Pain Sensitivity and Analgesic Effects of Mindful States in Zen Meditators: A Cross-Sectional Study

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Objective: To investigate pain perception and the potential analgesic effects of mindful states in experienced Zen meditators. **Methods:** Highly trained Zen meditators (n = 13; >1000 hours of practice) and age/gender-matched control volunteers (n = 13) received individually adjusted thermal stimuli to elicit moderate pain on the calf. Conditions included: a) baseline-1: no task; b) concentration: attend exclusively to the calf; c) mindfulness: attend to the calf and observe, moment to moment, in a nonjudgmental manner; and d) baseline-2: no task. **Results:** Meditators required significantly higher temperatures to elicit moderate pain (meditators: 49.9°C; controls: 48.2°C; p = .01). While attending "mindfully," meditators reported decreases in pain intensity whereas control subjects showed no change from baseline. The concentration condition resulted in increased pain intensity for controls but not for meditators. Changes in pain unpleasantness generally paralleled those found in pain intensity. In meditators, pain modulation correlated with slowing of the respiratory rate and with greater meditation experience. Covariance analyses indicated that mindfulness-related changes could be partially explained by changes in respiratory rates. Finally, the meditators reported higher tendencies to observe and be nonreactive of their own experience as measured on the Five Factor Mindfulness Questionnaire; these factors correlated with individual differences in respiration. **Conclusions:** These results indicated that Zen meditators have lower pain sensitivity and experience analgesic effects during mindful states. Results may reflect cognitive/self-regulatory skills related to the concept of mindfulness and/or altered respiratory patterns. Prospective studies investigating the effects of meditative training and respiration on pain regulation are warranted. **Key words:** pain, meditation, Zen, mindfulness, respiration, psychophysics.

ECG = electrocardiogram; **HF** = high frequency; **HRV** = heart rate variability; **LF** = low frequency; **LF/HF** = low/high frequency ratio; **FFMQ** = Five Factor Mindfulness Questionnaire; **MBSR** = Mindfulness Based Stress Reduction; **VAS** = Visual Analogue Scale.

INTRODUCTION

Considerable scientific attention has been devoted recently to mindfulness (1), a particular attentional stance with historic origins in Buddhist meditative traditions. Mindfulness can be described as an equanimous state of observation of one's own immediate and ongoing experience. Although much debate exists around the definition of mindfulness, both within spiritual traditions and between scientists, common ground can be found. Mindfulness can be considered a particular manner of attending, which can be developed through practice. This attentional stance is not restricted to time spent in formal meditation and scales have been developed to measure mindfulness in both meditators and nonmeditators (2–4). Mindfulness has been described as "intentional self-regulation of attention from moment to moment . . . of a constantly changing field of objects . . . to include, ultimately, all physical and mental events. . . ." (5). Furthermore, an attitude of acceptance toward any and all experience is stressed. Traditional accounts of mental and emotional transformation accompanying mindful practice (6,7) are supported by scientific findings of psychological and biological effects on practitioners (8–10) and patients (5,11–15). Here the potential of mindful attention to influence the perception of pain was investigated in highly trained meditators.

A growing body of research lends support to a proposed link between mindfulness practice and emotional processing. Mindfulness-based therapies have reported success treating anxiety (11,15), obsessive compulsive disorder (13), and depression (12,14). Positive correlations between meditation experience of Buddhist monks and positive affect (10) have been reported. Increases in positive affect have also been observed in a longitudinal study in which naïve subjects were trained to meditate (8). Additionally, positive relationships have been found in a sample of 174 newly trained practitioners between the time spent meditating, changes in trait mindfulness, stress, psychological and medical symptoms and well-being (16). The proposed relationship between mindful attention and the affective systems of the body and brain raises interesting questions concerning the effect of mindfulness on emotionally salient experiences, such as pain.

It is well known that cognitive manipulations, such as hypnosis, attention, expectancy or placebo, can influence the experience of pain and the associated neurophysiological activity (17–19). There is also mounting evidence that mindfulness may be effective in treating chronic pain. However, most of the available clinical studies have suggested an effect primarily on emotional and functional aspects of pain conditions and little or no long-term effects on pain sensation. Over the course of 5 years, Kabat-Zinn et al. reported on a group of chronic pain patients who had completed the Mindfulness Based Stress Reduction (MBSR) program (5,20,21). The final paper of the series included measures of present moment pain as well as symptom, mood, and psychiatric evaluations before and after MBSR training in 225 patients, with follow-up data of up to 4 years (21). Significant positive improvements were found on all measures immediately after the 10-week training

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Received for publication September 10, 2007; revision received June 2, 2008.

Supported jointly by a Canadian Institutes of Health Research (CIHR) operating grant (P.R.) and a Mind and Life Institute Varela Grant (J.A.G.). Dr. Grant has been supported by fellowships from the Fonds de la recherche en santé du Québec (FRSQ) and CIHR.

DOI: 10.1097/PSY.0b013e31818f52ee

0033-3174/09/7101-0106

program. However, follow-up evaluation showed stable improvements on most measures with the exception of present moment pain. The authors interpreted the results as the acquisition of an effective coping strategy for pain, where the pain itself did not change but the relation or stance taken toward the pain was positively altered. Morone et al. demonstrated improvements in pain acceptance in patients with low back pain after an 8-week meditation program (22). Further, the MBSR program has been used effectively to treat female patients with fibromyalgia, resulting in improvements in quality of life, pain coping, anxiety, depression, pain complaints, as well as Visual Analog Scales (VAS) of pain severity—effects not observed in an active control group (23,24). These positive effects remained stable at 3 years post intervention. Similar conclusions were reached by McCracken et al. (25) in a correlational study involving 105 patients with chronic pain showing inverse associations between mindfulness and depression symptoms, pain-related anxiety, and disability, after controlling for other patient-related factors including pain intensity. However, this study further found a negative correlation between pain intensity and mindfulness evaluated using a questionnaire. Taken together, clinical studies suggested a) significant benefits of mindfulness-based interventions on pain-related emotional and functional measures and b) individual differences in pain sensory processing associated with mindfulness.

