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Mindfulness Training Affects Attention—Or Is It Attentional Effort?

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Improvements in attentional performance are at the core of proposed mechanisms for stress reduction in mindfulness meditation practices. However, this claim can be questioned because no previous studies have actively manipulated test effort in control groups and controlled for effects of stress reduction per se. In a blinded design, 48 young, healthy meditation novices were randomly assigned to a mindfulness-based stress reduction (MBSR), nonmindfulness stress reduction (NMSR), or inactive control group. At posttest, inactive controls were randomly split into nonincentive and incentive controls, the latter receiving a financial reward to improve attentional performance. Pre- and postintervention, 5 validated attention paradigms were employed along with self-report scales on mindfulness and perceived stress and saliva cortisol samples to measure physiological stress. Attentional effects of MBSR, NMSR, and the financial incentive were comparable or significantly larger in the incentive group on all reaction-time-based measures. However, selective attention in the MBSR group improved significantly more than in any other group. Similarly, only the MBSR intervention improved the threshold for conscious perception and visual working memory capacity. Furthermore, stress-reducing effects of MBSR were supported because those in the MBSR group showed significantly less perceived and physiological stress while increasing their mindfulness levels significantly. We argue that MBSR may contribute uniquely to attentional improvements but that further research focusing on non-reaction-time-based measures and outcomes less confounded by test effort is needed. Critically, our data demonstrate that previously observed improvements of attention after MBSR may be seriously confounded by test effort and nonmindfulness stress reduction.

Keywords: meditation, MBSR, stress, cortisol, relaxation

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Mindfulness-based stress reduction (MBSR; Kabat-Zinn, 1994) is a meditation-based treatment program applied to diverse clinical conditions with positive results (Baer, 2003; Grossman, Niemann, Schmidt, & Walach, 2004). Two reviews of MBSR as a tool for stress reduction reported promising results, but hardly any of the reviewed trials were blind and appropriately randomized, and control groups were often inadequate (Chiesa & Serretti, 2009; Irving, Dobkin, & Park, 2009). In addition, the factors contributing to change as a result of MBSR are poorly understood, and the need for rigorous research on this issue is widely recognized (Baer et al., 2006; K. W. Brown, Ryan, & Creswell, 2007; Chiesa & Serretti, 2009; Dimidjian & Linehan, 2003; Hayes, Luoma, Bond, Masuda, & Lillis, 2006; Irving et al., 2009; S. L. Shapiro, Carlson, Astin, & Freedman, 2006).

It has been proposed that the mechanisms responsible for positive change following MBSR involve attentional improvements, the cultivation of a nonjudgmental attitude, and an intention to be present in the now (Baer, 2003; S. L. Shapiro et al., 2006). This is in line with the most common definitions of mindfulness. Jon Kabat-Zinn, the founder of MBSR, defines *mindfulness* as "paying attention on purpose, in the present moment, and nonjudgmentally" (Kabat-Zinn, 2003, p. 145). Furthermore, attentional training and improvement are core elements in traditional meditation practices, and meditation types are often defined according to their attentional characteristics (Andresen, 2000; Lutz, Slagter, Dunne, & Davidson, 2008).

There is tentative support for meditation-related improvements in attention, but methodological flaws have been plentiful. A recent large review concluded: "The primary psychological domain mediating and affected by meditative practice is attention . . . but relatively few empirical evaluations of meditation and attention have been conducted" (Cahn & Polich, 2006, p. 200). Studies of experienced meditators or intensive meditation retreats provide compelling evidence: Tibetan monks showed extraordinary abilities to sustain perceptual focus on one visual field (Carter et al., 2005), and participants on long-term retreats showed improved performance on the attentional blink task (Slagter, 2007; Slagter, Lutz, Greischar, Nieuwenhuis, & Davidson, 2009), a dichotic listening task (Lutz et al., 2009), and a visual discrimination task

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(MacLean et al., 2010). Functional brain imaging has also shown increased stability in the amygdala response to a negative distractor during a sustained attention task in experienced meditators compared with incentive controls, and the stability in amygdala was furthermore positively associated with hours of meditation practice (Brefczynski-Lewis, Lutz, Schaefer, Levinson, & Davidson, 2007). Likewise, structural brain studies have found experience-related thickening or the absence of age-related thinning of areas involved in interoceptive awareness and attention, such as the insula, putamen, and prefrontal cortex (Hölzel et al., 2008; Lazar et al., 2005). This has been replicated and further corroborated by a corresponding absence of age-related decreases in sustained attention (Pagnoni & Cekic, 2007). Experience-related findings within the nonnovice groups support the notion of a causal relationship between meditational training and neurocognitive attentional improvements. However, these findings cannot be directly transferred to mechanisms of change in MBSR for meditation novices. Studies of experts are mostly cross-sectional, and meditator samples are small and not representative of the persons for whom meditation training is part of a therapeutic intervention, not a lifestyle. Likewise, intensive retreats in remote mountain settings are not directly comparable to MBSR.

The Importance of Attentional Effort

To our knowledge, no previous studies of MBSR have actively manipulated test motivation in the control groups, even though issues related to motivation have been noted repeatedly (D. H. Shapiro & Walsh, 1984). Intervention participants may experience performance pressure during posttesting due to demand characteristics (the perceived expectations of the experimenter) or be more motivated because of culturally endorsed expectations of meditation effects. The potential impact of such expectations is firmly supported in mainstream cognitive neuroscience. Closely related to motivation stands the concept of "attentional effort," which can be defined as "a function of the task's cognitive incentive [which] primarily [represents] the subjects' motivation to perform" (Sarter, Gehring, & Kozak, 2006, p. 147). Research shows that the cognitive incentive of a task can have a wide range of neuronal effects. For example, increased effort modulated activity in regions and circuits involved in processing attended target stimuli (Serences et al., 2005), synchronized neuronal firing (Fries, Reynolds, Rorie, & Desimone, 2001; Moran & Desimone, 1985), and modified neuronal firing rate (Fries et al., 2001; Treue & Maunsell, 1996). Increased effort also improved performance on a choice reaction time (RT) task (Pashler, 1998, p. 384), a sustained attention task (Tomporowski & Tinsley, 1996), and the Stroop color–word task (Chajut & Algom, 2003), an acknowledged test of inhibition and selective attention.

Critically, similar results have been reported in the meditation literature without controlling for (i.e., assessing or manipulating) attentional effort. Synchronized neuronal firing is a common finding in electroencephalographic (EEG) studies of meditation (Cahn & Polich, 2006), and improved sustained or selective attention (e.g., on the Stroop task) has been reported with no or only brief assessments of attentional effort (Bögels, Hoogstad, van Dun, de Schutter, & Restifo, 2008; Wenk-Sormaz, 2005). One study that is frequently cited as support for the beneficial attentional effects of meditation found improvements in sustained attention after short-term meditation, but the authors noted that "many controls" complained about "how boring" the task was (Valentine & Sweet, 1999, p. 66) and considered this a possible explanation for their findings. Another frequently cited study found improved attentional orienting after MBSR, indexed by faster RTs in a spatial cuing paradigm (Jha, Krompinger, & Baime, 2007), but this study did not consider attentional effort. However, Fan & Posner (2004), cocreators of the applied paradigm, acknowledged: "It is also possible that *increased effort* may facilitate more efficient use of the peripheral cue, [which] could indicate improved orienting" (p. S212, italics added). Accordingly, the MBSR participants in Jha et al. (2007) may have simply "tried harder" during the second test session. Semple (2010) reported enhanced vigilance after MBSR but also did not consider attentional effort during the postintervention test. In a cross-sectional study using functional neuroimaging, Farb et al. (2007) found increased deactivation in midline cortical areas in MBSR patients compared with wait-list controls when asked to sustain moment-to-moment awareness. The authors suggested that MBSR had improved this ability by strengthening midline cortical suppression. However, studies have shown that task effort alone can suppress activity in regions representing nontarget features (O'Connor, Fukui, Pinsk, & Kastner, 2002; Shulman et al., 1997). Farb et al. assessed the perceived ease or ability to sustain focus on the present moment but not the motivation to do so, or general task effort. The importance of controlling for test effort in attentional research was further accentuated by an imaging study comparing meditators with two groups of novices, one of which was offered a monetary reward. This modest cognitive incentive resulted in significantly higher blood flow in almost every attention-related region of interest in the incentive controls compared with the nonincentive controls (Brefczynski-Lewis et al., 2007).

An important part of the present study was to investigate whether response speed variability would be more resistant than raw RTs to effects of attentional effort, and thus recommendable for future studies. We chose the coefficient of variation (CV) of the raw RTs (defined as the *SD* of RT/mean RT) as our measure of response speed variability. Cognitive meditation studies often focus on response speed and accuracy, whereas mainstream cognitive researchers have discussed the advantages of assessing response speed variability for a century (Vanbreukelen et al., 1995). In a large study of healthy adults using several attentional tests, only the CV-based outcomes proved to be "virtually unaffected by practice effects" (Flehmig, Steinborn, Langner, Anja, & Westhoff, 2007, p. 141). The CVs on a range of attentional tests were better predictors of school performance in children than were mean RT and *SD*s (Steinborn, Flehmig, Westhoff, & Langner, 2008) and were proposed as an indicator of overall vigilance performance (Dockree et al., 2006). Variability measures are also more useful indicators of attentional function in cognitive impairment (Flehmig et al., 2007). Thus, the CV was also hypothesized to be more ecologically valid than simple RTs.

Another Achilles' heel in MBSR research has been designing control interventions that can effectively disentangle the mechanisms of change. Ideally, the control intervention should "filter out" prespecified factors and thus promote an understanding of the "active ingredient" in MBSR (Chiesa & Serretti, 2009, p. 598). However, non-MBSR activities may enhance mindfulness (Hayes & Shenk, 2004), and stress reduction itself generally improves attention (Chajut & Algom, 2003). Thus, it is important to clearly define the elements of MBSR being tested.

