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Greater efficiency in attentional processing related to mindfulness meditation

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Greater efficiency in attentional processing related to mindfulness meditation

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In this study, attentional processing in relation to mindfulness meditation was investigated. Since recent studies have suggested that mindfulness meditation may induce improvements in attentional processing, we have tested 20 expert mindfulness meditators in the attention network test. Their performance was compared to that of 20 age- and gender-matched controls. In addition to attentional network analyses, overall attentional processing was analysed by means of efficiency scores (i.e., accuracy controlled for reaction time). Better orienting and executive attention (reflected by smaller differences in either reaction time or error score, respectively) were observed in the mindfulness meditation group. Furthermore, extensive mindfulness meditation appeared to be related to a reduction of the fraction of errors for responses with the same reaction time. These results provide new insights into differences in attentional processing related to mindfulness meditation and suggest the possibility of increasing the efficiency in attentional processing by extensive mental training.

Keywords: Attention; Attention network test; Mental training; Mindfulness meditation.

Recent studies have shown that attention and the quality of moment-to-moment awareness are flexible skills that can be trained and improved through mental training such as meditation (Chan & Woollacott, 2007; Jha, Krompinger, & Baime, 2007; Slagter et al., 2007; Tang et al., 2007).

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Over the last few decades, there has been a large increase in clinical applications and empirical research on mindfulness-meditation-based interventions, such as the Mindfulness-Based Stress Reduction programme (MBSR) and Mindfulness-Based Cognitive Therapy (MBCT). The mindfulness-meditation-based practices have proven to be effective in reducing the clinical symptoms in a considerable number of psychological, psychosomatic, and emotional disturbances (Atin, 1997; Baer, 2003; Giommi, 2006; Grossman, Niemann, Schmidt, & Walach, 2004; Kabat-Zinn, 1990, 1992, 2003; Kabat-Zinn, Lipworth, & Burney, 1985; Kristeller & Hallett, 1999; Speca, Carlson, Goodey, & Angen, 2000; Teasdale, Segal, & Williams, 1995; Teasdale et al., 2000). Despite the fact that a growing body of scientific literature about the clinical applications of mindfulness meditation seems to reveal promising results of its effectiveness (Kabat-Zinn, 1994, 2003), surprisingly few studies have addressed the neuropsychology and the neurophysiology of mindfulness meditation, and very little is known about the mechanism(s) by which mindfulness meditation exerts its effect(s) (Bishop et al., 2004; Shapiro, Carlson, Astin, & Freedman, 2006). As mindfulness meditation has been described as "a particular way to pay attention" (Kabat-Zinn, 1990, 2003), a putative candidate mechanism for its effect(s) is a modification in attentional processing. More specifically, recent conceptualizations have suggested mindfulness meditation to improve the self-regulation of attention (Bishop et al., 2004; Shapiro et al., 2006).

William James defined attention as: "the taking possession of the mind in clear and vivid form of one out of what seem several simultaneous objects or trains of thought" (James, 1890, Vol. 1, pp. 403–404). For about a century thereafter, several theoretical models of attention have been put forward, one of which is that by Posner and Petersen (1990). Their tripartite model has been highly influential in modifying the view on attention, considering it as an organ system with its own anatomy and circuitry (Fan, McCandliss, Fossella, Flombaum & Posner, 2005; Fan & Posner, 2004; Posner & Petersen, 1990).[1] In their model, attention has been conceptualized as comprising three separate functional components or attentional networks: the alerting, orienting, and executive attention networks. The aim of the alerting network is to achieve and maintain a vigilant or alert state of preparedness; the orienting network regulates directing and limiting attention to a subset of possible inputs; and the executive attention network resolves conflict among multiple responses.

In 2002, Fan and others (Fan, McCandliss, Sommer, Raz, & Posner, 2002) presented the attention network test to investigate the functioning of the three different attention networks proposed by Posner and Petersen. Because of the reliability of the scores obtained with the attention network test and its easy use in a wide variety of subjects and patients (Fan et al., 2002), the attention network test has since then been used in many studies on both normal and clinically impaired attentional processing (Hövels-Gürich et al., 2007; Leskin & White, 2007; Neuhaus et al., 2007; Wang et al., 2005).

In a recent pioneering study, Jha et al. (2007) used the attention network test to examine changes in attentional processing induced by mindfulness meditation. They performed a longitudinal study with three groups: a retreat, MBSR, and control group.[2] During the baseline measurement, they found a significantly better executive attention network in the retreat group, both in reaction time (RT) and in error score (ES) data, where ES was defined as the percentage of incorrect responses. No significant differences were observed on both the alerting and orienting networks.

[1] An organ system is defined as differentiated structures made up of various cells and tissues and adapted for the performance of some specific function and grouped with other structures into a system (Posner & Petersen, 1990).