Little attention has been devoted to the effects of mindfulness on pain, using experimental methods in healthy subjects. Kingston et al. (26) found increased tolerance to a cold pressor test and decreased reports of pain in a group of individuals trained in mindfulness compared with a group trained with visual imagery. However, changes in pain were completely independent from changes in mindfulness post training (i.e., correlation coefficients $<.1$). Those partly negative findings may be explained by the relatively limited amount of training provided to the subjects. The present study sought to clarify these effects in healthy individuals highly trained in meditation.

The aim of the present study was to assess the effect of mindfulness and mindful states on pain perception in experienced meditators. Practitioners of Zen (a mindfulness-based practice) (27) and age/gender-matched control subjects were recruited to participate in a psychophysical study involving thermal pain. The cross-sectional experimental design allowed us to examine potential differences in pain sensitivity between experienced meditators and individuals without meditation experience. Meditators were further expected to show greater reductions in pain than controls in a condition involving mindful attention. Secondarily, based on clinical studies showing benefits of mindfulness on stress and negative emotional states, effects were expected to be more pronounced on the affective-motivational aspect of pain (i.e., unpleasantness) as opposed to the sensory discriminative aspect (i.e., pain intensity). Furthermore, we examined associations between the amount of meditation experience, self-assessed mindfulness, the degree of pain modulation, and physiological activity. A cross-sectional design was used to take advantage of the extensive training of the meditation group, with the assumption that highly trained meditators would display more robust and stable effects. This approach was considered prerequired to future prospective, randomized studies involving intensive training of naïve individuals and extensive quantitative psychophysical testing pre and post training.

MATERIALS AND METHODS

Participants

All participants provided their written informed consent to participate in a study investigating the cognitive modulation of pain and received a monetary compensation. The recruitment process involved visiting meditation centers and posting advertisements in local newspapers and online classifieds. Exclusion criteria included current medication use, history of chronic pain, neurological or psychological illness, claustrophobia, and for control participants, previous experience with meditation or yoga. A list of possible meditators was first compiled ($n = 68$). The list ranged greatly in experience level and spanned many meditative traditions. The largest possible sample controlling for homogeneity of training and meeting the arbitrary requirement of 1000 hours of experience consisted of 13 Zen practitioners. Meditators from other disciplines were not tested. Thirteen age- and gender-matched control subjects, with no previous experience with meditation or yoga, were recruited (Table 1). Experiments were conducted between May and December of 2006 at the Centre de recherche de l'Institut universitaire de gériatrie de Montréal. All procedures were approved by the local Ethics Committee (CMER-RNQ 05-06-020).

TABLE 1. Description of Subjects, Baseline Pain Sensitivity, and Scores on the Subscales of the Five Factor Mindfulness Scale in the Trained Meditators and Control Subjects

	Meditators 5 Females/8 Males		Controls 5 Females/8 Males	
	Mean ± SD	Range	Mean ± SD	Range
Age	33.77 ± 10.99	22–56	34.38 ± 10.18	23–55
Meditation experience (hr)	6247 ± 11789	1139–45,000	—	—
Moderate-pain level (°C)[a]	49.92 ± 1.75	47–53	48.23 ± 1.36	45–50
FFMQ observe[a]	31.85 ± 31.85	26–39	24.54 ± 5.38	13–33
Describe	14.54 ± 3.76	8–20	13.23 ± 5.54	8–21
Act with awareness	17.46 ± 3.84	11–25	20.15 ± 6.26	10–31
Nonjudge	16.46 ± 3.57	10–24	17.08 ± 5.98	8–29
Nonreact[a]	26.31 ± 3.09	20–31	21.23 ± 6.38	13–31

[a] Significant group effect, $p < .05$ (or less).
SD = standard deviation; FFMQ = Five Factor Mindfulness Questionnaire.

Thermal Stimuli

Thermal stimulation was produced by a Medoc Thermode with a 9-cm^2 contact probe (TSA Neuro-sensory analyzer, Medoc Ltd. Advanced Medical System, Israel). Each stimulation consisted in a 1-second ascending ramp from 37°C to the target temperature, a 4-second plateau, and a 1-second descending ramp back to 37°C (Figure 1). In the experimental conditions, the target temperature was always 43°C for nonpainful warm trials for all participants. The target temperature for painful hot trials was adjusted individually to produce moderate pain (up to a maximum of 53.0°C). To minimize the likelihood of habituation or sensitization, the stimulation was applied in a pseudorandom order to six different locations of the lateral/posterior portion of the left calf, such that each position was stimulated twice at the painful and nonpainful levels in each condition.

Experimental Protocol

First, a prebaseline measure of the temperature required to elicit moderate pain was determined in each individual, using the ascending method of limits. Beginning at 42°C and increasing in steps of 1°C, a series of thermal stimuli was applied to the inner surface of the left calf. The moderate-pain level was defined as the temperature required to elicit a pain intensity rating of 6 to 7 on a 10-point scale in which 0 corresponded to "no pain" and 10 corresponded to "extremely painful." This was done to account for individual differences in pain sensitivity. Moderate pain was selected specifically to minimize the risk of ceiling or floor effects across the experimental conditions. The temperature required to produce moderate pain was evaluated again in a subset of 19 participants attending a separate experimental session. This allowed us to evaluate the test-retest reliability of this measure. Each subject's moderate-pain level was subsequently used in all painful trials in each of the following experimental conditions.

