–62). The afferent sensory and visceral responses ("interoceptive signals") that give rise to the conscious and subconscious perception of body states interact continuously with cognitive appraisals to inform response selection (31). In the present study, we focus on the interoceptive signals associated with initial emotional responses and their association with subsequent regulatory selections (63).

Importantly, MBIs, which involve the cultivation of sustained attention toward bodily sensations, are considered one of the major ways to enhance interoceptive abilities (21,51,52,64–68). Even a short MBI such as an MBSR course is enough to elicit interoception-specific functional plasticity in related brain areas such as the insula (48,58,69,70).

Accumulating theoretical and empirical work suggests that interoceptive signals play an important role in emotion regulation processes (3,12,44,71). Individuals with greater trait-interoceptive abilities are better at emotion regulation (72–76), for both engaging (reappraisal; (74)) and disengaging (suppression of response; (76)) regulatory strategies. However, only one study to date has directly investigated interoceptive signals during an emotional task and how they affect the way individuals choose emotion regulation strategies. Birk and Bonanno (19) assessed participants' interoceptive signals using physiological reactivity measures while they viewed emotional evocative pictures. They were then instructed to choose whether they wanted to switch to distraction after initially implementing cognitive reappraisal. They found that individuals whose high physiological reactivity to a highly emotional stimulus predicted their decision to switch from reappraisal to distraction, that is, where interoceptive signals guide adaptive emotion regulation choices (ERCs), also reported greater life satisfaction. However, there is scant research on whether it is possible to *enhance* the influence of interoceptive signals on regulatory selection patterns.

The main aim of the current study was to investigate whether MBIs can affect the influence of interoceptive signals on regulatory selection patterns. To do so, we adapted the main setup from our previous study (20) where regulatory selection patterns were measured using the well-established ERC task (15,16,77). In the ERC, emotional context is manipulated by presenting aversive emotional images of low and high emotional intensities, and participants

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are asked to choose to implement distraction or reappraisal. All participants were randomized into the experimental MBSR training workshop group or the WLC group and were assessed twice at baseline and again after the MBSR group completed the workshop.

Because we were specifically interested in interoceptive signals associated with ongoing emotion regulation, we measured the physiological responses to the emotional images that preceded regulatory selection using reactivity measures of the autonomic nervous system and assessed their impact on participants' behavioral regulatory selections. This setup in which physiological responses preceded behavioral responses enabled assessing the predictive impact of interoceptive signals on behavioral regulatory decision. Based on prior evidence that MBIs may increase sensitivity to interoceptive signals (21,51,52,64–66), and that interoceptive processes affect regulatory processes during stressful events (48), we hypothesized that (1A) after the MBSR workshop, autonomic reactivity to emotional stimuli would have a greater influence on regulatory selection patterns; that is, greater autonomic reactivity was predicted to be associated with more selection of distraction over reappraisal.

Based on prior work (19), such association between autonomic reactivity and regulatory selections (i.e., greater autonomic reactivity leads to more selection of distraction) is considered adaptive and related to higher levels of well-being. To validate that this is indeed the case, we administered subjective reports of well-being. We predicted that (1B) a greater difference in autonomic reactivity when selecting distraction than when selecting reappraisal (indicating a greater differentiation between situations) would be associated with greater subjective well-being.

In addition to the main hypothesis, we also predicted that (2) MBSR training would shift regulatory selection patterns relative to participants' baseline selection patterns. This prediction is based on recent theoretical accounts and several empirical findings, suggesting that MBIs may facilitate flexibility into the creation of autobiographical meaning, fostering the ability to create novel and more positive reappraisals of negative situations (21,26,31,33,35,37,39,78). Thus, we predicted we would observe *more reappraisal selection* after MBSR.

METHODS

Participants

Approximately 350 individuals responded to advertisements on community Web sites and the university's mailing lists offering a discount of $250 on an MBSR workshop in return for participating in a study (a self-selected group). Candidates who were willing to commit to the study's requirements and workshop schedule ($n = 132$) were screened by a research assistant and then by the MBSR instructor using the standard MBSR screening protocol[1]. Thirty-eight candidates were excluded on the basis of previous mind-body practice. Thirty were excluded for substantial physical and mental health problems (addiction, suicidality, psychosis, posttraumatic stress disorder, acute depression, severe social anxiety, recent difficult life events, hypo/hyper blood pressure syndrome, chronic pain), or use of medication that affects immune, cardiovascular, endocrine, or psychiatric functioning. Blood pressure abnormalities and chronic pain were added as exclusion criteria to the standard MBSR screening protocol to avoid introducing confounds to the autonomic and interoception measurements.

The remaining participants ($n = 84$) signed informed consent forms and were randomly assigned to one of four MBSR workshops that were given between January 2018 and July 2018. Forty-three participants (mean [standard deviation], or M [SD] age = 31.11 [8.26] years, 21 males) were assigned to two workshops and served as the experimental group. Forty-one participants (M [SD] age = 29.82 [9.63], 18 males) were assigned to two workshops that served as a WLC group and began their workshop only after the data collection stages were complete. This study was approved by the Ethics Committee of the Interdisciplinary Center, Herzliya, Israel (Table 1).