The Present Study

In light of the issues just described, we tested effects of MBSR on attention in meditation novices in a blinded, randomized trial. We compared four groups: (1) MBSR, (2) an active control group receiving a nonmindfulness stress reduction (NMSR) course, (3) an inactive group receiving an incentive, and (4) a nonmanipulated inactive group. Pre- and postintervention, participants completed five validated tests of attention, as well as questionnaires on mindfulness and perceived stress, and we assessed saliva cortisol levels in response to awakening. To our knowledge, no previous study of attentional effects of MBSR has used a similar design.

Leading researchers have predicted improved sustained attention, selective attention, and attentional set shifts after mindfulness training "which can be measured using standard vigilance tests" (Bishop et al., 2004, p. 232). In accordance with this operational definition of mindfulness and the preliminary, experimental MBSR literature, we hypothesized that MBSR would improve vigilance. We included two vigilance paradigms: one based on sustained *dual attention,* including a set-shifting task, and one based on sustained *selective attention*. To test selective attention, we also included a Stroop paradigm, as proposed by Bishop et al. (2004). Because returning attention to the present moment is a cardinal part of MBSR (Kabat-Zinn, 1990) and most meditational practices (Lutz et al., 2008), we also considered it relevant to include a *temporal attention* paradigm to assess this skill. Finally, we considered it important both theoretically and empirically to include a test of *visual attention*. On the basis of phenomenological reports, historical texts, and a few empirical studies, we hypothesized that MBSR would result in unique decreases in the perceptual threshold. We also expected that performance on a perceptual task that is not based on RTs would be less likely to be confounded by attentional effort (see the Instruments and Outcomes section for a detailed account of the choice of tests and more specific predictions).

We provide consistent evidence across several tasks that previously reported attentional improvements after MBSR (especially results based on RTs or task speed) may be seriously confounded by attentional effort as well as general stress reduction. Thus, these previous results may be caused by factors such as increased performance pressure or nonspecific stress reduction rather than by mindfulness training per se. Although this is our main conclusion, we also found that only MBSR led to improvements in the perceptual threshold and a measure of sustained, selective attention. These are the first findings on attentional improvements after MBSR that cannot be ascribed to NMSR or attentional effort. Primarily, however, we argue for methodological refinements of study design and choice of attentional measures in order to improve the validity of future investigations of the mechanisms of change in MBSR.

Method

Participants and Procedures

The Danish Ethics Committee approved the applied protocols (#21161 and KF 01 2006-20). Participants were recruited through oral presentations and posters at the Department of Psychology, University of Copenhagen, and all provided informed consent before the study. Controls were paid $250, and incentive controls an additional $50. To ensure honest completion of the practice diaries, intervention participants were paid $850, disregarding their compliance.

Participants and compliance. Figure 1 illustrates the participant flow. After 2 weeks, inclusion was closed and screening for age, health, and experience with meditation and yoga resulted in 60 eligible persons. All eligible men ($n = 18$) were included, and the inclusion of 30 women was randomized. The remaining 12 women were put on a wait list, and three were randomly selected for baseline testing. Three groups (each $n = 16$)—balanced for age, sex, marital status, education, and perceived stress—completed ECTS[1] points during the semester, and all five subscales on the NEO Personality Inventory—Revised (Costa & McCrae, 1992) were created and randomly assigned to one of the following groups: collapsed inactive controls (CICO), NMSR, or MBSR. One MBSR participant was hospitalized after 8 days, so a random participant was included from the baseline-tested wait list. After 22 days, one person from NMSR left the study due to illness, but no replacement was included this late in the study.

In total, 49 participants were included, and 47 (66% women) 20–36 years of age completed the study. The majority (94%) were university students (mean education = 15 years) taking exams corresponding to a full semester (29 ± 6 ECTS). All were physically and psychologically healthy as evaluated on the Symptom Checklist-90—Revised (Derogatis, 1977) and a screening questionnaire (70 items) used at the Copenhagen University Hospital. All reported to be meditation and yoga novices on a brief questionnaire and when interviewed.

CICO was randomly split before the posttest by one of the authors (Steen G. Hasselbalch). *Incentive controls* (INCO; $n = 8$) were offered a financial bonus of $50 if they could "improve" (not defined to them) compared with baseline. One researcher (Christian G. Jensen) carried out all tests blinded to participants' group status within 3 weeks prior to and 2 weeks after the interventions.

Compliance was monitored through diaries in which daily home (formal and informal) practices and course attendance were noted. Compliance was considered satisfactory. MBSR participants attended 7.6 ± 0.8 courses (NMSR: 7.0 ± 0.8), including the retreat, and practiced 35 ± 7 times formally (NMSR: 30 ± 9) and 32 ± 12 times informally (NMSR: 31 ± 14).

Intervention programs.

MBSR. The detailed methodology of MBSR has been described elsewhere (Kabat-Zinn, 1990, 1994). A standard MBSR program was implemented by a licensed psychologist and experienced mindfulness instructor. The program was designed as an 8-week course with one weekly meeting for 2.5 hr to develop mindfulness skills and talk about stress and coping. "Formal" home assignments (45 min/day) following CDs with guided meditation practices—as well as "informal" (15 min/day) assignments to be carried out during other, daily activities—were given every week to support training outside the courses. An intensive retreat (7 hr) was held during the sixth week. The three most central exercises in MBSR are the body scan, the sitting meditation, and hatha yoga postures. During the body scan, participants are lying

[1] European Credit Transfer and Accumulation System.

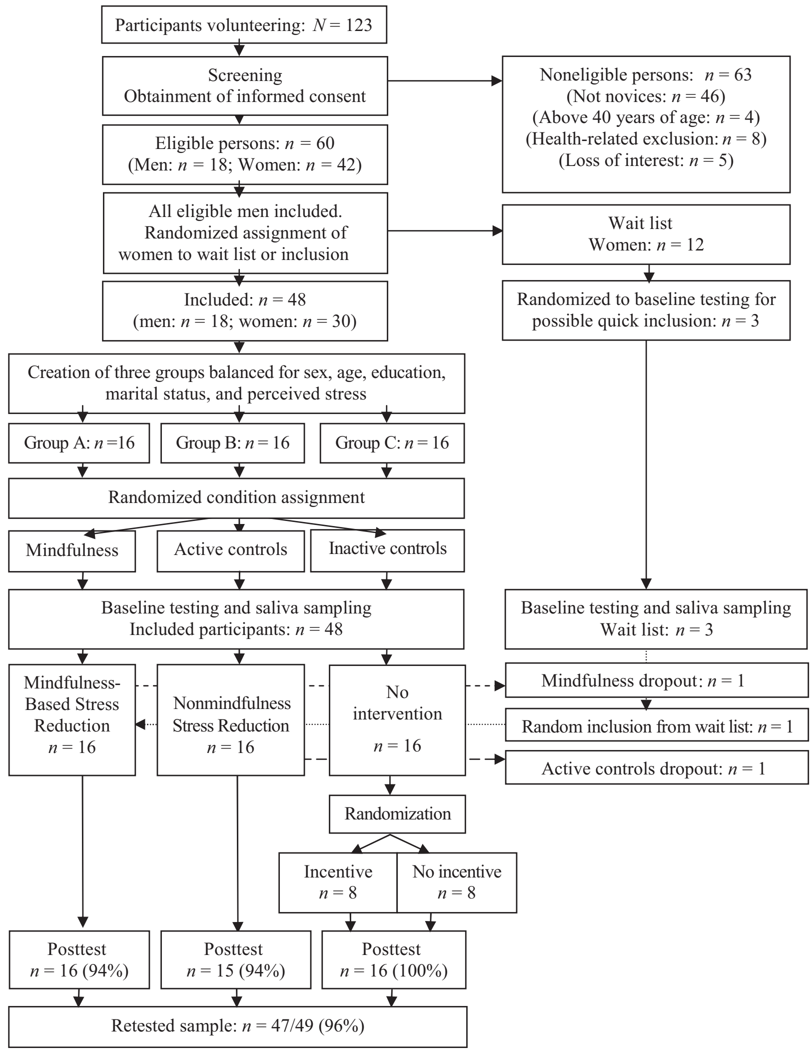

Figure 1. Participant flow throughout the study.

down with eyes closed, carefully observing areas of the body, just noticing how they feel moment by moment with a nonjudgmental attitude. Instructions are open and generally without suggestions (e.g., "Notice how your legs are in this moment—whether they are heavy or light. Just notice how they are, and let it be okay"). Likewise, breath exercises and hatha yoga train mindfulness in part through continued, nonjudgmental noticing of bodily sensations. In sitting meditation, participants are encouraged to observe and be curious about their thoughts as they wander—but crucially not to judge them as "good" or "bad." Thus, an essential goal is a renewed relation to the total life experience, incorporating a nonjudgmental attitude toward all things, beings, thoughts, and emotions. Awareness of the transiency of all things is aimed for to improve the central ability to "let go" of, for example, painful thoughts and emotions. This presumably reduces tendencies to ruminate and eases the nonjudgmental returning of awareness to the present moment, a cardinal skill developed specifically in MBSR.

NMSR. We decided to focus our investigation on two central MBSR elements: meditation and training in a nonjudgmental attitude. Accordingly, the NMSR control intervention was designed to resemble MBSR but did not include (a) meditation practices or (b) training in a nonjudgmental attitude. The NMSR course was implemented by an authorized psychomotrician. The course took place in the same physical room as the MBSR course and was structurally similar to it, including one weekly meeting for 2.5 hr, equal amounts of formal (also following a CD) and informal home assignments, and an identical practice diary. This was meant to "filter out" nonspecific effects of stress reduction, contact with an instructor, and social support. Guided relaxations, during which participants were lying down with their eyes closed, were carried out, but instructions were deliberately based on suggestions, such as "Feel your legs resting against the floor. Now imagine how the muscles in your calves are relaxing. Feel how the lower legs are becoming heavier as they are getting more and more relaxed." This is contrary to MBSR, in which the guided instructions are far more open and generally nonsuggestive (see previous paragraph). Therefore, NMSR did not train the nonjudgmental attitude through accepting whatever bodily sensations were experienced or through psychoeducation on the presumed value of this attitude. Each course also included yoga, grounding exercises, and 20 min of circulatory training. A central strategy was to increase participants' body consciousness, helping them to become aware of ways to relax during stress.