Participants were in the supine position and received brief thermal stimuli in four experimental conditions (Figure 1). Conditions were administered in the same order across all participants and differed only in the instructions given before the upcoming series of thermal stimuli. The first and fourth conditions were control conditions (baseline-1, baseline-2) in which these instructions were given: *Keep your eyes closed and try not to fall asleep*. The second condition was termed concentration and the instructions were: *Keep your eyes closed and focus your attention exclusively on the stimulation of your left leg*. This condition was designed to reflect the style of attending employed in various meditation techniques referred to as concentrative meditation (27) and was always performed immediately before mindfulness. In this type of meditation, one attempts to focus solely on a single object considering everything else distraction with the goal of eventually becoming absorbed in the object. The concentration condition was used as an attentional control condition for mindfulness and allowed comparisons to be made with previous studies of pain and attention. The third condition was always mindfulness and the instructions were: *Keep your eyes closed and focus your attention on the stimulation of your left leg. Try not to judge the stimulation but simply observe the sensation, moment by moment*. The mindfulness condition involved attentional deployment patterned around that used during mindfulness meditation, of which Zen is one example (27).

Each condition was approximately 7 minutes in duration and contained 12 nonpainful trials and 12 painful trials administered in a predetermined pseudorandom order. Each trial began with a 3- to 5-second auditory cue (1 kHz or 100 Hz steady tones), which correctly indicated whether the subsequent stimulus was painful (hot) or nonpainful (warm). Cues were used to help orient the subject, maximizing the efficacy of the attentional deployment during stimulation, and reducing potential effects of surprise or uncertainty regarding the occurrence of pain stimuli. A variable delay of 3 to 12 seconds separated successive trials.

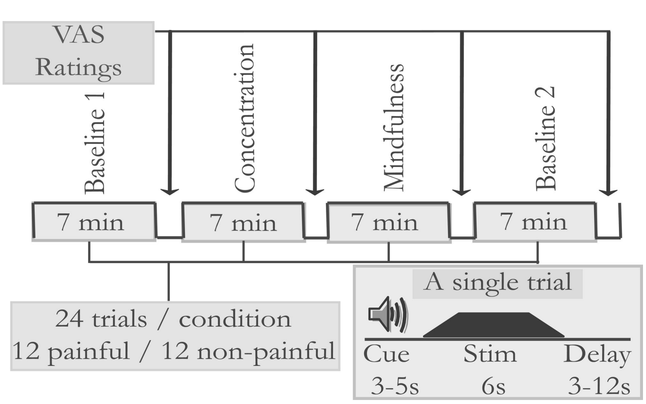

Figure 1. Experimental conditions. The experiment consisted in four blocks of 24 trials with each block lasting 7 minutes. Blocks differed in terms of the instructions given to subjects on how to attend to the stimulation (see Methods). Following each block, subjects rated the intensity and unpleasantness of the pain experienced, using electronic visual analogue scales. A single trial began with an auditory cue that correctly identified the subsequent stimulus as either painful hot or nonpainful warm. The intertrial interval varied between 3 and 12 seconds.

Dependent Measures

Subjects were asked to rate the pain induced by the painful stimuli immediately after each series of stimuli in each condition. Pain perception was assessed using electronic VAS measuring pain intensity and pain unpleasantness. Scales ranged from 0 to 10 with verbal anchors at 0 (not painful or not unpleasant) and 10 (extremely painful or extremely unpleasant). Instructions to distinguish between the intensity of pain and the unpleasantness of pain were based on those reported in previous studies (28,29).

Cardiac and respiratory activity was monitored continuously to document possible modifications in ongoing physiological activity during all experimental conditions. Indices of heart rate variability (HRV) were computed according to the guidelines of the Task Force of the European Society of Cardiology and the North American Society for Pacing and Electrophysiology (30). Respiration and heart rates were recorded with a Biopac MP150 system (Goleta, California) and analyzed using the Acknowledge software version 3.7.1. (Biopac Systems Inc.). Six minutes of continuous recording, beginning 30 seconds after the initiation of each condition, to allow for acclimation, was analyzed. Electrocardiogram (ECG) was measured using a three-electrode array and the peak of the R wave was detected automatically to obtain a continuous R-R interval tachogram. The ECG was visually inspected offline to detect artifacts; the R-wave detection procedure was also verified and the tachogram was corrected accordingly. Respiration was measured with a strain-gauge belt placed over the lower ribs.

Participants completed the Five Factor Mindfulness Questionnaire (FFMQ) (4), a 39-item questionnaire designed to measure five skills thought to be associated with mindfulness: observing, describing, acting with awareness, accepting without judgment, and nonreactivity. A brief questionnaire was also developed to assess the meditative history of participants including: type of practice, number of years practicing, frequency and length of practice in days per week, length of individual sessions in hours, amount of time spent in retreat, and motivation for practicing.