Procedure

All participants (MBSR and WLC) were requested to come to the laboratory before (T1) and after (T2) the MBSR workshops attended by the experimental group. Before each visit, they completed an online battery of self-report questionnaires, including demographics. During each laboratory session, the participants were hooked up to physiological sensors and completed two behavioral tasks: the interoceptive accuracy heartbeat counting task (79,80) followed by the ERC task (6,16) (see hereinafter). For the MBSR group, reports of home practice time were acquired on a weekly basis. The study reported here was part of a larger study. In addition to measuring interoceptive signals during the ERC task, we measured trait interoception using the heartbeat counting task and the Multidimensional Assessment of Interoceptive Awareness scale (81). Because these measures do not address the main focus of this article, we do not report them in the main text (for details regarding these measures, see the supplementary section, http://links.lww.com/PSYMED/A774).

MBSR Workshops

Mindfulness was cultivated using the MBSR program developed by Kabat-Zinn (49). This structured, group-format, 8-week program consists of weekly 2.5-hour sessions led by skilled certified MBSR instructors with more than 20 years of mindfulness practice. It also includes an 8-hour full-day silent retreat during the sixth week of the program and assignments for home practice accompanied by guided meditation recordings. The workshop consists of a range of contemplative practices such as body scan, focused attention meditation, open awareness meditation, movement exercises, and mindfulness practice in daily life. These practices are believed to foster

TABLE 1. Participant's Demographic Information

Demographics	WLC (n = 41)	MBSR (n = 43)	Total (n = 84)
Age, y	29.82 (9.63)	31.11 (8.26)	30.91 (8.29)
Sex (female)	23 (56%)	22 (51%)	45 (54%)
Education level			
High school	20 (49%)	19 (45%)	39 (47%)
Higher education	21 (51%)	24 (55%)	45 (53%)
Religiosity			
Secular	29 (70%)	32 (74%)	61 (73%)
Traditional	11 (28%)	11 (26%)	22 (26%)
Orthodox	1 (2%)	0 (0%)	1 (1%)
Income			
Below average	13 (32%)	12 (28%)	25 (30%)
Average	11 (27%)	15 (35%)	26 (31%)
Above average	17 (41%)	16 (37%)	33 (39%)

Data are presented as n (%) or mean (standard deviation).

WLC = wait-list control; MBSR = mindfulness-based stress reduction.

[1]Mindfulness-Based Stress Reduction (MBSR): Standards of Practice (2014). Edited and Revised by: Saki F. Santorelli, The Center for Mindfulness in Medicine, Health Care, and Society, University of Massachusetts Medical School.

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individuals' abilities to *engag*e and *disengage* with various aspects of experience including bodily sensations, emotions, thoughts, and external stimuli (see Ref. (20) and Supplementary Materials, http://links.lww.com/PSYMED/A774 for details).

Participants in the MBSR groups attended most MBSR classes (M [SD] = 86.1% [9.22%]) and devoted time during the week for home practice (average minutes per day: M [SD] = 28.11 [24.91]; average days a week: M [SD] = 3.6 [1.6], based on self-reports).

Measures

Questionnaires

The changes in mindfulness after MBSR were assessed using the Five Facet Mindfulness Questionnaire (82), which comprises five related facets: observing ($\alpha = .71$), describing ($\alpha = .69$), acting with awareness ($\alpha = .72$), nonjudging ($\alpha = .70$), and nonreactivity ($\alpha = .84$). Because changes in subjective mindfulness were mainly assessed as a manipulation check, a composite index was calculated for further analysis. Well-being was assessed on several questionnaires, including the Satisfaction With Life Scale (SWLS; $\alpha = .87$) (83), the Beck Anxiety Inventory ($\alpha = .93$) (84), and the Connor-Davidson Resilience Scale ($\alpha = .91$) (85).

Emotion Regulation Selection Measures

To test the main hypotheses, participants' regulatory selections were measured using the well-established ERC paradigm developed by Sheppes et al. (15). In this task, participants are presented with negative images and requested to select the regulatory strategy they want to implement on each trial. The internal reliability of this task was reported to be high (Kuder-Richardson-20 = 0.8, (13)), and the test-retest reliability for a 1-week duration was moderate ($r = 0.44$, $p < .001$; see Ref. (3)). Images were taken from the International Affective Picture System (EmoPicS) and the Nencki Affective Picture Systems.

The behavioral task was preceded by a training phase in which participants viewed negative images and were instructed to practice the implementation of distraction (thinking about something that was emotionally neutral) or cognitive reappraisal (thinking about an image in a different way, to reduce its negative impact). Two training trials were presented for each strategy, in a counterbalanced order between participants. This was followed by an eight-trial strategy-selection training phase in which participants were asked to select either distraction or reappraisal and describe how they implemented their selected strategy aloud. They were corrected by the experimenter when needed.

The regulatory selection task comprised 144 experimental trials (72 for high-intensity images and 72 for low-intensity images), divided into six blocks of 24 trials each with an interblock interval of 1 minute between blocks. Figure 1 depicts the structure of each trial. On each of the 144 trials, participants viewed a picture for 4000 milliseconds ("initial exposure phase") and then were asked to select either the reappraisal or the distraction strategy by pressing one of two buttons ("regulation stage"). Assignment of the reappraisal and distraction strategies to the response buttons was counterbalanced across participants. This was followed by a preparatory stage in which a blank screen appeared for 3500 milliseconds, followed by the implementation stage in which the picture reappeared for 5000 milliseconds and participants implemented their strategy. Participants were videotaped to ensure that they viewed each picture the whole time. Intensity ratings were obtained to encourage participants' engagement. The main difference in ERC task administration between the present study and our previous study (20) was that initial image presentation was longer (4000 versus 500 milliseconds). This adjustment was made to allow for the autonomic responses enough time to build up.