Instruments and Outcomes

Five attentional tasks were presented in randomized order. Computerized tasks were presented in E-Prime (Version 1.2; Psychology Software Tools, Pittsburgh, PA) using stationary IBM computers (1.3 GHz, 1GB RAM) with 20-in. CRT screens (refresh rate 100 Hz) seen at a distance of approximately 60 cm. Rooms were semidarkened and situated in a designated, experimental area. A test session lasted 2 hr including a 10-min break between each task.

Dual attention to response task (DART; Dockree et al., 2006). DART was developed from an established vigilance test, the Sustained Attention to Response Task (Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), by including a continuous performance task to increase the sensitivity in healthy adults. Both tests have been found to correlate with self-reported everyday attentional failures. In an operational definition of mindfulness, leading researchers predicted improved vigilance and attentional set shifts after mindfulness training. DART provides measures of both set shifts and vigilance. Thus, we predicted that MBSR would improve overall DART performance and set-shifting RTs.

Accordingly, there were two DART outcomes. The first was *RT CV for white digits* (white digits *SD*/white digits mean RT), proposed as an indicator of overall DART performance (Dockree et al., 2006). To test the validity of this proposal, we examined bivariate correlations between the white-digit CV and commission errors, premature presses, and reaction omissions, respectively. The second was *RTs on gray digits*, a measure of attentional switching (Dockree et al., 2006). To further test the resistance of CV-based outcomes to attentional effort, we also analyzed the gray-digit RTs after transforming them into a *gray-digit CV*.

In the version applied, white and gray digits from 1 through 9 were presented sequentially in 28 cycles, including three practice cycles. Participants were instructed to monitor the digit color, pressing *1* after white digits and *2* after gray digits but to always withhold the response after the digit *3*. Digits were presented for 150 ms above a fixation cross on a light gray background. Of the 225 test digits, 10 were gray. The interstimulus interval was either 1,000 ms or 1,500 ms, yielding a duration of 1,400 ms from digit onset to digit onset. Participants pressed *1* with their favored index finger (right in all cases) and *2* with the middle finger of the same hand. The task lasted 6 min.

Spatial and temporal attention network (STAN; Coull & Nobre (1998). The STAN task expands on the widely used spatial orienting tasks (see e.g., Posner, Snyder, & Davidson, 1980), incorporating research on temporal orienting (Correa, Lupiáñez, Madrid, & Tudela, 2006). It has been validated for use in healthy adults (see Coull, 2009). Temporal orienting relies on an established (see e.g., Posner & Petersen, 1990) left-lateralized frontoparietal network and is recruited "particularly [when] directing attention toward a particular moment in time" (Coull & Nobre, 1998, p. 7434). Because returning attention to the present moment is a cardinal part of MBSR training (Kabat-Zinn, 1990), STAN was considered a theoretically relevant test. We chose two primary, RT-based outcomes. The first was *RTs after invalidly cued, short temporal trials*. In these trials, the temporal cue indicated a long (1,500 ms) cue–target interval (CTI), but in fact the target appeared after a short (750 ms) CTI. Thus, these RTs indicated how quickly a participant was able to return attention to the present moment and react at an unexpected point in time. Our second, primary outcome was *RTs after uninformative cues* (neutral cues), measuring the ability to stay alert in the absence of external temporal information and again orient attention to the moment when the target suddenly appeared. To further examine the resistance of CV-based outcomes to attentional effort, we also transformed and analyzed our second outcome to a *neutral trials CV*. The functionality of the task was corroborated by examining, across groups, the disadvantage of invalid cues compared with neutral cues, and the advantage of valid cues compared with neutral cues and invalid cues, respectively.

Each trial displayed a central cue (100 ms) and two peripheral boxes, inside one of which a target (× or +) appeared for 50 ms (see Figure 2). Participants were instructed to focus on the fixation cross, covertly detect the targets, and react as fast as possible by pressing a button with their favored index finger (right in all cases). Targets were preceded by either spatial cues predicting target location (left or right); temporal cues predicting the CTI (750/1,500 ms; also referred to as "short" or "long" trials); or neutral, uninformative cues. Spatial and temporal cues were either valid (80% of trials, indicating the correct location or CTI) or invalid (indicating the opposite location or CTI). Participants were informed that cues were "likely" to be valid. One practice block of each condition (spatial, temporal, or neutral) preceded the experimental task consisting of nine blocks (of 40 trials each): three temporal, three spatial, and three neutral, in that order. The total task duration was 12 min 45 s. The data were filtered using cutoff points at 100 ms and 750 ms. No outliers were removed. We analyzed only the 750-ms temporal trials, because the 1,500-ms temporal trials were confounded by mounting expectations (Coull, 2009; Coull & Nobre, 1998; Nobre, 2001) and motor preparation (Coull, Frith, Büchel, & Nobre, 2000).

Stroop color–word task (Stroop, 1935). This task is widely used as a reliable test of selective attention and of cognitive flexibility and control (MacLeod, 1991, 2005). These factors are presumably affected by mindfulness training, leading Bishop et al. (2004) to specifically propose Stroop as a relevant paradigm in an operational definition. Benefits on the Stroop test after short-term (Wenk-Sormaz, 2005) and long-term (Moore & Malinowski, 2009) meditation have been found, but other studies have found no effects of short-term mindfulness training (Alexander, Langner, Newman, Chandler, & Davies, 1989; Anderson, Lau, Segal, & Bishop, 2007). In addition, attentional effort has consistently been demonstrated as a prominent factor in Stroop (Chajut & Algom, 2003; Huguet, Dumas, & Monteil, 2004; Huguet, Galvaing, Monteil, & Dumas, 1999; MacKinnon, Geiselman, & Woodward, 1985). On the basis of this literature, we hypothesized that attentional effort would be an important factor in Stroop. Thus, both theoretically and empirically the Stroop test was important to investigate.

We presented two blocks of 100 color words (*red, blue, yellow,* or *green*) printed in red, blue, yellow, or green ink (font: Times New Roman; height: 0.4 cm) and arranged in a 10 × 10 word matrix on two separate pieces of paper with a small space in between. The first block presented "congruent" color words (e.g.,

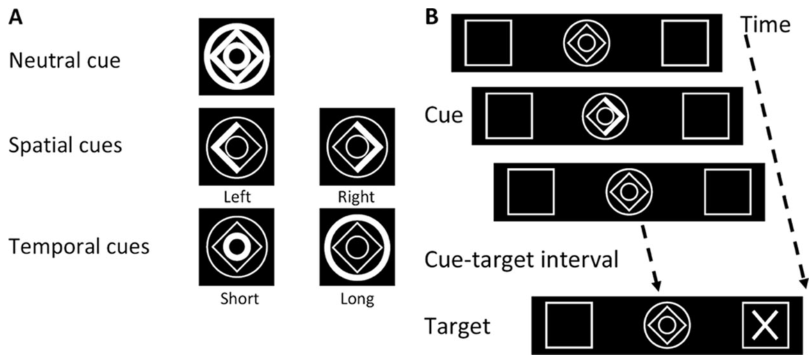

Figure 2. A: Cue types used in the spatial and temporal attention network task to direct attention to a particular location or stimulus-onset time. The neutral cue does not provide spatial or temporal information. Spatial cues direct attention to the left or right. Temporal cues direct attention to a short or long cue–target interval (CTI). B: A valid spatial trial, directing the participant's attention to the right location, with no information about the CTI. Adapted from "Where and When to Pay Attention: The Neural Systems for Directing Attention to Spatial Locations and to Time Intervals as Revealed by Both PET and fMRI," by J. T. Coull and A. C. Nobre, 1998, *Journal of Neuroscience, 18,* p. 7427. Copyright 1998 by the Society for Neuroscience.

red in red ink), whereas the second block presented "incongruent" words (e.g., *red* in green ink). Instructions were to state the ink color as fast as possible while avoiding mistakes. Naming errors were allowed to be corrected. Block completion time was measured in seconds with a handheld stopwatch and naming errors noted on a response sheet. Because effects on response speed are hard to discover in healthy adults on Stroop due to floor effects (MacLeod, 2005), and because MBSR was primarily hypothesized to change the inhibition process (Bishop et al., 2004), our outcome for group comparisons was the *incongruent block error rate*. Block RTs (in s) and the Stroop interference effect (the difference between incongruent and congruent block RTs) were examined across and within groups in secondary analyses to confirm the task functionality (see supplemental materials, Table I).

The d2 Test of Attention (Brickenkamp, 2002; Brickenkamp & Zillmer, 1998). The d2 Test of Attention is a paper-and-pencil cancelation task measuring sustained and selective attention. The test was chosen because these abilities were again predicted to be positively affected by mindfulness training (Bishop et al., 2004), and d2 performance was superior in experienced meditators compared with controls (Moore & Malinowski, 2009). The psychometric properties of the test have been well supported (Bates & Lemay, 2004).

The d2 sheet contains 14 lines of letters, and the task is to cross out *d*s with two dashes, which are interspaced with distractors. The time limit for each line is 20 s. Again, because MBSR has been predicted to improve selective attention by leading researchers (Bishop et al., 2004), for our group comparisons we chose three outcomes hypothesized to be the most sensitive in this young, healthy sample. They each measured one of the following error performances: (1) the *total error rate* (E; commissions and omissions); (2) the *error percentage* (E%, calculated as E/TN $\times$ 100, where TN represents the total number of processed items); and, following the d2 manual, (3) the *error distribution* (ED), defined as the error sums for three test sections (lines 1–5, lines 5–10, and lines 11–14). Pre–post results for TN and also TN adjusted for errors (TN $-$ E) are provided in Table I of the supplemental materials. The *concentration performance* measure (Bates & Lemay, 2004) was irrelevant due to too few incorrectly canceled items.