Statistical Analysis

The temperature required to reach the moderate-pain level was compared between meditators and control subjects, using an independent sample t test. For the experimental conditions, between-group differences in pain ratings and physiological measures were assessed via the interaction term of analyses of variance (ANOVAs) testing for the effects of Condition (baseline-1, concentration, mindfulness, and baseline-2) as the within-subject factor and Group (meditators and controls) as a between-subject factor. Simple effects of conditions were also examined within each group, using separate repeated-measure ANOVAs. To address a priori hypotheses on pain modulation during different attention conditions, planned contrasts were also applied to examine specifically the difference between concentration and baseline and between mindfulness and baseline. Adding gender as an additional between-subject factor did not yield any significant interaction and this factor was not included in the present report. Relations between measures were assessed, using Pearson and Spearman correlations. Pain modulation values used to correlate with other measures were calculated by subtracting the baseline-1 rating from

the rating in the condition of interest. Covariance was further used to examine the pain modulation effects after accounting for changes in physiological activity. Percent pain modulation was calculated by dividing the pain modulation value by the baseline-1 value. Partial eta-squared (η_p^2) was used as the effect size for ANOVAs and Cohen standard deviation (SD) (31) was used for pairwise contrasts (adjusted for r and using Hedges' bias correction) (32). The threshold for significance was set to $p < .05$, based on two-tailed tests, unless otherwise specified.

RESULTS

Pain Sensitivity

An individual adjustment procedure was used in the prebaseline phase of the study to ensure that subjects felt moderate pain in the baseline condition. This procedure was found to be highly reliable (test-retest: $R = .76$, $p < .001$) and revealed important group differences. The moderate-pain level was significantly different between groups [$t(24) = 2.75$, $p = .01$, d $= 1.04$] (Table 1; Figure 2A), with meditators requiring higher temperatures compared with controls (mean ± SD = 49.9 ± 1.75°C versus 48.2 ± 1.36°C, respectively). Notably, two meditators reached the highest temperature allowed in this study (53.0°C). One of these subjects rated 53°C as 6.5/10 whereas the other rated it as 5/10, i.e., lower than the target perceptual level. Thus, a ceiling effect prevented the full group difference from being captured. Nevertheless, the pain reported in the baseline-1 condition, using those individually adjusted stimuli, was comparable across groups [independent sample t tests; intensity: $t(24) = -0.92$, $p = .37$, d $= -0.34$; unpleasantness: $t(24) = -1.70$, $p = .10$, d $= -0.65$]. This indicates that trained meditators had lower pain sensitivity, which was adequately controlled in the baseline-1 condition, before testing the acute effects of concentration and mindfulness states.

Effects of Concentration and Mindfulness on Pain

Self-reported pain intensity and unpleasantness were acquired immediately after each experimental condition (Table 2). There was a significant Group × Condition interaction [$F(3,72) = 2.76$, $p = .05$, $\eta_p^2 = 0.10$] (Figure 2B) for intensity ratings, indicating differing patterns between groups. The contrast analysis revealed that the overall interaction was accounted for by a) an increase in pain during concentration

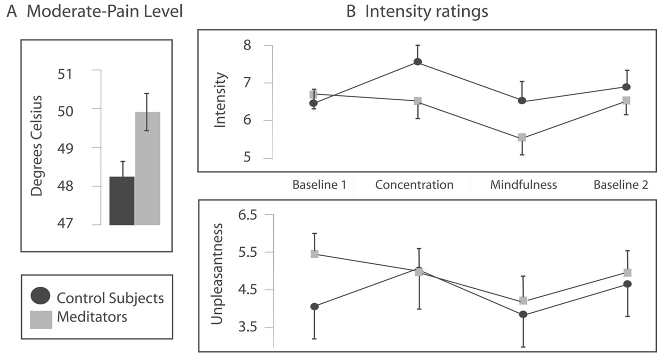

Figure 2. Perceptual results: (**A**) Mean ± SEM temperature required to produce a pain sensation of moderate intensity in the baseline condition; (**B**) mean ± SEM intensity; and (**C**) unpleasantness ratings of each group in each condition. SEM = standard error of the mean.

TABLE 2. Pain Ratings in the Trained Meditators and Control Subjects Across Experimental Conditions

	Meditators Mean ± SD	Controls Mean ± SD
Baseline-1		
Intensity	6.84 ± 1.26	6.43 ± 1.25
Unpleasantness	5.46 ± 1.76	4.06 ± 2.78
Concentration		
Intensity	6.57 ± 1.55	7.37 ± 1.62
Unpleasantness	4.86 ± 1.95	4.90 ± 3.12
Mindfulness		
Intensity	5.59 ± 2.01	6.46 ± 1.93
Unpleasantness	4.20 ± 2.24	3.66 ± 2.98
Baseline-2		
Intensity	6.48 ± 1.55	6.92 ± 1.55
Unpleasantness	5.16 ± 1.96	4.69 ± 2.99

SD = standard deviation.

(versus baseline-1) in controls whereas meditators showed a slight decrease [$F(1,24) = 5.66$, $p = .02$, $\eta_p^2 = 0.19$] and b) a decrease in pain during mindfulness (versus baseline-1) in meditators but not in control subjects [$F(1,24) = 6.00$, $p = .03$, $\eta_p^2 = 0.20$]. Planned within-group contrasts revealed that the increase in intensity ratings during concentration was significant for controls (+14.6%) [$F(1,12) = 17.50$, $p < .001$, d $= 1.80$] and that the decrease in intensity ratings during mindfulness was significant for meditators (−18.3%) [$F(1,12) = 6.23$, $p = .02$, d $= -0.99$]. Additionally, the meditators showed a significant reduction in pain (−15%) between the concentration and mindfulness conditions [$F(1,12) = 4.8$, $p < .05$, d $= -0.86$; this effect did not reach significance in control subjects: $p = .09$]. This finding confirms that concentration increased pain in controls and that mindfulness decreased pain in trained Zen meditators.