The sets of images that were used for the T1 and T2 tests were matched for combinations of normative ratings of arousal and valence (the full details on the T1 and T2 image set properties can be found in the supplementary section and in Refs. (6,15,16)). By measuring the actual autonomic reactivity of the individual participants to each image (see hereinafter), we could also assess the way the image was registered in the participant's internal milieu.

Physiological Data Collection and Preprocessing

Continuous physiological activity was recorded using Bionomadix (BIOPAC Systems Inc., Santa Barbara, California) MP150 data acquisition system and Biopac AcqKnowledge 4.4 software at 1000-Hz sampling rate. We collected data from three physiological channels, including facial electromyography from the *corrugator supercilii* (electromyography [EMG]), electrocardiography (ECG), and electrodermal activity (EDA). Unfortunately, because of equipment failure, EMG data acquisition during the post-intervention assessments was compromised so that EMG data could not be presented in this article.

The ECG signal was recorded with a modified lead II configuration using Ag/AgCl electrodes. The heart period series (interbeat interval) was assessed using the Mindware HRV 2.16 Biosignal processing module (Mindware, Westerville, Ohio). This procedure included the following: a) identifying the R-R intervals, b) detecting physiologically improbable R-R intervals based on the overall R–R distribution using a validated algorithm (71), and c) manually identifying the missing R waves. Finally, the interbeat interval series was transformed into a continuous heart rate (HR) time series using custom software.

EDA was recorded using two disposable Ag/AgCl electrodes with a 1-cm diameter contact area attached to the middle phalanges of the index and middle fingers. The EDA data were visually inspected to exclude gross motion artifacts and low-quality recordings resulting in a lack of responses. The remaining EDA data were down-sampled to 10 HZ for the reactivity analysis.

To quantify autonomic reactivity on each trial, the mean HR and EDA responses were calculated by averaging across the 4-second period of the initial presentation of the picture and the 2.5-second fixation period window preceding stimulus presentation. The mean baseline activity was then subtracted from the presentation time activity for each trial within each physiological channel. Finally, for further analysis, average autonomic reactivity was calculated separately for trials leading to distraction selections versus trials leading to reappraisal selections.

To assess whether the emotional task elicited autonomic reactivity as expected (as a manipulation check), we examined whether we could detect significant changes in HR and EDA responses from the fixation period to negative pictures presentation, as found in previous research (86). We found a significant decrease in HR from fixation both at T1 (M [SD] = −3.3 [2.0], $t(71) = -13.86$, $p < .001$) and T2 (M [SD] = −3.2 [2.4], $t(63) = -10.751$, $p < .001$), and a significant increase in EDA at T1 (M [SD] = 0.085 [0.12], $t(75) = 6.1$, $p < .001$) and T2 (M [SD] = 0.02 [0.06], $t(66) = 2.5$, $p = .013$).

Statistical Analysis

Cross-Classified Multilevel Modeling Analysis

The main analysis conducted in this article to analyze the ERC paradigm is the cross-classified multilevel modeling analysis (see Ref. (20) and the online supplementary section for a detailed explanation of this approach, including random and fixed effects, and the model equations). This analysis has several central advantages. First, it enables a *trial-by-trial* analysis that takes into account the physiological response and the behavioral selection response for each trial. Because the physiological response always preceded the behavioral selection response, and these two measures are independent, this enabled us to test whether autonomic reactivity levels could predict behavioral regulatory selections.

In addition, this analysis enables to take advantage of the special structure of the ERC paradigm to account for a larger portion of the variance. In the ERC paradigm, each individual was repeatedly measured on responses to emotional pictures of varying intensity, and each picture was repeatedly

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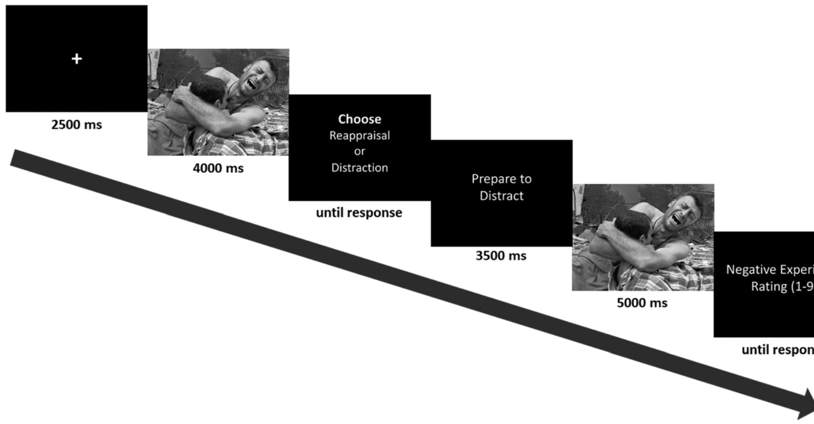

FIGURE 1. Trial structure of the emotion regulation choice task. An example of a high emotional intensity distraction preference trial (based on Shafir et al. (15)). Each trial consisted of a fixation phase (2500 milliseconds), followed by the initial exposure phase in which the target image appeared (4000 milliseconds), followed by a prompt to select between reappraisal and distraction (selection phase), followed by a prompt to prepare to use the selected strategy (3500 milliseconds), followed by a longer presentation of the target image in which the participants implemented the selected strategy (5000 milliseconds, implementation phase), followed by an appearance of intensity rating scale.

measured across participants. These multiple information sources provided variation coverage for each measurement controlled by individual and picture nesting, thus making it possible to account for a larger portion of the variation.