The CombiTVA paradigm. The theory of visual attention (TVA; Bundesen, 1990) is a computational theory that accounts for behavioural and neurophysiological attentional effects and provides an ideal framework for investigating and quantifying attentional performance. In contrast to most computerized attention tests using RTs, TVA-based testing employs unspeeded, accuracy-based measures of basic visual perception and attention unconfounded by motor components. We considered the CombiTVA paradigm, which combines both whole and partial reports, an important test to include both theoretically and empirically. First, phenomenological reports and historical texts indicate that meditative training changes and improves especially attention and visual perception (D. P. Brown, 1977). Early studies also found perceptual alterations with more meditative experience (D. P. Brown & Engler, 1980), improved the perceptual threshold and discriminatory ability for visual flashes after an intensive mindfulness retreat (D. Brown, Forte, & Dysart, 1984), and improved visual perception after just 2 weeks of transcendental meditation training (Dilbeck, 1982). In a recent review of this field, Bushell (2009) argued that Buddhist meditation practices should facilitate near-threshold perception in the visual domain, and a study of experienced meditators showed improved ability to detect target stimuli presented in rapid succession (attentional blink task) after an intensive retreat (Slagter, 2007, Slagter et al., 2009). Thus, we were particularly interested in the possibility of separating effects on the visual threshold for conscious perception and the speed of information processing (see later). Finally, we also expected this accuracy-based measure to be less sensitive to attentional effort, given that task does not require speeded motor responses involving cortical motor areas. We hypothesized that MBSR would result in unique improvements of the perceptual threshold, because this was assumed to be affected primarily by meditation, which was not included in NMSR.

TVA-based testing has previously been shown to be a highly sensitive tool for quantifying separate functional components of visual attention in healthy participants (see e.g., Finke et al., 2005). The *CombiTVA* paradigm (see Vangkilde, Bundesen, & Coull, 2011) employed is a combination of two classical attention paradigms (whole and partial report; see Sperling, 1960, and Shibuya & Bundesen, 1988). The test comprised one practice block of 24 trials and nine test blocks of 36 trials and took 40 min to complete. Trials were initiated by a red fixation cross in the middle of a black screen, succeeded by a 100-ms blank screen before the stimulus display with six possible locations was presented on an imaginary circle (r = 7.5 degrees of visual angle) centered on the fixation cross. After a variable stimulus duration, the display was masked by a 500-ms mask display made from red and blue letter fragments. Then the screen turned black, and the participant could type in the letter(s) that he or she had seen. In whole report trials, either two or six red target letters were presented, whereas partial report trials contained two red target letters and four blue distractor letters. Displays with six target letters were shown for each of six stimulus durations (10, 20, 50, 80, 140, or 200 ms), whereas all other displays were shown for 80 ms. All trial types were intermixed, and the letters were chosen randomly without replacement from a set of 20 letters (ABDEFGHJKLMNOPRSTVXZ) in the font Ariel broad with a point size of 68. Participants were to make an unspeeded report of all red letters they were "fairly certain" of having seen (e.g., to use all available information but refrain from pure guessing).

The number of correctly reported letters in each trial constituted the main dependent variable. The performance of the participants was computationally modeled using a maximum likelihood fitting procedure (for details see Kyllingsbæk, 2006, and Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011) to derive estimates of four attentional parameters. First is t_0, the threshold of conscious perception, defined as the longest ineffective exposure duration measured in milliseconds below which the participant has not consciously perceived, and therefore cannot report, any letters. Because this value is estimated from performance, the perceptual threshold need not be exactly at any of the presented stimulus exposure durations. Second is K, the maximum capacity of visual working memory measured in number of letters. Third is C, the speed of visual processing measured in letters processed per second. Fourth is alpha, the top-down controlled selectivity, defined as the ratio between the attentional weight of a target and the attentional weight of a distractor. The alpha value is estimated by comparing performance in the partial report trials with performance in the two-target whole report trials. A participant with perfect selection should be unaffected by distractors and thus report the same number of targets regardless of the number of distractors. Efficient attentional selection is indicated by α values close to 0, whereas α values close to 1 indicate no prioritizing of targets compared with distractors.

Physiological Stress, Self-Report, and Compliance

Saliva cortisol sampling. Physiological stress was characterized by cortisol secretion in response to awakening, a valid indicator of the hypothalamic–pituitary–adrenal (HPA) axis activity (Pruessner et al., 1997). Noninvasive, minimally stressing cotton swab sampling following written instructions was performed at home after a practice sampling prior to the sampling day. Five samples were taken: Sample 1 upon awakening, and Samples 2–5 every 15 min for the subsequent hour. Participants registered the exact time of awakening and of each sampling and stored the samples in glass tubes below 5 degrees Celsius. Within 48 hr, samples were received and stored at −80 degrees Celsius. The entire batch was analyzed in one step using electrochemiluminescens immunoassay on Cobas equipment (Roche, Mannheim, Germany). Using principal component analyses, Fekedulegn et al. (2007) demonstrated that saliva cortisol outcomes fall in two categories relating primarily to either the magnitude of the secretion or the pattern of the secretion over time. Following Fekedulegn et al., we calculated *area under the curve with respect to ground* (AUC_G), representing the total magnitude of cortisol secretion, and *area under the curve with respect to increase from awakening* (AUC_I). Higher AUC_I values denote a more reactive or less stable HPA system. Both outcomes were supported as valid, always showing significant correlations with two or three of their highest loading factors (Fekedulegn et al., 2007, Table 5).

Self-reported mindfulness and stress. The Mindfulness Attention and Awareness Scale (MAAS; K. W. Brown & Ryan, 2003) is often used in MBSR research and has been demonstrated to yield a reliable measure of mindfulness level. As a single-factor measure, the MAAS does not capture facets of mindfulness but was chosen as a phenomenological counterpart to the behavioral tests because it focuses on everyday experiences of attentional functions. Perceived stress was evaluated with Cohen's Perceived Stress Scale (PSS; Cohen & Williamson, 1988), one of the more widely used scales for indexing perceived stress during the past 14 days. Cronbach's α for MAAS and PSS in the present study was always .85–.90. Both scales were completed in Danish. The PSS was a back-translated version approved by Cohen (see Olsen, Mortensen, & Bech, 2004). The MAAS was a professionally translated version that has now been slightly edited, back-translated, and approved by K. W. Brown. Questionnaires on health and history of illnesses, lifestyle, psychiatric symptoms, and personality were also completed, but results are not reported here.

The influence of MBSR compliance. As an exploration, we tested correlations between attentional change scores (Time 2 [T2] score – T1 score) and each of four compliance variables (number of courses attended, number of formal home practices, number of informal home practices, and total activity, which equaled the sum of the first three variables), as well as correlations between compliance variables and change scores for cortisol secretion and self-report.

Data Analyses

On attentional tests, group differences at baseline (T1) and posttreatment (T2) were tested in three to four nonorthogonal comparisons. First, MBSR was compared with *nonincentive controls* (NOCO) and INCO, respectively. If this did not yield significant group differences, the inactive controls were collapsed into one group (CICO), and MBSR was compared with this inactive control group representing an intermediate level of increased attentional effort. Finally, MBSR was compared with NMSR. Although orthogonal comparisons are preferable, they are no longer considered as crucial as once was the case (Howell, 2007). Furthermore, considering the lack of previous studies using a similarly rigorous design, the possibility of detecting new systematic group effects was prioritized. On self-report scales and cortisol levels, MBSR was compared with CICO (the inactive controls were always collapsed, because the financial incentive was unrelated to these data) and NMSR. "Corrected" p values were Bonferroni-corrected for the total number of tests carried out on the outcome (excluding explicitly termed "post hoc" tests). Conducting Bonferroni corrections for the total number of tests in settings where dependent variables are related (as many attentional outcomes are) is often considered too conservative a strategy (see e.g., Nakagawa, 2004). Time × Group interactions for single outcomes were evaluated in mixed model analyses of variance (ANOVAs) treating time (pre/post) as the within-subject variable and group as the between-subjects variable. On exploratory grounds, we tested bivariate correlations between change scores (T2 – T1) on MAAS and change scores on attentional parameters to probe whether increases in mindfulness were associated with attentional improvements. The use of change scores limits the influence of absolute T1 or T2 scores. Mediation analyses were deemed inappropriate due to the low sample size. Effect sizes relating to associations between variables were estimated with Pearson's r or R^2. Cohen's d was used for the between-group differences and pre–post effects and was adjusted for dependence among means (Morris & Deshon, 2002, formula 8). Effect sizes for Time × Group interactions were estimated with omega squared. Dropouts ($n = 2$) were excluded, but no other data were excluded from attentional tests or self-report scales. Different outlier criteria (e.g., >2.58 *SD*s, $p < .01$) changed these results only by a small and nonsignificant degree. We received 45 saliva sets pre and post. A few scores were not calculable due to incorrect sampling. The total data set from one MBSR participant was excluded, all cortisol values always being >3.0 *SD*s from the grand mean. Thus, 162 of 188 potential scores (86%; 47 × 2 times × 2 scores) were included. Statistical analyses were carried out in SPSS (Version 18.0), and effect sizes were calculated in Microsoft Excel 2007.

Results

Tasks

DART. The CV was supported as a valid indicator of DART performance. A higher CV (lower stability) was related to more omission errors and more premature presses at both time points (rs = .38 – .60, ps < .04 [corrected]). A lower stability was not related to more commission errors at T1 ($r = .22$, $p > .1$), but this expected finding was present at T2 ($r = .38$, $p = .03$ [corrected]). Baseline correlations between white-digit RTs and the corresponding CV ($\rho = -.20$, $p > .17$) and between gray-digit RTs and the gray-digit CV ($\rho = .17$, $p > .27$) were nonsignificant. This supported the relative independence of the CV from RTs. MBSR did not differ from any other group at baseline on the DART outcomes (ps ≥ .12). Posttreatment, MBSR showed slower RTs on gray digits compared with those for INCO ($p < .05$, $d = 0.87$). Other RT analyses showed no group differences at T2 (ps > .15). Concerning RT stability, MBSR demonstrated more stable RTs on white digits (a lower CV) than did NOCO at T2, $t(22) = 2.10$, $p < .05$, $d = 0.95$. As INCO descriptively decreased their RT stability from pre–post ($d = -0.26$), while MBSR descriptively improved it ($d = 0.19$), it was supported that the higher stability in MBSR compared with NOCO at T2 was not due to increased attentional effort. NMSR, however, improved with a descriptively higher effect size than that for MBSR ($d = 0.68$; see supplemental materials, Table I). A post hoc t test revealed that NMSR was also more stable than NOCO at T2 ($p < .02$ [corrected], $d = 1.56$). Importantly, these results indicated that general stress reduction, rather than mindfulness training specifically, affected the CV.