The overall Group × Condition interaction did not reach significance for unpleasantness ratings [$F(3,72) = 1.92$, $p = .13$, $\eta_p^2 = 0.07$]. However, examination of the means (Figure 2C) and the planned contrasts suggested effects similar to those observed for pain intensity. A significant interaction was found between baseline-1 and concentration with controls showing increased unpleasantness ratings whereas meditators showed decreased ratings [$F(1,24) = 4.27$, $p = .05$, $\eta_p^2 = 0.15$]. The Group × Condition interaction was not significant between baseline-1 and mindfulness [$F(1,24) = 2.36$, $p = .14$, $\eta_p^2 = 0.09$]. However, the planned within-group contrasts revealed that the decrease in unpleasantness between baseline-1 and mindfulness for meditators (−23.1%) was significant [$F(1,12) = 5.25$, $p = .04$, d $= -0.88$]. The change in unpleasantness during mindfulness was significantly correlated with the corresponding changes in pain intensity across all subjects ($R = .76$, $p < .001$). Control subjects, on the other hand, showed a marginally significant increase (+20.7%) in unpleasantness ratings [$F(1,12) = 4.54$, $p = .055$, d $= 0.85$] between baseline and concentration. Additionally, the meditators showed a significant reduction in unpleasantness (−14%) between the concentration and mindfulness condi-

tions [$F(1,12) = 6.2$, $p = .03$, d $= -0.95$]. Although the general ANOVA did not reach significance, these planned analyses and the correlation between change scores, suggest that, similar to pain intensity, pain unpleasantness is reduced during mindfulness for meditators and increased during concentration for control subjects.

Importantly, both pain intensity and unpleasantness ratings returned to the pretest baseline (baseline-1) in the last condition (baseline-2). Direct statistical contrasts between the baseline values did not reach significance on pain intensity [control: paired t test $t(12) = -1.72$, $p = .11$, d $= 0.68$; meditators: paired t test $t(12) = 0.97$, $p = .35$, d $= -0.37$] or pain unpleasantness [control: $t(12) = -1.88$, $p = .08$, d $= -0.73$; meditators: $t(12) = 0.54$, $p = .60$, d $= 0.21$]. This indicates that subjects did not habituate or sensitize significantly to the stimuli over the repeated blocks of painful stimulation.

Changes in pain were further examined in relationship to meditation training. The amount of meditation experience of individual practitioners predicted the degree of pain intensity modulation (i.e., versus baseline) with more hours of experience leading to greater reductions in pain intensity during the mindfulness condition [$r(9) = -.82$, $p < .01$]. Hours of experience correlated to a lesser extent and not significantly with reductions in unpleasantness [$r(9) = -.42$, $p = .20$]. Two cases were classified as outliers based on Cook's Distance and Centered Leverage values and excluded from those correlations. One of these was a Zen monk, with ~45000 hours of experience versus the second highest at ~7000 hours. Both subjects were in the upper end of the analgesic effect. To include all 13 subjects, nonparametric (Spearman) correlations were performed and reached significance on pain intensity [rho(11) $= -0.56$, $p = .04$] but not unpleasantness [rho(11) $= -0.33$, $p = .28$]. Notably, clinically significant analgesic effects (>2/10 on the pain intensity VAS) were obtained only in meditators with >2000 hours of experience whereas the subjects with 1000 to 2000 hours of experience showed no changes or slight increases in pain.

Physiological Measures

Physiological activity was affected by the experimental conditions and this effect differed between groups as demonstrated by a significant Group × Condition interaction in respiration rate [$F(3,69) = 3.30$, $p = .04$, $\eta_p^2 = 0.13$; also, note a marginally significant main effect of Group: $F(1,23) = 3.85$, $p = .06$, d $= -0.76$]. The contrast analysis revealed that the overall interaction effect was accounted for by an interaction between baseline and mindfulness with controls having slightly increased breathing rates and meditators substantially decreased breathing rates [$F(1,23) = 4.25$, $p = .05$, $\eta_p^2 = 0.16$] (Figure 3). The decrease in breathing rate observed in meditators did not reach significance in the follow-up pairwise contrast [$F(1,12) = 2.88$, $p = .11$, d $= 0.66$]; however independent sample t tests confirmed that meditators breathed at a slower rate than the controls in the concentration and mindfulness conditions [baseline-1: $t(23) = 1.51$, $p = .07$, d $= -0.58$; concentration: $t(23) = 2.03$, $p = .03$, d $= -0.77$; mindfulness: $t(23) = 2.50$, $p = .01$, d $= -0.95$; baseline-2: $t(23) = 1.61$, $p = .12$, d $= -0.61$].

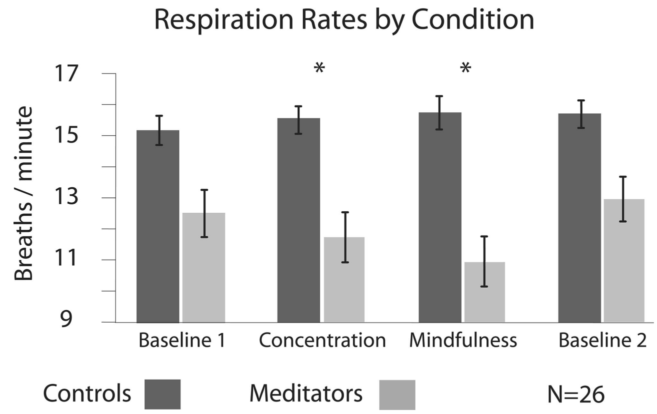

Figure 3. Respiratory rates across groups and conditions. Meditators breathed at a slower rate during each condition. The respiration pattern followed that of their pain ratings (Figure 2B–C). *$p < .05$ for the independent sample t test contrasting groups.