Analyses related to picture intensities were performed at the picture level (level 2), the group effect was analyzed at the individual level (level 2), and the analyses for the behavioral response (regulatory decision) and the autonomic reactivity were conducted at the measurement level (level 1). The reported coefficients were indexed accordingly (i.e., "b_{pictures}," "$b_{\text{participants}}$," "$b_{\text{measurement}}$"). This enabled a trial-by-trial multilevel model analysis of the behavioral response (decision to reappraise or distract) to each negative image and the ECG and EDA reactivity response to each negative image.

Other statistical analyses included the following: all measures were also subjected to aggregated analysis using analyses of variance (ANOVA and multivariate ANOVA) methods. Interactions in these models were subsequently investigated using *t* tests. Correlations between measures were examined using Pearson correlations and corrected using the Bonferroni method in case of multiple comparisons.

Missing data occurred as follows: four participants from each group were unable to complete the study (because of pregnancy and medical issues; for details, see the supplementary section, http://links.lww.com/PSYMED/A774). In addition, because of technical issues, acquisition failures, gross motion artifacts, or low-quality data, the following data attrition occurred: self-reports (at T2), three MBSR and three WLC participants; ERC task (at T1), one MBSR participant; ERC task (at T2), three MBSR and two WLC participants; ECG data (at T1), five MBSR and six WLC participants; ECG data (at T2), four MBSR and three WLC participants; EDA data at T1, five MBSR participant and three WLC participants; and EDA data at T2, one WLC participant.

RESULTS

Preliminary Analysis

As a manipulation check, we first examined whether subjective mindfulness increased after the MBSR workshop. As expected, a repeated-measures multivariate ANOVA revealed a significant time by group interaction effect ($F(5,64)$ =2.99, p = .017, $\eta^2 = 0.17$) on subjective mindfulness (see Table S1, Supplemental Digital Content, http://links.lww.com/PSYMED/A774, for detailed outcome of the statistical analyses for the different Five Facet Mindfulness Questionnaire subscales).

Next, we tested the effects of the MBSR workshop on measures of well-being. A repeated-measures ANOVA revealed a significant time by group interaction effect for the SWLS (83) items ($F(1,68) = 7.13$, $p = .009$, $\eta^2 = 0.088$) and for the Beck Anxiety Inventory (84) items ($F(1,64) = 4.03$, $p = .049$, $\eta^2 = 0.060$) but no effects for the Connor-Davidson Resilience Scale (10-item; (85)). *t* Tests indicated a significant increase in life satisfaction ($p = .002$) and a decrease in anxiety levels ($p = .029$ (for the MBSR participants alone. Independent *t* tests revealed higher levels of satisfaction with life ($p = .001$) and lower levels of anxiety ($p = .019$) for the MBSR participants compared with the WLC at T2. Supplementary Table S1, http://links.lww.com/PSYMED/A774, provides the detailed outcomes of the statistical analyses for these measures.

Association of Autonomic Reactivity During Emotional Stimuli With Regulatory Selections

The main hypothesis (Hypothesis 1A) was that greater autonomic reactivity to emotional stimuli would be associated with increased selection of distraction over reappraisal. To test for this association, we examined the relationship between autonomic reactivity levels during the initial exposure stage and the regulatory selections during the regulation stage (Table 2).

For this, we used the cross-classified model analysis, which was performed separately for T1 and for T2. At T1, responses to varying HR reactivity ($b_{\text{measurement}} = 0.0.027$, estimated (posterior) SD = 0.031, 95% confidence interval [CI] = −0.034 to 0.090) or varying EDA reactivity ($b_{\text{measurement}} = 0.002$, posterior SD = 0.003, 95% CI = −0.004 to 0.007) did not show a higher probability for one regulatory strategy over the other. There was also no effect of group (HR by group effect on selection: $b_{\text{measurement}} = 0.002$, posterior SD = 0.003, 95% CI = −0.003 to 0.008; EDA by group effect on selection: $b_{\text{measurement}} = 0.014$, posterior SD = 0.031, 95% CI = −0.044 to 0.075).

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TABLE 2. Autonomic Reactivity Levels During the Fixation Phase and the Initial Picture Exposure Phase

	EDA, μS							
	Reappraisal				Distraction			
	T1		T2		T1		T2	
	Fixation	Mean Change	Fixation	Mean Change	Fixation	Mean Change	Fixation	Mean Change
WLC	0.23 (0.09)	0.08 (0.14)	0.24 (0.16)	0.04 (0.10)	0.24 (0.16)	0.10 (0.18)	0.25 (0.12)	0.04 (0.10)
MBSR	0.26 (0.11)	0.09 (0.12)	0.23 (0.1)	0.05 (0.08)	0.21 (0.13)	0.09 (0.14)	0.24 (0.17)	0.06 (0.11)

	HR, BPM							
	Reappraisal				Distraction			
	T1		T2		T1		T2	
	Fixation	Mean Change	Fixation	Mean Change	Fixation	Mean Change	Fixation	Mean Change
WLC	72.41 (8.22)	−3.04 (2.02)	75.02 (9.41)	−2.74 (2.60)	72.70 (8.33)	−3.18 (2.06)	73.06 (8.56)	−2.78 (2.63)
MBSR	74.13 (8.87)	−3.19 (2.16)	76.25 (9.63)	−2.41 (1.56)	71.94 (9.10)	−3.46 (2.12)	75.11 (9.82)	−3.55 (2.35)

For both HR and EDA, the table presents: a) the mean (standard deviation) values during fixation phase and b) the mean (standard deviation) change from fixation during the initial picture exposure phase and before selection and implementation of the regulatory strategy. Values are presented separately for trials in which reappraisal was subsequently selected and for trials in which distraction was subsequently selected, at T1 and T2, and for WLC and MBSR groups.