In the pre–post analyses for gray-digit RTs, the Time × Group interaction was highly significant between MBSR and INCO, $F(1, 22) = 15.37$, $p < .01$ (corrected), $\omega^2 = .30$. This was driven by a remarkable improvement in INCO on this measure of attentional switching ($p = .02$ [corrected], $d = 1.44$), as well as a nonsignificant slowing in MBSR (see Figure 3, Panel A). T1 scores predicted T2 scores ($R^2 = .37$, $p < .001$), but the aforementioned Time × Group interaction was still significant in an analysis of covariance (ANCOVA) using T1 scores as a covariate ($p = .002$, $\omega^2 = .24$). An explorative mixed-model ANCOVA comparing all four groups supported that changes in gray-digit RTs differed between the groups, $F(3, 41) = 4.77$, $p = .006$, $\omega^2 = .14$. These important results indicated that the RT-based measure of attentional switching (gray-digit RT) was seriously confounded by attentional effort. Equally important, therefore, the gray-digit CV proved more resistant to effects of task effort (see supplemental

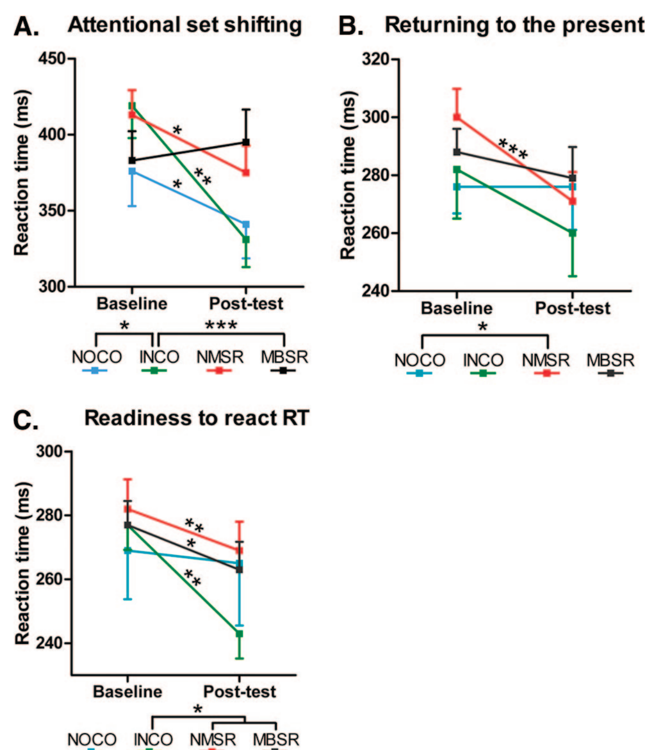

Figure 3. Attentional outcomes confounded by attentional effort. Time × Group interactions are indicated below each panel. A: Gray-digit trials in the dual attention to response task (DART), measuring the speed of task-switching processes. Incentive controls (INCO) improved significantly more than did mindfulness-based stress reduction (MBSR) participants. B: Invalidly cued, short temporal trials in the spatial and temporal attention network (STAN) task, measuring the ability to reorient attention to the present moment. Nonmindfulness stress reduction (NMSR) participants (but not MBSR participants) improved significantly, and significantly more than did nonincentive controls (NOCO). C: Mean reaction time (RT) across neutral trials using noninformative cues in STAN. INCO improved significantly more than did the intervention groups combined. * $p < .05$. ** $p < .01$. *** $p < .001$. p values are uncorrected for multiple comparisons. Error bars indicate one standard error of the mean.

materials, Figure S1). The data for the gray-digit CV was negatively skewed and therefore log-transformed, yielding normally distributed data. No pre–post group differences were significant ($ps > .12$), and MBSR did not at all differ from INCO or NMSR ($ps > .55$). Likewise, no groups improved on the gray-digit CV ($ps \geq .08$; the nonsignificant results were not due to the log-transformation, as seen from explorative analyses of the untransformed CV data). Other Time × Group interactions in DART yielded $ps > .1$. (In the supplemental materials, Table I displays descriptive results and within-group pre–post effects for DART, the Stroop color–word task, the CombiTVA test, and the d2 test, and Table III displays all significant Time × Group interactions.)

STAN. Overall, the STAN paradigm functioned as expected. Valid cues speeded up RTs compared with neutral cues and invalid cues, respectively, whereas invalid cues slowed RTs compared with neutral cues ($ps \leq .003$). As found in DART, the CV of RTs on neutral trials was supported as independent of the raw RTs, because these outcomes were not at all related ($\rho = .02$, $p > .9$). Group differences at T1 as well as T2 were nonsignificant ($ps > .26$). Likewise, pre–post changes in MBSR were not significantly different from those in any other group ($ps \geq .15$). Furthermore, when we examined the within-group changes on the central condition measuring the ability to reorient attention to the present moment (temporally invalidly cued trials), we found that MBSR did not improve ($p > .3$, $d = 0.29$), whereas NMSR did ($p < .01$ [corrected], $d = 1.09$). A post hoc test even showed that NMSR improved significantly more than did NOCO, $F(1.21) = 5.28$, $p = .03$, $\omega^2 = .13$. INCO did not improve significantly and showed a lower pre–post effect size ($p > .13$, $d = 0.61$). Once again, these results demonstrate the importance of active control interventions in attentional short-term meditation studies.

On the noninformative (neutrally cued) trials measuring the ability to stay vigilant in the absence of information, changes in MBSR were not different from those in any other group ($ps > .06$). In fact, the only pre–post group difference approaching significance was found when comparing MBSR with INCO, and this test indicated that the financial incentive nearly resulted in significantly larger improvements than in the MBSR intervention (ANCOVA adjusting for baseline), $F(1, 21) = 3.91$, $p = .061$, $\omega^2 = .07$. A post hoc ANCOVA comparing INCO with the collapsed stress reduction groups showed that the incentive did improve neutral RTs significantly more than did stress reduction in general, $F(1, 39) = 6.41$, $p = .016$, $\omega^2 = .05$. Within groups, MBSR did improve ($p = .04$, $d = 0.57$) descriptively more than did NOCO ($p > .6$, $d = 0.21$), but NMSR ($p < .01$, $d = 0.91$) and especially INCO ($p < .01$, $d = 1.56$) improved to an even larger effect than did MBSR. These large effect sizes on the neutral trials again emphasize the importance of incentive and active control groups in RT-based tasks measuring the ability to remain vigilant and react to sudden target stimuli.

The CV results measuring the stability of RTs on neutral trials were quite different from the simple RT-based results. First, no groups improved their CV ($ps \geq .15$). Second, pre–post group differences were not approaching significance ($ps > .24$). These results again supported the resistance of the CV to attentional effort and practice effects (see supplemental materials, Figure S2), as we also found for the gray-digit CV in DART. This important methodological point should be of interest to all fields of attentional research.

Stroop color–word task. The interference effect was robust, because incongruent blocks slowed completion times at both test sessions ($ps < .0001$, $ds > 4.0$). MBSR did not differ from any group at baseline ($ps \geq .37$). Posttreatment, MBSR made fewer errors on incongruent blocks than did NOCO ($p = .04$, $d = 1.00$). However, a post hoc test showed that INCO now also committed fewer errors than did NOCO ($p < .04$, $d = 1.15$; baseline $p = .25$). Pre–post changes did not differ between the groups ($ps > .7$). Within groups, INCO showed the largest pre–post response speed effect size on both the congruent block ($p < .05$, $d = 0.92$) and the incongruent block ($p < .05$, $d = 1.21$; see supplemental materials, Table I). In summary, our Stroop results indicated that Stroop performance was confounded by attentional effort on both the incongruent error rate and the task speed. MBSR did not produce unique effects on this measure of selective attention.

The d2 Test of Attention. Groups did not differ on d2 outcomes at T1 ($ps \geq .37$). At T2, the error distribution, ED, in MBSR differed from that in CICO ($p = .02$ [corrected], $\omega^2 = .11$), NMSR ($p = .052$ [Greenhouse-Geisser-, then Bonferroni-corrected], $\omega^2 = .11$), NOCO ($p < .03$ [corrected], $\omega^2 = .13$), and INCO ($p = .050$, $\omega^2 = .08$), respectively. A post hoc, overall comparison supported ED differences between the four groups, $F(6, 84) = 2.30$, $p = .052$ (Greenhouse-Geisser corrected), $\omega^2 = .08$. These Group × Section interactions were clearly interpretable (see Figure 4, Panel A). Whereas NOCO, INCO, and NMSR increased the error rate from the first to the second section ($ps \leq .02$) and decreased from the second to the third ($ps \leq .05$), MBSR did not change between any sections ($ps \geq .32$). Importantly, the increase in errors during the middle section was present in all groups at T1 ($ps \leq .04$), and it was even especially pronounced in MBSR ($p < .01$). The middle increase in ED is dependent on the number of lines per test section (4, 6, and 4, respectively), so in order to better interpret the ED findings, we also examined the errors per line (EL) within-group for each section. Whereas all other groups descriptively increased their EL during the middle section ($ps = .07$–$.10$), suggesting a tiring effect, MBSR descriptively decreased ($p = .07$). Other group contrasts at T2 yielded $ps > .1$. Pre–post changes in the ED differed significantly between MBSR and NOCO ($p = .050$), MBSR and CICO ($p = .051$), MBSR and NMSR ($p < .01$ [corrected]) but not between MBSR and INCO ($p > .3$). Other changes did not differ significantly between groups ($ps \geq .1$). However, only MBSR improved significantly on the total error rate, E ($p = .01$ [corrected], $d = 0.93$). Tests of E changes within other groups yielded $ps > .3$. NMSR improved the error percentage, E% ($p = .04$, $d = 0.62$), but only MBSR improved after Bonferroni-correction ($p < .01$ [corrected], $d = 1.14$). In summary, MBSR showed improvements on all measures of error performance in the d2 test, suggesting that meditation training and training in a nonjudgmental attitude improved selective attention to a degree that was not achieved by stress reduction or attentional effort alone.