Notably, pain modulation induced by mindfulness (relative to baseline-1) was correlated with the corresponding changes in respiratory rate across all subjects [intensity: $r(23) = .37$, $p = .03$; unpleasantness: $r(23) = .42$, $p = .02$]. Furthermore, the significant decrease in pain intensity reported above in the meditators during the mindfulness condition relative to baseline-1 (Figure 2) did not reach significance after including the changes in respiration as a covariate [$F(1,11) = 3.02$, $p = .11$]. In contrast, the significant increase in pain intensity reported by the control subjects in the concentration condition remained significant after accounting for changes in respiratory rates [$F(1,11) = 20.94$, $p = .001$]. These effects suggest that the changes in pain induced by mindfulness, but not concentration, may be at least partly accounted for by changes in respiration.

Heart rate, measured in beats per minute across each condition, differed over time but not between groups [main effect of condition: $F(3,72) = 4.76$, $p = .04$, $\eta_p^2 = 0.17$; main effect of group: $F(1,24) = 0.49$, $p = .49$, d $= 0.27$; Group × Condition interaction: $F(3,72) = 1.97$, $p = .17$, $\eta_p^2 = 0.08$]. The significant effect consisted of a steady slowing of the heart rate for both groups from baseline-1 through baseline-2. Spectral analyses of HRV revealed no significant main effects of condition or Group × Condition interactions for low-frequency (LF) power, high-frequency (HF) power or the ratio of LF to HF [LF main effect: $F(3,72) = 2.02$, $p = .17$, $\eta_p^2 = 0.08$ and interaction: $F(3,72) = 1.11$, $p = .30$, $\eta_p^2 = 0.05$; HF main effect: $F(3,72) = 0.65$, $p = .43$, $\eta_p^2 = 0.03$ and interaction: $F(3,72) = 1.54$, $p = .23$, $\eta_p^2 = 0.06$; LF/HF main effect: $F(3,72) = 2.79$, $p = .11$, $\eta_p^2 = 0.10$ and interaction: $F(3,72) = 2.27$, $p = .15$, $\eta_p^2 = 0.09$]. There was, however, a main effect of group for the LF/HF ratio [$F(1,24) = 7.13$, $p = .01$, d $= 1.01$]. Independent sample t tests revealed that meditators had a higher LF/HF ratio during baseline-1 [$t(24) = -2.15$, $p = .05$, d $= 0.81$], concentration [$t(24) = -2.41$, $p = .03$, d $= 0.91$], and mindfulness [$t(24) = -2.10$,

$p = .05$, d = 0.78]. These differences are likely accounted for by the respiratory rates (i.e., respiratory sinus arrhythmia) of six meditators that breathed in the LF range of HRV (0.05–0.15 Hz) as opposed to the more typical breathing rates found in the HF range (0.15–0.40 Hz) that seven meditators and all 13 controls displayed. This difference in LF/HF may, therefore, be the result of either or both (a) an increased sympathetic activity in meditators or (b) a shift in respiratory sinus arrhythmia, mediated by the parasympathetic nervous system, into the LF range.

FFMQ

Groups also differed on psychological characteristics associated with mindfulness assessed, using the FFMQ. There were significant group differences on the observe [$t(24) = 4.01$, $p < .001$, d = 1.53] and nonreact [$t(24) = 2.58$, $p = .02$, d = 0.98] subscales (Figure 4) with meditators rating themselves as more observant and less reactive to their own experience than control subjects. Considering the entire sample, the correlation of the moderate-pain level reached significance with the observe subscale [$r(24) = .43$, $p = .04$] and approached significance with the nonreact subscale [$r(24) = .34$, $p = .08$]. Lower reactivity (nonreact subscale) was also associated with slower respiratory rates in each condition [baseline-1: $r(23) = .47$, $p = .02$; concentration: $r(23) = .40$, $p = .04$; mindfulness: $r(23) = .42$, $p = .04$; baseline-2: $r(23) = .41$, $p = .04$].

DISCUSSION

Thermal pain perception was investigated in a group of trained Zen meditators and compared with a group of untrained, age- and gender-matched, control subjects. The main findings are the following:

1) Meditators required hotter temperatures than controls to experience moderate pain.
2) As hypothesized, meditators experienced less pain while attending mindfully, whereas control subjects did not show such modulation.
3) Unexpectedly, analgesic effects of mindfulness were more clear on the sensory dimension of pain (i.e., perceived intensity) than the affective dimension of pain (i.e., pain unpleasantness), although effects were observed in the same direction.
4) The magnitude of the analgesic effect of mindfulness was predicted by the number of hours of meditation practice in meditators.
5) When attention was directed toward the stimulation, with no mention of attending mindfully, control subjects showed the expected increase in pain intensity and unpleasantness whereas meditators did not differ from baseline.
6) Physiologically, meditators had slower breathing rates than controls, consistent with their self-assessed reduced reactivity. Importantly, changes in respiratory rate predicted the changes in felt pain and the analgesic effect of mindfulness states was no longer significant after accounting for changes in respiratory rates (covariance).
7) On a mindfulness scale, meditators scored higher on the tendency to be observant and nonreactive. Higher scores on these dimensions of mindfulness were further associated with lower pain sensitivity and slower respiratory rates.