EDA = electrodermal activity; WLC = wait-list control; MBSR = mindfulness-based stress reduction; HR = heart rate; BPM = beats per minute.

At T2, there was again no main effect of HR on regulatory selection ($b_{measurement}$ = 0.004, posterior SD = 0.003, 95% CI = −0.002 to 0.01). However, there was a significant HR by group effect on regulatory selection ($b_{measurement}$ = 0.01, posterior SD = 0.003, 95% CI = 0.005 to 0.02). Analysis of each group separately revealed a significant effect for HR reactivity on regulatory selection ($b_{measurement}$ = 0.02, posterior SD = 0.01, 95% CI = 0.01 to 0.03) for the MBSR group alone, indicating that they tended to select distraction more for high HR reactivity. For the WLC, there was no significant effect of HR reactivity on regulatory selection ($b_{measurement}$ = −0.01, posterior SD = 0.004, 95% CI = −0.02 to 0.00). Again, this is a qualitative description because there was no inferential basis for a direct comparison. This interaction is displayed in Figure 2.

There was no HR by intensity effect on regulatory selection when analyzed for both groups ($b_{measurement}$ = 0.005, posterior SD = 1.58, 95% CI = −3.13 to 3.30) or for each group separately: MBSR ($b_{measurement}$ = 0.067, posterior SD = 1.58, 95% CI = −3.08 to 3.13) and WLC ($b_{measurement}$ = −0.075, posterior SD = 1.57, 95% CI = −3.08 to 3.18). In other words, the effect of HR reactivity on regulatory selection found in the MBSR group did not differ for the two intensities. We additionally conducted an ANOVA. There was no significant time by group by intensity interaction (F(1,58) = 0.275, p = .6). When examined for each group and for each time separately, no significant effects of intensity were found (all p values > .25).

For EDA, there was no main effect ($b_{measurement}$ = −0.01, posterior SD = 0.04, 95% CI = −0.07 to 0.08) and no group effect ($b_{measurement}$ = 0.01, posterior SD = 0.04, 95% CI = −0.06 to 0.10).

Overall, these results indicated that HR reactivity predicted regulatory selection only for the MBSR group and only at T2. Another way of viewing these results is that after MBSR there was a greater dissociation between autonomic states and how they impact behavioral selections. Negative situations that evoked less HR reactivity led to implementation of different regulatory approaches from negative situations that evoked greater HR reactivity. Importantly, no effect of time or intensity was found for HR reactivity, indicating that picture sets were balanced between T1 and T2, between groups, and across low- and high-intensity images (based on normative ratings), and the observed difference could not be associated with different emotional evocativeness of the picture sets.

Association Between Well-Being Levels and Differences in Autonomic Reactivity When Selecting Distraction Versus Reappraisal

Next, we investigated whether, after the MBSR workshop, a greater difference in autonomic reactivity when selecting distraction from when selecting reappraisal would be associated with higher levels of well-being (Hypothesis 1B). For this purpose, for each participant, we calculated the average autonomic differentiation score DeltaHR = $HR_{reappraisal} - HR_{distraction}$, where $HR_{reappraisal}$ is the average HR reactivity at the initial exposure phase for all trials in which reappraisal was chosen and $HR_{distraction}$ is the average HR reactivity for all trials in which distraction was chosen. This measure was then correlated with the indices of well-being using Pearson correlations. Overall, we found that at T2, DeltaHR for MBSR participants was significantly and positively correlated with the SWLS scale (Pearson r(29) = 0.527, p = .003). No other correlations emerged. Table S2, http://links.lww.com/PSYMED/A774, in the supplementary section presents the results for all correlations.

Hypothesis 2: The Effect of MBSR on Behavioral Regulatory Choice Patterns

Next, we analyzed whether selection patterns changed after MBSR. A repeated-measures ANOVA was used, with rate of selection of reappraisal as the dependent variable, time and intensity as a

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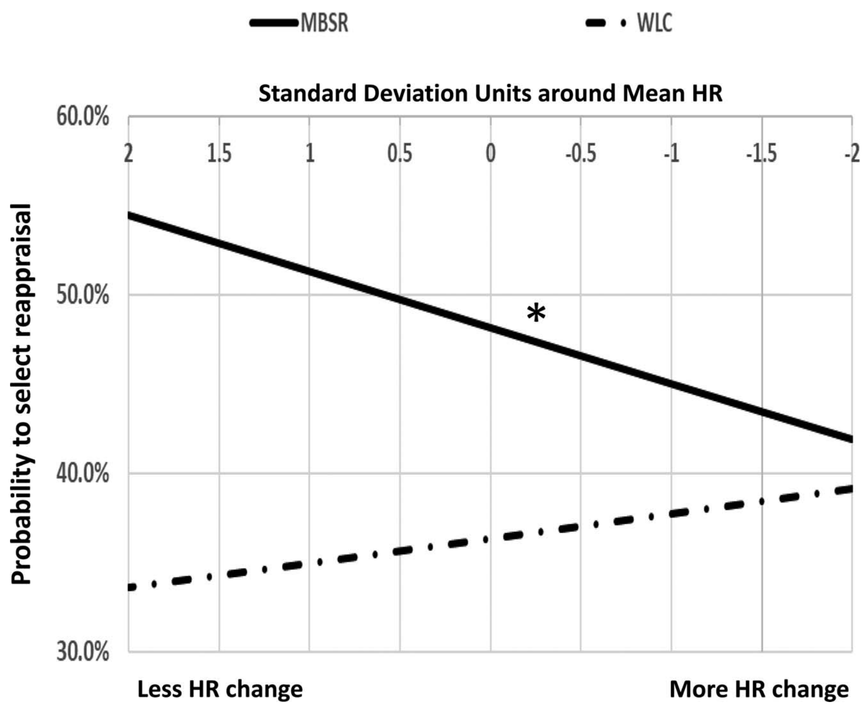