The CombiTVA paradigm. Parameters C and K have often been found to be positively correlated in normal samples (see e.g., Finke et al., 2005), reflecting faster processing in participants with larger visual working memory capacities. This was replicated at T1 and T2 ($rs = .70$–$.77$, $ps < .001$). All other parameters were unrelated ($ps \geq .08$). Groups did not differ on any parameters at T1 or T2 (all $ps > .12$; (see descriptives in supplemental material, Table I).

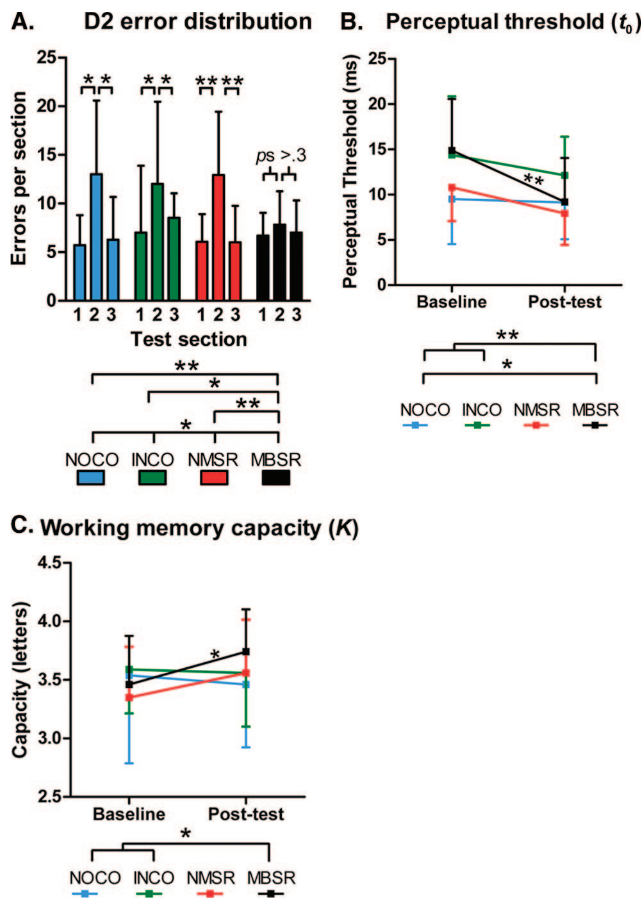

Figure 4. Attentional measures affected especially by mindfulness-based stress reduction (MBSR). Section × Group interactions (see Panel A) or Time × Group interactions (Panels B and C) are indicated below the figures. A: Sectionwise distribution of errors in the d2 Test of Attention. MBSR participants did not show a significant increase in errors during the middle test section. B: Pre–post changes in the perceptual threshold (t_0) in the theory of visual attention-based task (CombiTVA). Only MBSR participants improved significantly, and this represented a significantly larger improvement than in the inactive controls. C: Pre–post changes in visual working memory capacity (K) in the CombiTVA task. MBSR improved significantly more than did collapsed inactive controls (CICO). Nonmindfulness stress reduction NMSR), but not attentional effort, was a confounding factor. Error bars indicate one standard error of the mean. NOCO = nonincentive controls; INCO = incentive controls.

Pre–post, however, MBSR showed a marked improvement in the threshold of conscious perception, $t_{0,}$ which was effectively unchanged in NOCO, yielding a significant Time × Group interaction, $F(1, 22) = 7.31$, $p < .05$ (corrected), $\omega^2 = .16$ (see Figure 4, Panel B). This was also significant compared with CICO, in which half of the participants were motivated, $F(1, 30) = 6.85$, $p = .014$ (Bonferroni-corrected $p = .056$), but not compared with INCO or NMSR ($ps > .15$). T1 scores were predictive of T2 scores ($R^2 = .69$, $p < .001$). Thus, T1 score was used as a covariate in two ANCOVAs. The Time × Group interaction in MBSR versus NOCO remained significant ($p < .04$, $\omega^2 = .04$), though with unequal variances (Levene's $p = .012$). However, the Time × Group interaction in MBSR versus CICO also remained significant ($p < .02$), variances were equal ($p = .09$), and the effect size was slightly increased ($\omega^2 = .05$). This refuted the idea that the larger improvements in MBSR compared with inactive controls could be explained by baseline differences, and the increased effect size when including the incentive controls supported that attentional effort was not confounding these results. Within groups, only MBSR improved significantly on t_0 ($p = .02$ [corrected]), whereas other groups' pre–post tests yielded $ps > .1$. This MBSR effect size was descriptively twice as large as in any other group (see supplemental materials, Table I). Of potential importance, within MBSR, MAAS changes also correlated with t_0 changes ($r = -.67$, $p = .02$ [corrected]), indicating that increases in mindfulness were associated with improvements of the threshold. This finding was further supported in a post hoc baseline test showing that MAAS was negatively associated with t_0 ($\rho = -.40$, $p = .005$), indicating that higher levels of mindfulness were related to a lower perceptual threshold across participants. MBSR increased their visual working memory capacity, K, significantly more than did CICO, $F(1, 30) = 4.74$, $p < .04$, $\omega^2 = .10$. T1 scores predicted T2 scores ($R^2 = .66$, $p < .0001$), but the group effect was still significant when using T1 scores as a covariate, $F(1, 29) = 5.11$, $p = .03$, $\omega^2 = .05$, and only MBSR demonstrated significant improvement on K ($p < .03$, $d = 0.64$). The exploratory analyses of correlations between changes in K and mindfulness level showed that K score was not associated with MAAS score across groups at any time ($ps > .4$). However, for MBSR only, MAAS change scores correlated with K change scores ($r = .68$, $p = .02$ [corrected]), indicating that increases in mindfulness were associated with improved working memory capacity. For processing speed, C, and attentional selectivity, α, pre–post changes did not differ between groups ($ps \geq .2$). INCO showed the largest descriptive improvement on the measure of attentional selectivity (see supplemental material, Table I).

Physiological Stress and Self-Report

The groups did not initially differ on any cortisol measures ($ps > .2$). At T2, MBSR showed a tendency toward a lower AUC_G than did CICO ($p = .068$, $d = 0.76$). Other T2 contrasts were nonsignificant ($ps > .4$). For AUC_G ($R^2 = .32$.) and AUC_I ($R^2 = .19$), baseline levels predicted T2 levels ($ps < .03$). Time × Group interactions adjusted for baseline revealed that MBSR decreased more than did CICO, $F(1, 23) = 7.50$, $p = .02$ (corrected), $\omega^2 = .14$, but not NMSR ($p > .5$). On AUC_I, MBSR tended toward a larger decrease than did CICO in an uncorrected ANOVA, $F(1, 24) = 3.76$, $p = .064$, $\omega^2 = .09$, but not when using baseline as a covariate ($p > .16$). MBSR did not decrease more than did NMSR ($p > .4$). Within groups, MBSR decreased near-significantly on AUC_G, $t(12) = 2.13$, $p = .054$, $d = 0.68$. Descriptively, NMSR decreased ($d = 0.27$), whereas CICO increased ($d = -0.54$, $ps > .1$; see Table 1). Only MBSR decreased significantly on AUC_I, $t(12) = 2.23$, $p < .05$, $d = 0.64$. NMSR decreased descriptively ($d = 0.59$, $p = .09$). CICO showed no change ($p = .5$). These results supported that MBSR reduced both the magnitude of cortisol secretion and the HPA axis reactivity.

Self-report measures. Higher levels of mindfulness were associated with lower levels of perceived stress (PSS) at baseline ($r = .40$, $p < .01$). Groups did not differ on PSS initially ($p > .7$), but MBSR displayed lower baseline MAAS levels than did NMSR

Table 1
Descriptives for Cortisol Secretion Measures and Self-Report Scales

Outcome and time	Inactive controls			Nonmindfulness course			Mindfulness course		
	M	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*
Cortisol secretion (nmol/L per hr)									
AUC_G									
Time 1	577	276	14	634	204	13	543	303	14
Time 2	745	451	14	555	258	11	416	189*	15
AUC_I									
Time 1	618	329	14	170	137	13	173	306	14
Time 2	680	211	14	186	83	11	119	228*	15
Self-report scales									
MAAS									
Time 1	4.24	0.54	15	4.24	0.45	15	3.57	0.78	16
Time 2	4.33	0.65	13	4.46	0.54	15	4.30	0.74***	16
PSS									
Time 1	13.2	6.4	15	12.1	6.0	15	13.8	6.2	16
Time 2	13.7	5.6	13	13.2	6.1	15	10.8	3.4*	16

Note. AUC_G = area under the curve with respect to ground; AUC_I = area under the curve with respect to increase from awakening; MAAS = Mindfulness Attention Awareness Scale; PSS = Cohen's Perceived Stress Scale.
* $p < .05$. *** $p < .001$. Within-group pre–post change is significant at the .05 level/.001 level (uncorrected for multiple tests).

and CICO (*p*s $<$ .05 [corrected]) due to unknown factors and despite the careful balancing on many factors. Posttreatment, groups did not differ on PSS (*p*s $>$ .15) or on mindfulness levels (*p*s $>$ .4). Pre–post, MAAS and PSS change scores (T2 score – T1 score) were negatively related ($r = –38$, $p = .01$), indicating that increases in mindfulness were associated with decreases in stress. Only MBSR increased significantly on MAAS, $F(1, 15) = 25.53$, $p < .001$ (corrected), $d = 1.27$. NMSR increased descriptively ($p = .09$, $d = 0.58$). Because baseline mindfulness level predicted the posttreatment level ($R^2 = .43$, $p < .001$), and due to the initial group differences, T1 scores were used as a covariate. The two ANCOVAs indicated that after correction for baseline levels, MBSR still displayed a larger increase in mindfulness compared with CICO ($p = .015$, $\omega^2 = .09$) but not with NMSR ($p > .15$, $\omega^2 = .02$).

PSS decreased significantly in MBSR ($p = .04$, $d = 0.61$), whereas it increased marginally in CICO and NMSR. Baseline PSS scores were significantly related to T2 scores ($p = .002$, $R^2 = .20$). ANCOVAs with baseline scores as a covariate indicated that MBSR decreased significantly more than did CICO ($p < .03$, $\omega^2 = .11$) but not more than did NMSR ($p > .07$, $\omega^2 = .06$).