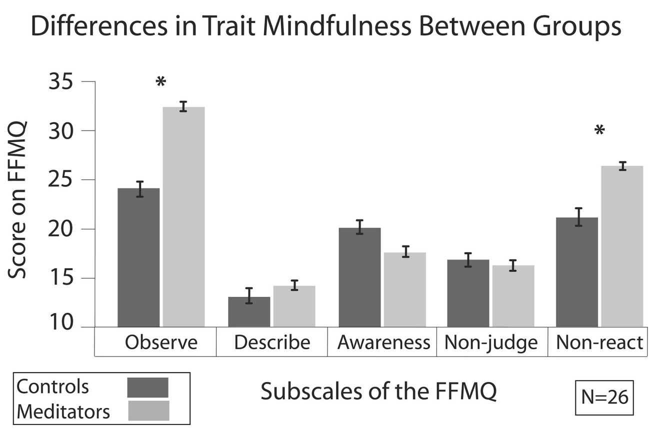

Figure 4. Mean ± SEM scores on the subscales of the FFMQ. Scores on the observe and nonreact subscales were different between groups with meditators rating themselves as more observant and less reactive than control subjects. *$p < .05$). SEM = standard error of the mean; FFMQ = Five Factor Mindfulness Questionnaire.

Zen meditation was associated with lower pain sensitivity as demonstrated by the higher temperatures required to produce moderate pain. The observed difference (49.9°C versus 48.2°C) should be considered large as it typically corresponds to an increase of about 50% on a ratio scale of pain perception or 20 to 25 points on a 0 to 100 numerical pain scale, based on similar psychophysical methods (28,33). The procedure for acquiring the moderate-pain level did not involve explicit instructions in how to attend, was conducted before testing began, and was intended to assess pain sensitivity at the time the subject was attending as naturally as possible. Zen practitioners are taught to generalize the skills learned in their formal mental training sessions to everyday life, to be mindful both in and out of meditation. Thus, one potential explanation for the group difference in pain sensitivity is the attentional stance generally taken toward any sensory event. This group difference was related parametrically to two facets of mindfulness. As subjects' scores increased on the observe and nonreact subscales of the FFMQ, the temperature required for moderate pain also rose. These correlations spanned all subjects with meditators concentrated at the high end of both scales and controls at the lower end of both scales. Whether this effect can be attributed to meditative training or preexisting individual differences is discussed below.

Over and beyond the large pain sensitivity difference between groups, explicit instruction to attend mindfully had analgesic effects in meditators but not in control subjects. Furthermore and quite importantly, the magnitude of the analgesic effect was related to training. While attending mindfully, the Zen practitioners showed reductions of 18% pain intensity. Remarkably, individuals with more extensive train-

ing experienced greater reduction in pain. This finding is extremely important as it suggests that the observed pain reduction may not simply reflect a predisposition to meditation (individual differences) but may also involve experience-dependent changes associated with practice. This is in line with other studies linking meditation training with mindfulness, medical symptoms, and well-being (16); attention performance, anxiety, depression, anger, cortisol and immunoreactivity (34); an inverted U-shaped function of attention-related brain activity (35); electrophysiological markers of positive affect (10); positive affect and stronger immune responses (8); and cortical thickness and gray matter density (9,36,37). Taken together, these studies are consistent with the notion of meditation as a transformative practice evolving from the development of concentrative skills to more compassionate and mindful states associated with structural and functional changes in the brain, leading to more positive emotional states, less pain, and improved health.

Consistent with previous studies (38,39), directing attention toward pain (i.e., the concentration condition) resulted in increased pain for control subjects. Pain intensity increased by 15% and pain unpleasantness increased by 21%. However, the Zen meditators showed a slight nonsignificant reduction from baseline during this condition. In the meditators, a greater tendency to adopt a mindful stance may underlie the absence of the typical enhancing effect of attention on pain. This is consistent with the group differences observed on the FFMQ and in pain sensitivity. Having trained to be mindful in everyday life, it may be difficult for such individuals to not exercise this attentional stance.

The reduction in unpleasantness ratings for meditators while attending mindfully fits well with allegations that this type of meditation has an impact on affective processing. The efficacy of using mindfulness-based therapies for affective disorders, such as depression (12), anxiety (11,14), and obsessive compulsive disorder (13), has already been demonstrated. However, the analgesic effect of mindful attention in Zen meditators was not restricted to the affective dimension of pain, as measured by unpleasantness, but it was equally potent and it reached significance primarily on pain intensity. Consistent with this effect, pain sensitivity was also predicted by trait mindfulness. Taken together, these results suggest that mindfulness does not simply modify the emotional reaction to pain but may also interact with the sensory processing of the nociceptive input. Previous studies on the interaction of emotions and pain have generally found stronger effects of emotion on pain unpleasantness but significant effects have also been reported on pain sensation intensity (40). The putative reduction in affective reactivity associated with meditative practice may thereby contribute to the reduction in both sensory and affective processing of the nociceptive input.

The analgesic effects of mindful attention may relate to the physiological state induced as suggested by the respiration data. Overall, the meditators breathed at a slower rate than control subjects in all conditions and their mean respiratory pattern followed that of their pain ratings. In contrast, respiratory rate did not change noticeably across conditions in the control subjects. Slower breathing rates (typically meditators) were associated with less reactivity and with lower pain sensitivity. These relationships suggested that the meditators were in a more relaxed, nonreactive physiological state throughout the study, which culminated in the mindfulness condition and which influenced the degree to which they experienced pain. In the mindfulness condition, the change in respiration (from baseline) further predicted the change in pain, with subjects who breathed more slowly also showing larger reductions in pain. The covariance analysis suggested that this analgesic effect could be mediated at least in part by the observed change in respiration. Previous studies have proposed a parasympathetic dominant, relaxed, physiological state of meditation (41). However, there is also evidence suggesting that certain techniques are not simply physiologically relaxed states but can also involve high autonomic arousal (42). A relaxed yet alert state may be reflected by the tendencies seen here to be nonreactive yet highly observant. Interestingly, heart rate did not differ between groups or conditions but meditators had a tendency to have more variable heart rates throughout the experiment. Taken together, the changes observed are consistent with effects of mindfulness on both respiration and pain, possibly reflecting an impact on at least partly common brain mechanisms underlying pain, emotion, and self-regulatory/homeostatic function (43–46).