FIGURE 2. Probability to select reappraisal in response to changing cardiac reactivity levels during T2. Results of the analysis based on the cross-classified model. For the MBSR group, the probability of selecting reappraisal was significantly higher when cardiac reactivity to the negative pictures was low (less change in HR) in comparison to exposure to pictures that elicited high cardiac reactivity (more change in HR). This effect was not observed in the WLC group. Here, levels of change in HR are displayed as units of standard deviation around the mean collapsed across all pictures. Negative standard deviation values indicate greater cardiac reactivity (more change in HR). MBSR = mindfulness-based stress reduction; HR = heart rate; WLC = wait-list control.

within-subject variable, and group as a between-subject variable. Importantly, here intensity relates to the division of the emotional pictures to "low" and "high" intensity based on normative ratings. As depicted in Figure 3, we found a significant time by intensity by group interaction effect on proportions of reappraisal selections ($F(2,139) = 5.60$, $p = .005$, $\eta^2 = 0.075$). No difference between groups in average rates of selection of reappraisal for low and high intensities was found at T1 ($t(81) = 1.15$, $p = .252$; $t(81) = 0.72$, $p = .474$, respectively). Also, at T1, the difference between reported rates of reappraisal choice in low compared with high intensities (WL: low = 63%, high = 35%, $t(40) = 6.84$, $p < .001$; MBSR: low = 66%, high = 33%, $t(41) = 12.21$, $p < .001$) did

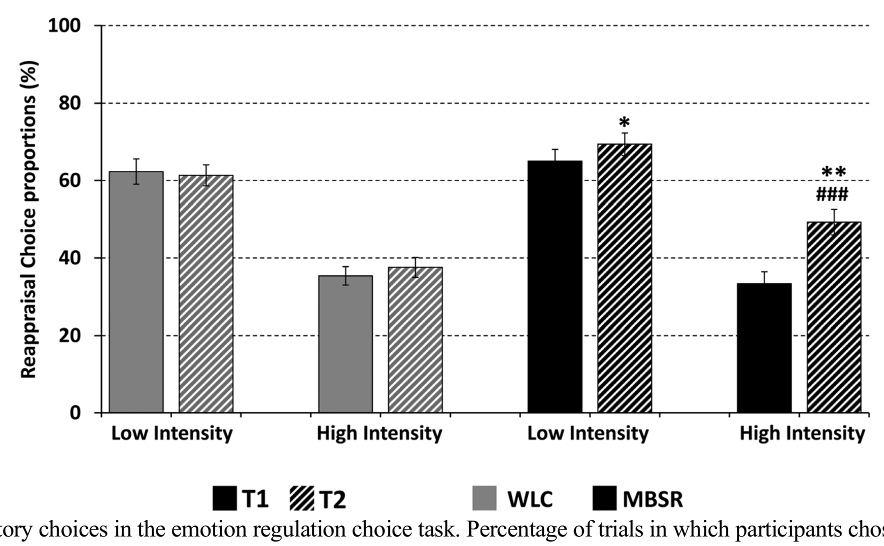

FIGURE 3. Regulatory choices in the emotion regulation choice task. Percentage of trials in which participants chose to distract for high and low emotional intensities before and after the intervention (mean ± standard error). * Significant difference between WLC and MBSR at T2, $p < .05$. ** Significant difference between WLC and MBSR at T2, $p < .01$. ### Significant difference between T1 and T2 values, $p < .001$. WLC = wait-list control; MBSR = mindfulness-based stress reduction; HR = heart rate.

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not differ from reports in the literature (6,15), serving as a manipulation check for the ERC task. At T2, independent *t* tests revealed a higher percentage of reappraisal selections by MBSR participants for both low ($t(69) = 2.02$, $p = .046$) and high ($t(69) = 2.78$, $p = .007$) intensities compared with WLC. Comparisons using paired *t* tests also revealed a significant increase in the proportions of reappraisal selections for high intensity at T2 compared with T1 alone for the MBSR participants ($t(35) = 3.64$, $p = .001$).

Similar results were obtained for the cross-classified model analysis, which was performed separately for T1 and for T2. At T1, we found a main effect for intensity on regulatory selections ($b_{\text{picture}} = -0.83$, posterior SD = 0.29, 95% CI = −0.87 to −0.76), indicating that the probability of selecting distraction was higher when the intensity of the picture was higher. No significant intensity by group effect on regulatory selection was detected ($b_{\text{picture}} = -0.09$, posterior SD = 1.26, 95% CI = −2.87 to 2.41), which implies that the preference for one strategy over the other at different levels of subjective intensity did not differ between the MBSR group and the control group. This was consistent across all levels of the model, indicating that at T1 there was no difference between groups.