Compliance with the MBSR intervention. Compliance was not related to attentional change scores, changes in self-report, or changes in cortisol secretion (*p*s $>$ .05), and no clear patterns were evident.

Discussion

This study examined whether mindfulness-based stress reduction (MBSR) would result in larger beneficial attentional effects than would a nonmindfulness stress-reduction (NMSR) course and increased task incentive invoked by a financial reward offered during the postintervention test session. First, in support of the generalizability of our findings to other MBSR programs with healthy novices, is it important to note that the attentional results are based on an MBSR intervention that was effective in reducing stress, according to both self-report and physiological measures. Thus, the overall absence of unique attentional effects from MBSR (discussed later) was not due to an inefficient intervention.

MBSR led to increased mindfulness, and to a significantly greater degree than the inactive group. As intended, NMSR did not affect mindfulness, suggesting that mindfulness meditation and training in a nonjudgmental attitude are in fact important elements of MBSR. Perceived stress (PSS) decreased significantly for those in the MBSR group—and more so compared with the inactive controls—but decreases in PSS did not differ between the MBSR group and the active controls, which was also the intended effect. The decrease following MBSR was comparable ($d = 0.61$) to effects generally found on well-being scales after mindfulness courses ($d = 0.50$; Grossman et al., 2004). Finally, mindfulness was negatively associated with PSS, and the greater the increase in mindfulness from pre- to posttest, the greater the perceived decrease in stress. Physiologically, the MBSR group showed significantly decreased cortisol secretion and significantly lower secretion than did the inactive controls at T2. From pre- to posttest, cortisol secretions were reduced significantly more in the MBSR group than in the inactive controls, whereas MBSR did not differ from NMSR in any cortisol analyses. There are some limitations to the cortisol results, including small sample size, the relatively large variability in the data, and the single sampling day. Still, these results are supportive of a beneficial effect of MBSR on cortisol secretion, consistent with previous findings (Matousek, Dobkin, & Pruessner, 2010).

Attentional Measures Confounded by Attentional Effort

Incentive controls (INCO) improved remarkably on the measure of attentional set shifting indexed by gray-digit RTs in DART and to a significantly larger degree than did the MBSR participants. This reveals a potentially substantial effect of attentional effort on forced choice performance within a vigilance test. The MBSR group did not even improve descriptively, which is inconsistent with the proposed beneficial role of mindfulness in processes of attentional set shifting (Bishop et al., 2004). This is in accordance with a previous study finding improvements on working memory and vigilance but not switching (Chambers, Lo, & Allen, 2008). Attentional set shifting, however, is not a uniform phenomenon that allows simple inferences from highly abstract tests to discussions of complex abilities, such as shifts from negative judgments to cognitive–emotional acceptance (for reviews see Kiesel et al., 2010; Monsell, 2003). To the contrary, measures of attentional shifts may be mediated by context-dependent networks (Rushworth, Krams, & Passingham, 2001). *Attentional* switching, as defined by Posner and Petersen (1990), may also be mediated by different networks than *intentional* set shifts (Rushworth, Paus, & Sipila, 2001), and the financial incentive presumably affected the intentional aspect of participants' performance specifically. The DART measure of switching abilities might also have been confounded by factors such as working memory load, whereas alternating runs paradigms using a fixed number of trials in each task condition may provide a purer measure of switching costs (Kiesel et al., 2010).

In STAN, the incentive controls improved, especially on neutrally cued trials, and to a significantly greater degree than did the stress reduction groups combined. In neutral trials, the cue is uninformative, and thus, the target can appear at both locations after both intervals, requiring a sustained readiness to react. The mindful ability to sustain a vigilant state has been argued (Jha et al., 2007) to be validly indexed by RTs in a spatial cuing paradigm, the attention network task (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002). Jha et al. (2007) found lower RTs in meditators than in controls on the no-cue trials, which was taken as an indication of improved attentional "orienting." As noted in the introduction, however, the MBSR participants in the study by Jha et al. may simply have tried harder during the second test session. This interpretation was supported by our data, because we found remarkable improvements on noninformatively cued (neutrally cued) trials for the incentive group. Therefore, the improvements found in Jha et al. might have been caused by factors other than MBSR. Another study found no effects on the ANT after a brief mindfulness course (Tang et al., 2007). More research is clearly needed to draw any conclusions about the effects of MBSR and test effort on such trial types.

The ability to remain vigilant and return to the present moment is quintessential to many meditative practices (Lutz et al., 2008). This ability, as well as other temporal attention functions, may also be important in real-life situations, for example when estimating the temporal moment at which moving objects will collide (Coull, Vidal, Goulon, Nazarian, & Craig, 2008) and when perceiving fast speech (Correa et al., 2006). The temporal trials in STAN have been found to be specifically associated with increased activation in left-lateralized ventral prefrontal areas assumed to be involved in top-down control of attention (Coull et al., 2000; Coull & Nobre, 1998; Nobre, 2001). Thus, cognitive stress research should continue to evaluate temporal attention using STAN or similar paradigms, but our results clearly argue for a rigorous consideration of the potential confounding effects of attentional effort on RTs. Likewise, general stress reduction should be considered as a potential factor leading to improved temporal attention, because the NMSR group improved markedly on temporal invalid trials in STAN and to a significantly greater degree than did NOCO. This potential confound in RT measures was less pronounced for RT stability, as argued later.

The Stroop results further corroborated the importance of attentional effort in MBSR studies. Both the MBSR and incentive groups demonstrated significantly fewer naming errors on the incongruent block than did the nonincentive group at T2, with similar effect sizes between the groups. Likewise, when considering pre–post effect sizes, the INCO group demonstrated descriptively larger improvements on completion times for both congruent and incongruent blocks than did any other group. Moore and Malinowski (2009) found superior selectivity on the Stroop task for experienced meditators compared with novices, and Stroop performance improved after just three meditation sessions for novices (Wenk-Sormaz, 2005). In contrast, another MBSR study using a Stroop task found no effects (Anderson et al., 2007), and mindfulness training did not lead to improved Stroop performance in a study that included elderly participants (Alexander et al., 1989). Wenk-Sormaz (2005) assessed effort (task compliance) briefly on a Likert scale but did not manipulate test effort directly. Importantly, in mainstream Stroop research, contextual factors such as social competition and rewards have consistently been found to improve Stroop performance (Huguet et al., 2004, 1999; MacKinnon et al., 1985). Thus, attentional effort may be a serious confounding factor in studies using the Stroop task to assess effects of short-term meditation on selective attention.

In addition, the selectivity parameter derived from the CombiTVA test, α, improved in NMSR but not in MBSR, whereas INCO once more demonstrated larger descriptive improvements than did MBSR. Thus, this selectivity measure seemed more susceptible to improvements from the NMSR course and a cognitive (financial) incentive than to MBSR (see supplemental materials, Table I). In accordance with the Stroop results, these findings support the idea that stress reduction—as well as the perceived task incentive during the test session—can affect top-down attentional selectivity.

In summary, our results on attentional effects of NMSR and attentional effort challenge the validity of many previous studies claiming attentional benefits after short-term meditation or MBSR without considering (either by assessing or by manipulating) these two factors. The main weakness of the present study is the limited sample size and the number of attentional measures and statistical tests. However, our results consistently showed serious confounding effects of attentional effort on RT-based measures. We therefore recommend a future emphasis on finding attentional measures that are less susceptible to these influences.

Attentional Measures Less Confounded by Attentional Effort

Three central measures of RT stability in DART and STAN were based on the RT coefficient of variation, CV, because RT stability was expected to be less sensitive to attentional effort and practice effects and more ecologically valid (cf. Flehmig et al., 2007; Steinborn et al., 2008). First, supporting the independence of CV from simple RTs, the three applied CV measures did not correlate with the corresponding RTs, though faster RTs can be moderately associated with less variance in some tests (Flehmig et al., 2007). We also found support for the possibility that CV for white-digit RTs in DART is a valid indicator of overall DART performance (Dockree et al., 2006), showing significant, negative relationships with the rate of omission errors, premature presses, and commission errors. This supports the proposal by Dockree et al. (2006) that CV is a measure of overall performance on the vigilance task. Changes in DART CV scores were not significantly different between groups, but MBSR showed significantly more stable RTs than did NOCO at T2, suggesting that MBSR improved CV. Stability decreased for the INCO group between pre- and posttest, refuting the idea that attentional effort is a confound for CV in DART. However, the higher stability at T2 in the MBSR compared with the NOCO group might have been a random effect of allocating the least stable persons to NOCO (see descriptives in the supplemental material, Table I), and the effect size for the change in the NMSR group was larger than for the MSBR group. Thus, MBSR did not lead to any unique effects on the CV in DART. Still, we consider it methodologically important that increased motivation improved only RTs and not CV. The impenetrability of CV to attentional effort was replicated in STAN. On the neutral trials, which require a sustained readiness to react, the INCO group showed significant and large pre–post effects on simple RTs, which amounted to a significantly larger improvement than the stress reduction groups combined. However, on CV for the neutral trials, INCO did not improve, and all between-groups pre–post comparisons were not significant.

In STAN, we were particularly interested in the invalidly cued, temporal trials as a measure of the ability to return attention to the present moment (which is required in short, invalid temporal trials when a long CTI is cued), because this is a pivotal component of MBSR (Kabat-Zinn, 1994). However, the within-group results indicated that RTs decreased significantly for only the NMSR group, whereas the MBSR group did not improve. This can be seen as an example of how an activity not directly aimed at training mindfulness may nonetheless increase aspects of mindfulness (Hayes & Shenk, 2004), complicating research strategies as well as the conceptual definition of a “nonmindfulness” intervention. The NMSR group did not increase on the MAAS, but returning attention to the present moment is only one facet of mindfulness, whereas MAAS taps the overall construct. The incentive controls did not show as large an improvement as did the NMSR group for the invalidly cued temporal trials. More studies are needed to determine the important factors for temporal attention performance.