A neuro-chemical model of meditation put forth by Newberg and Iversen (47) offers a possible explanation for our results. Meditation practice, involving volitional regulation of attention, seems to activate prefrontal cortex (35,48,49); this has been observed during Zen practice (50). Increases in prefrontal activation can stimulate the production of b-endorphin (e.g., in the arcuate nucleus of the hypothalamus) (47). B-endorphin is an opiate associated with both analgesia and a reduction in respiratory rate as well as decreases in fear and increases in joy and euphoria (47). Interestingly, the direction of attention toward breathing and the volitional control of breathing rates are part of many meditative techniques; however, causation can obviously not be inferred from those observations. A study of meditation has also demonstrated changes in b-endorphin rhythms associated with practice (51). Another related possibility is that meditation leads to reductions in stress and stress-related chemicals, such as cortisol which interact with the opiate system. A reduction of cortisol can greatly enhance the binding potential/efficacy of endogenous opioids (27), possibly contributing to a downregulation of nociceptive responses. Studies have reported evidence of reduced cortisol responses in meditators (34,52,53). Taken together, a picture emerges of a highly efficacious endogenous opioid system in trained meditators. This could be readily tested by measuring cortisol at several times points during a pain study, examining the effect of the opioid antagonist naloxone, and using brain imaging techniques allowing for a quantification of the opioid-binding potential (54–56). Although these possibilities should be considered hypothetical in the current state of knowledge, these observations offer promising avenues for future research.

Several limitations of the current study should be noted. The first is a confounding effect of keeping the order of the conditions constant across subjects. The concentration condition always preceded mindfulness to respect the normal sequence of attention that is said to lead to a successful mindful state. It is taught that the mind must first be calmed via concentrative meditation or restricted focus before moving into mindful meditation. Had the reverse order also been used, some carryover effects of mindfulness into concentration may have decreased the potential to separate the two states. Furthermore, the introduction of a second order as an additional between-subject variable would have required the testing of a larger sample, a goal difficult to achieve given the highly selective population. Two observations argue against an order effect. First, the analgesic effect of mindfulness was only observed in the meditators. Second, pain returned to baseline in both groups in the last condition. An effect of sensitization or habituation to repeated stimulation would be inconsistent with those observations.

Although a modest sample size may be viewed as a limitation, the multiple effects found in this study seem robust and consistent with one another. Again, given the highly selective population and the amount of training necessary to participate in the study (>1000 hours), a larger sample was not available and a cross-sectional design was necessary. This design admittedly limits the interpretation of a causal relation between meditation training and the observed effects. It is possible that preexisting individual differences, beyond meditation training, underlie some of the observed results. Significant correlation with mindfulness scores may reflect such a priori individual differences, at least partly independent from meditation training (consistent with effects reported in the work of McCracken et al.) (25). However, the significant correlation between meditation experience and analgesia is consistent with previous studies, suggesting training-induced changes (8–10,16,35–37). Although this study was not designed to tease apart all potential contributing factors in the relationship between pain perception and meditation, these issues could be dealt with effectively using a prospective design in which naïve subjects are trained (8). This would also allow one to control for factors such as self-selection biases, self-efficacy, and the effect of expectation, driven by prior experience of, or beliefs about, meditation-related hypoalgesia. However, the prospective design may not adequately capture the larger effects associated with more extensive meditation training as demonstrated by the correlation analyses in the present results.

Another potential limitation is the possible confounding effects of expectancy. In the present study, it is possible that the meditators expected mindful attention to diminish some aspects of their painful experience or responded in compliance with the perceived expectation of the experimenter. However, the more robust changes observed in pain intensity than unpleasantness did not confirm our hypothesis of a stronger effect on pain affect. Furthermore, Zen students are not taught that meditation reduces the perceived intensity of a stimulus but rather that it may reduce the suffering associated with aversive experiences. Such teaching promotes acceptance and a nonjudgmental, nonreactive stance toward all experiences. Therefore, possible expectancy or compliance effects seem inconsistent with the more robust results observed on measures of pain intensity. Furthermore, the significant correlation relating experience levels with the analgesic effects of attending mindfully were such that advanced practitioners (>2000 hours) had large pain decreases whereas the most novice subjects had slight increases or no changes in pain. For these correlations to exist, individuals would need a priori knowledge of the experience level of other participants and of how that experience level interacts with pain; this seems rather unlikely. Finally, correlations between respiration and pain reduction are consistent with the notion that mindful states and/or meditation training are associated with central physiological change that modulate nociceptive processing and pain perception. Admittedly, this physiological effect and the proposed neural mechanisms discussed above are not inconsistent with a contribution of expectancy. Future investigation of pain-related brain responses may provide more direct evidence demonstrating how meditation affects central neurophysiological processes underlying pain and how much overlap there might be between expectancy- and meditation-related analgesia.

To conclude, the present study joins a growing body of work suggesting both state and trait properties of mindfulness-based meditative practice. The benefit of these practices, whether viewed scientifically, clinically, or spiritually, could be of great importance for the health and well-being of practitioners and patients alike and should thus be considered an important avenue of research.

We thank Jerome Courtemanche for his input at all stages of this project; Myokyo (Abbess of Centre Zen de la Main, Montreal, Qc, Canada) for her support, help in subject recruitment, and guidance with the protocol and interpretation; and Gary Duncan and members of the Rainville laboratory for their valuable feedback.

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