At T2, we again found a main effect for intensity across participants, such that distraction was the preferred strategy for pictures of subjectively higher intensity ($b_{\text{picture}} = -0.068$, posterior SD = 0.08, 95% CI = −0.83 to −0.52). This time we also found a group effect ($b_{\text{subject}} = 0.26$, posterior SD = 0.13, 95% CI = 0.02 to 0.52), indicating that MBSRs were more likely to select reappraisal in comparison to the controls. However, there was no intensity by group effect, suggesting that, in general, the intensity-strategy association remained consistent across groups. Analysis of each group separately revealed that the MBSR group tended to select reappraisal more often (even for high intensities; $b_{\text{picture}} = -0.64$, posterior SD = 0.09, 95% CI = −0.82 to −0.47) relative to the WLC ($b_{\text{picture}} = -0.72$, posterior SD = 0.08, 95% CI = −0.89 to −0.55); however, these separate analyses preclude comparative inferences.

Overall, both analyses indicated that, at baseline, selection patterns replicated previous findings (serving as a manipulation check). Importantly, the main effect of the MBSR workshop was to increase the overall probability of selecting reappraisal.

Interestingly, we also found a trend toward a significant association between the overall propensity to select reappraisal over distraction for both intensities and the average number of days in which participants practiced at home (Pearson $r(36) = 0.313$, $p = .063$).

DISCUSSION

The main goal of the present study was to examine whether an MBSR program—considered the criterion standard of MBIs (50)—affects the way interoceptive signals guide regulatory selections in different emotional contexts and whether this is associated with well-being.

As expected (e.g., (87)), training in MBSR increased subjective mindfulness and satisfaction with life and reduced subjective anxiety, indicating that the program was beneficial for the participants. Crucially, our main hypothesis was supported: after the MBSR program, interoceptive signals related to emotional stimuli had a greater, more adaptive influence on regulatory selections. Specifically, we found that greater cardiac reactivity in response to emotional stimuli (indicating a higher physiological response to emotion) was associated with increased selection of distraction over reappraisal. Moreover, greater differences in cardiac reactivity when selecting distraction versus when selecting reappraisal were associated with a central subjective well-being measure (the SWLS). These results lend weight to the claim that MBSR can improve the ability to select different regulatory strategies in a manner that is sensitive to the internal emotional context (2,8,10,20,88), and that this is enabled through increased involvement of interoceptive signals in regulatory selections. In addition, we found that behavioral selection patterns on the ERC task shifted after MBSR: compared with their regulatory selections before the program and compared with the WLCs, MBSR participants preferred overall to reappraise than to distract. In the next section, we discuss these findings in more depth.

The Impact of MBSR on Regulatory Selections

In our main finding, we show that, after MBSR training, interoceptive signals associated with autonomic reactions to emotional stimuli (HR reactivity) could predict participants' subsequent regulatory selections. Such demonstration of associations between physiological signals and regulatory selections adds to two previous studies (19,77). Specifically, Shafir et al. (77) used the same ERC task and showed that increased neural responses to emotional stimuli, as indicated by the late-positive event-related potential—an EEG-based measure of emotional processing (see Ref. (89) for a review)—predicted increased selection of distraction over reappraisal. In addition, Birk and Bonanno (19) found that greater HR and EMG (another measure of emotional reaction) reactivity while implementing reappraisal was associated with increased decisions to switch to distraction.

Whereas these two studies detected physiological predictors of regulatory choices in untrained samples, our study demonstrated changes after training. Interestingly, in our study, cardiac signals emerged as predictors of regulatory selections only after the 8 weeks of mindfulness training. This suggests that cultivation of an intentional sensitivity to interoceptive signals may be required for fine-tuned cardiac feedback to inform regulatory selections. This is consistent with findings that greater body awareness training results in increased coherence between cardiovascular physiology and emotional experience (90).

Although EDA is also related to autonomic emotional responses, no association with regulatory selections was detected. This may be because MBSR practice emphasizes sensations related to breathing, leading to increased focus on the heart area. Pollatos and colleagues (91) showed that drawing participants' attention to heartbeat activated the brain region that overlaps with areas activated when cardiac reactivity increases. Thus, it is possible that of the several interoceptive axes (see Ref. (92)), the main one affected by MBSR was cardiovascular (51,52,64–66).

Our finding that people whose selections of regulatory strategies were driven by their interoceptive signals also reported higher satisfaction with life (a measure of subjective well-being; (93)) is consistent with reports in Birk and Bonanno (19), who also used this measure for well-being. In their study, people who tended to adjust an ongoing strategy based on their interoceptive signals also tended to report higher satisfaction with life. Future studies are needed to investigate the effect of MBIs on other stages of the regulatory process that require regulatory choices (see Ref. (3) for a review of the different regulatory stages and associated choices). In addition, future work should examine how other physiological

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channels (such as EMG and late-positive event-related potential) are affected by MBIs in relation to regulatory selection paradigms.

An additional finding of this study was that MBSR participants' selection patterns changed after the MBSR program and that they tended to choose more reappraisal overall, relative to their selection patterns before the intervention. This shift toward reappraisal is in line with our previous study (20) and with theoretical and empirical accounts of the effects of mindfulness practice on emotion regulation. For example, the mindfulness-to-meaning model (33) posits that mindfulness may introduce flexibility in the generation of cognitive appraisals by modifying how one attends to the cognitive, affective, and interoceptive sequelae of emotion provocation, even during stressful events (48). Accumulating evidence relates mindfulness to the positive reappraisal of stressful and painful situations (e.g., (23,26,32,94–97); see Garland et al. (33) for additional examples). Our findings support this model as we found both a shift in the way interoceptive processes effect regulatory selections and an increase in overall reappraisal after MBSR.