Attentional Measures Uniquely Affected by MBSR

In the d2 Test of Attention (Brickenkamp, 2002), the posttreatment ED for the MBSR group differed significantly from that in all other groups. Whereas all other groups, including INCO, increased error rates significantly during the middle section of the task, the MBSR group actually approached a significant decrease ($p = .07$), although the error increment in the middle section was present in all groups at baseline. We interpret this as an MBSR-induced attenuation of the tiring effect. This interpretation is in accordance with the attention-resource model that attributes vigilance decrements to the exhaustion of mental resources (Warm, Parasuraman, & Matthews, 2008). These results support attentional improvements after MBSR independent of both stress reduction and the perceived task incentive, which to our knowledge has never been shown before. The pre–post changes in ED within the MBSR group also differed significantly from NOCO, NMSR, and CICO (in which half of the participants were financially motivated to try harder). Pre–post changes for the MBSR group did not differ significantly from those for INCO, but INCO still showed a descriptive increase in errors during the middle test section at T2. The impression of unique effects of MBSR on error performance in the d2 test was further supported by the fact that the MBSR group was the only group to demonstrate highly significant (Bonferroni-corrected ps $\leq .01$) and large improvements in E and E% (see supplemental materials, Table I). All groups scanned significantly more items at T2 (see supplemental materials, Table I), but only the MBSR group committed significantly fewer errors, thus lowering E% markedly. The majority of errors were omission errors, supporting the idea that MBSR specifically improved the ability to sustain a selective focus in the presence of distractors, rather than the ability to inhibit error commission. Our d2 results therefore corroborate findings of superior d2 error performance in experienced meditators compared with novices (Moore & Malinowski, 2009). A causal role of long-term meditation is also possible, because the between-groups effect sizes calculated from Moore and Malinowski’s (2009) sample size and t values (formulas in Rosnow & Rosenthal, 1996; Rosnow, Rosenthal, & Rubin, 2000) were larger (total score: $d = 1.64$; errors: $d = 1.29$) than any posttreatment group differences in the present study. As opposed to the left-lateralized temporal orienting network supposedly employed in STAN, it has been proposed that sustaining attention in unarousing contexts may primarily involve right frontoparietal regions (Posner & DiGirolamo, 2000; Posner & Petersen, 1990). Thus, the d2 results are consistent with suggestions (Cahn & Polich, 2006; Newberg & Iversen, 2003) that meditation requiring sustained attention enhances this right-lateralized network.

Concerning the limitations of the d2 results, continuous performance tasks such as DART are also thought to challenge this network (Dockree et al., 2006), so the DART results are somewhat contradictory to the d2 results. However, DART and the d2 test differ in many respects, for example in their administration form (computer/paper), attentional demands (there are no set shifting or dual attention tasks in d2), and stimulus type (numbers/letters). Most important, d2 primarily measures selective attention, whereas DART measures sustained, dual attention. The between-groups d2 effect sizes, however, were small, and the p values did not survive Bonferroni-correction. Importantly, our results did not seem to be confounded by general stress reduction or attentional effort, but replications are encouraged.

Using an experimental paradigm based on TVA (Bundesen, 1990), we also quantified changes in four basic visual attentional functions: the threshold of conscious perception, visual working memory capacity, processing speed, and top-down controlled selectivity. Several interesting results were found. Only the MBSR group demonstrated large and significant improvement in visual threshold. This indicates a decrease in the amount of time required for encoding visual information into conscious, short-term memory (i.e., an ability to identify material presented for shorter durations). Intriguingly, the degree of improvement in the perceptual threshold was significantly (Bonferroni-corrected) associated with the increase in self-reported mindfulness within the MBSR group. This relationship was further strengthened by an association between higher levels of mindfulness and lower perceptual thresholds across groups at baseline ($r = -.40$, $p = .005$).

Bushell (2009) argued that the Buddhist meditative goal of developing superior perceptual and attentional capacities to "achieve penetrating insight into the nature of phenomena" (p. 348) should facilitate near-threshold perception in the visual domain. Bushell's claim is primarily based on psychophysical studies of human light detection capabilities, but our finding supports his claim by showing that the conscious threshold of vision can be modulated in novices after MBSR. Semple (2010) used signal detection methods to evaluate performance in a sustained attention task and found that an MBSR group showed higher stimulus discriminability than did both active and passive control groups. MacLean et al. (2010) found that an intensive meditation retreat increased discriminability after 6–7 weeks, which was sustained at follow-up. Increased discriminability or sensitivity in signal detection reflects an increase in the signal-to-noise ratio, which is pivotal for near-threshold perception. Thus, heightened sensitivity could also explain the decrease in the perceptual threshold found here. Furthermore, in the TVA-based test a fixation cross was always presented 500 ms before the stimulus display. If the participants are able to use the appearance of the cross as a temporal warning cue, this could potentially help them focus their attention at the exact moment in time when the stimulus displays are presented. The results from STAN did not support improved temporal orienting of this type in the MBSR group, but unpublished data from the Center for Visual Cognition (where the TVA test was developed) suggest that valid temporal cues can actually lower the perceptual threshold. The improvement in MBSR was significant compared with NOCO and CICO, although between-groups effect sizes were small (see supplemental materials, Table III). Also, changes in MBSR did not differ significantly from changes in NMSR and INCO. Still, the pre–post effect in MBSR was numerically twice as large as in INCO and NMSR (see supplemental materials, Table I). This descriptive difference suggests that MBSR in novices can result in unique attentional modulations not caused by mere test effort or general stress reduction. Though this positive finding is in need of replication, it is in line with studies showing beneficial effects of short-term meditative training on other measures of visual perceptual threshold or visual discrimination (D. Brown et al., 1984; Dilbeck, 1976; Vani, Nagaranthna, Nagendra, & Telles, 1997). An intensive meditation retreat also improved experienced meditators' detection of both the first and second of two target visual stimuli presented in close temporal proximity on an attentional blink task, which may reflect faster visual processing (Slagter, 2007; Slagter et al., 2009). Greater psychological sensitivity to colors was demonstrated in a projective test (Rorschach) as a function of meditation experience (D. P. Brown & Engler, 1980). A recent review of the few existing empirical studies, phenomenological reports, and historical texts (Bushell, 2009) also predicted improvements in visual perceptual threshold and visual attention in general after Buddhist meditation practices.

Only the MBSR-participants showed a positive, significant increase in working memory capacity, and this also constituted a significantly larger improvement than in the inactive controls. Paying the control participants to perform better did not improve memory capacity, supporting the interpretation that heightened attentional effort did not cause the observed changes in the MBSR group. Furthermore, MBSR improvements in capacity were significantly associated with improved mindfulness, as indexed by the MAAS, again suggesting that training mindfulness in MBSR may actively promote an increase in working memory capacity. However, level of mindfulness was never associated with the capacity measure across groups. In addition, there is a lack of comparable studies testing the effects of MBSR on working memory capacity. Rather, studies have tended to include tests that require working memory but that do not yield a direct capacity measure. Jha, Stanley, Kiyonaga, Wong, and Gelfand (2010) showed that in military cohorts, mindfulness training prevented a decrease on an indirect measure of working memory capacity, which is regularly observed during a highly stressful predeployment interval. They proposed that mindfulness-related improvements in working memory capacity could mediate some of the positive effects observed after mindfulness-based interventions and that these practices could protect against functional impairments resulting from high-stress situations. Two studies employing the Digit Symbol Substitution subtest from the Wechsler Adult Intelligence Scale battery that requires intensive (visual) working memory involvement found a significant, but small, effect (Zeidan, Johnson, Diamond, David, & Goolkasian, 2010) or no effect (Semple, 2010) of MBSR. However, in an *n*-back task used as an additional effect measure, Zeidan et al. (2010) found that the working memory–related component was positively affected by MBSR, whereas processing speed was unaffected. Interestingly, this pattern is similar to the dissociation between the benefits of MBSR on visual working memory, but not visual processing speed, found in our study. Many investigations have shown that people with larger working memory spans have greater attentional control (Kane, 2005; Kane & Engle, 2002), so the improvement observed only within the MBSR group could be seen as supportive of unique improvements in top-down attentional control from MBSR. However, capacity improved descriptively for the NMSR group (whereas INCO descriptively decreased), so NMSR was a potential confounder. In addition, in the TVA-based test the capacity parameter is usually not associated with the measure of attentional selectivity, which we also replicated here. Again, further studies are needed to determine the specific MBSR-related effects on attentional control and working memory capacity.

We failed to find any relationships between MBSR compliance and changes in cognitive outcomes, self-report, or cortisol secretion. This could be seen as limitation of the results, but compliance findings are often negative in MBSR research. A review concluded that the correlations between program contact hours and outcome effect sizes were not significant for both clinical and nonclinical samples (Carmody & Baer, 2009), and cognitive effects of mindfulness training have been reported after just 3 days (Tang et al., 2007), 1 hr (Wenk-Sormaz, 2005), and even 15 min (Arch & Craske, 2006) of training. Obviously, these results call for more thorough investigations of compliance.

In summary, our results are the first to provide empirical support for the hypothesis that MBSR can uniquely improve attentional subsystems, such as the ability to sustain a selective attentional focus (error performance in the d2 test) and functional components of visual attention, including the threshold of visual perception and visual working memory capacity (CombiTVA paradigm). However, the d2 results were only marginally significant, and the CombiTVA paradigm did not show significantly larger effects of MBSR than did NMSR. Thus, taken together we feel that the most important demonstration here was that simply increasing test effort during the second test session, as well as NMSR, can have even larger effects than does MBSR on several attentional skills considered central to MBSR, such as temporal orienting, a sustained readiness to react (STAN test), and attentional set shifting (DART test). Thus, the main, and critical, conclusion that can be drawn from this study is that many previous investigations of MBSR or short-term meditation-specific attentional improvements should be regarded with caution because they do not control for attentional effort or nonspecific stress reduction. We found that attentional effort in particular affected raw RTs. In contrast, measures of RT stability and perceptual, attentional performance unconfounded by motoric processes (perceptual threshold, visual working memory capacity) were more resistant to effects of test effort. We encourage other researchers to apply a similar design with active and incentive control groups in larger studies, possibly also including more distressed individuals, for whom MBSR may lead to a greater improvement in attentional functions than for a young, healthy sample.

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