In a previous study (20), which used the ERC task on a different sample of participants, we also found an increase in reappraisal in the MBSR group relative to WLC, but mainly for the low-intensity pictures. We attribute the more significant shift toward reappraisal in the present cohort to several key differences between studies. First, in the present cohort, there was greater practice compliance, reporting approximately 60% more home practice time relative to the previous cohort. Mindfulness practice compliance has been found to predict greater recruitment of the posterior insula (31), suggesting practice time should result in more developed interoceptive abilities, which were attributed to enhanced appraisal abilities during stressful situations (48). This is further supported by our findings that average days of practice per week were correlated with overall rate of reappraisal. Other differences between studies may be due to the fact that in the present study, the ERC task was presented twice and not only after the MBSR program, and the time of initial exposure to the emotional image was eightfold longer to accommodate the autonomic measurements (see Methods).

Insights From Buddhist Psychology

The findings here and from our previous study (20) not only are in line with recent theoretical work (10,15,16,21,33) but also resonate with fundamental ideas in Buddhist psychology (which greatly inspired the development of programs like MBSR). A closer look at early Buddhist text reveals that lists of regulatory strategies to deal with negative thoughts and emotions appear extensively (e.g., The Sutta on Subduing Hatred [Aghatavinaya Sutta, AN 5.162; Bhikkhu, 2004], The Greater Exhortation to Rahula [The Maha-Rahulovada Sutta, MM62; Bhikkhu, 2006], The Sutta on All the Fermentations [Sabbasava Sutta, MN 2; Bhikkhu, 1997], About Meghiya [Meghiya Sutta, Ud 4.1; Bhikkhu, 2012], the Discourse on the Forms of Thought [or Vitakkasanthana Sutta, MN 20; Bhikkhu, 2007]; Retrieved from http://www.accesstoinsight.org). For example, the Discourse on the Forms of Thought (Vitakkasanthana Sutta) lists various strategies ranging from engaging strategies (such as deep experiential investigation of negative mind states or positive reappraisal of negative situations) to disengaging strategies (such as lack of attention to negative thoughts) (43). Batchelor (43) explains that according to this text, focusing one's attention on the disturbing situation is more adaptive at certain times, whereas at others (e.g., when certain thoughts are simply too strong or disturbing to confront), a more adaptive approach would be to focus attention away from them. Taken together, we suggest that MBIs that include a *range* of contemplative practices that both increase interoceptive sensitivity and can address a wide repertoire of regulatory capacities and strategies may be more effective in increasing mental health and resilience. This can explain the relative success of MBSR interventions (49) and MBCT (98) protocols, which are rooted in the Buddhist traditions and are based on a specific blend of contemplative practices (99). Future studies should address this issue and delineate the minimal combination and types of practices that can foster increased regulatory flexibility.

Limitations

The present study has several limitations. First, the sample was self-selected and was relatively healthy because we excluded—in addition to the regular MBSR exclusion recommendations—chronic pain and blood pressure syndrome conditions to avoid confounds in the interoception and cardiac measurements. For our main findings, the cross-classified model that accounts for greater variation in different levels increased statistical power, despite the relatively small sample size. However, this sample size precluded using mediation models to investigate whether explicit interoception and mindfulness changes mediated the relationship between regulatory selection and well-being measures. In terms of the cross-classified model, we could only assess T1 and T2 associations at either the picture or the individual levels. This limitation was due to the randomization of picture presentation in the ERC tasks, which prevented us from matching time 1 with time 2 at the trial level.

Another limitation is that the ERC task only addresses the two regulatory strategies commonly used in this task—cognitive reappraisal and attentional distraction—and does not test a wider range of strategies that are often cultivated in mindfulness practices (e.g., acceptance). In addition, the images used in the ERC task are aggregated to low and high negative intensity groups and do not represent a continuous spectrum of emotional intensities (which would have been more optimal for the physiological signal analysis). However, we believe that the advantages of using a well-validated paradigm outweigh these disadvantages. Another limitation of this study is the fact that a large number of tests were conducted. Thus, there is a possibility for statistical type 1 error. Finally, although we assessed several dimensions of well-being (satisfaction with life, resilience, and anxiety), and although both subjective anxiety and subjective satisfaction with life were affected by the MBSR program, differences in cardiac reactivity when selecting distraction versus when selecting reappraisal were only associated with satisfaction with life. There is presently no one validated measure for well-being, and satisfaction with life was previously used as a sole measure of well-being (19). However, future studies should replicate this finding with additional and more objective measures of well-being.

Conclusion

The present study expands previous work and demonstrates that MBSR improves participants' ability to select different regulatory strategies in a manner that is sensitive to internal emotional context, and that this increased sensitivity is associated with greater subjective well-being. Because regulatory choices that are sensitive to contextual and situational demands are believed to underlie well-being, resilience, and mental health (10,13,19), this may be a

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central pathway for the beneficial effects of MBIs such as MBSR. Future studies should directly investigate other MBI-induced capabilities that are theorized to improve regulatory choice sensitivity to varying emotional contexts, such as inhibition of automatic reactivity, broadening of attentional context, and having a wide repertoire of strategies. In addition, studies should examine whether the specific set of contemplative practices that characterize the MBSR protocol is necessary for fostering flexible regulatory choices, or whether any mindfulness practice sustained for a significant amount of time is sufficient. Finally, a direct demonstration that adaptive regulatory choices mediate the relationship between MBSR and mental health is needed.

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