[2] A retreat is a period of secluded, continuous, and intensive group practice of meditation, varying from 1 week to 1 month or even more (the retreat in the Jha et al. study lasted 1 month). MBSR is an 8-week programme with weekly group sessions of 3 hours and daily homework.

Although the results obtained by Jha et al. (2007) were very promising, their study raised several questions. First, recent research has revealed a positive interaction between the orienting and executive network (Callejas, Lupianez, Funes, & Tudela, 2005; Callejas, Lupianez, & Tudela, 2004). Therefore, it was somewhat surprising that Jha et al. did not report significant differences in the orienting network, while a significant effect was found in the executive network. In order to investigate this issue, we also used the attention network test and tested a group of more experienced meditators than those tested in the study by Jha et al. (mean 14.5 years, range 0.33–35 years in our group vs. mean 5 years, range 0.33–30 years in the study by Jha et al.). With this sample of more experienced meditators, we expected to increase the likelihood of finding differences within the orienting and executive network. Secondly, Jha et al. focused their analysis on attentional network scores, which is the standard approach when the attention network test is used. In our study, we were also interested in the analysis of grand mean RT and ES data, as these data are informative on overall differences in attentional processing between meditators and controls.

We hypothesized to find the following results for the group of experienced meditators as compared to controls: (a) considering the orienting and executive attention, we predicted to observe better functioning for experienced meditators, reflected by smaller network scores on the orienting and executive attention components of the attention network test. To further explain these hypotheses, we assumed that through mindfulness meditation—by which the meditator is trained to get attached to the stimuli as little as possible—a more receptive ("open field") form of attention is acquired, and, as a consequence, the orienting of attention is improved—that is, more flexible. In addition, since meditators have been trained in focusing attention, we hypothesized that they would be better in focusing to the relevant information embedded in the target environment while ignoring the irrelevant, distracting information. This is thought to be reflected in a better executive attention. Since only few studies did address the alerting network, no hypothesis was formulated for this attention component. (b) In addition to our interest in the functioning of specific components of attention, we were also interested in overall differences in attentional processing between meditators and control participants. Therefore, in addition to the attention network analyses, groups were also compared regarding grand mean RT and ES data, hereby probing (efficiency in) attentional processing at a more general and integrated level. This analysis may reveal possible changes in strategy and, moreover, possible differences in overall attentional processing, which cannot just be explained by changes in strategy. In other words, an attempt is made to dissociate "just" a speed–accuracy trade-off (strategy difference between groups) from a qualitative difference in overall attentional processing between groups). Since Chan and Woollacott (2007) had already suggested that mindfulness meditation enhances one's general performance on attentional tasks, we hypothesized that the meditators would show a better overall performance on this attention task.

Method

Participants

A total of 20 mindfulness meditators (mean age 48.1 years, *SD* 9.0, range 31–60 years; 9 male) and 20 control participants (mean age 48.1 years, *SD* 9.2, range 30–60 years; 9 male), who were matched to the mindfulness meditators in age and gender, participated in this study. The mean level of mindfulness meditation experience was high (mean period was 14.5 years, *SD* 11.1, range from 3 months to 35 years). Regular mindfulness meditation practice varied from 60 to 420 minutes each week. Mindfulness meditation is composed of both concentration meditation (śamatha) and insight (vipaśyanā) meditation. Whereas during śamatha meditation the practitioner is trained to maintain focus on an object for a theoretically unlimited period of time, during vipaśyanā meditation a typical kind of meta-awareness is trained.

None of the participants had any known psychological or neurological deficits. They all had normal or corrected-to-normal vision. A signed informed consent form was obtained from each participant before the experiment. The study has been conducted according to the principles expressed in the Declaration of Helsinki.

Attention network test

Participants were seated in front of a 19-inch computer screen at a distance of 65 cm. Stimuli were presented and responses were collected with Presentation software (Version 10.1 Neurobehavioral Systems, Albany, USA). Participants were instructed to respond as fast and as accurately as possible to a target stimulus that was presented in the centre of a horizontal row with five stimuli (see Figure 1C). The target stimulus was an arrow pointing either to the left or to the right and was flanked by two flanker stimuli on each side. Participants were instructed to press the left mouse button with their left thumb or the right mouse button with their right thumb as fast as possible when the target arrow pointed to the left or right, respectively. The four surrounding flanker stimuli were all arrows pointing in the same or the opposite direction of the target stimulus or were just neutral stripes. The condition in which all five arrows pointed in the same direction was called the congruent target condition. The condition in which the flanker arrows pointed in the direction opposite to the target arrow was named the incongruent target condition. The condition when the four flanker stimuli were stripes was called the neutral target condition. The target stimulus and the flanker stimuli were presented at a visual angle of 1.1° above or below a fixation cross presented in the middle of the screen.

The target stimulus could be cued in four different ways. In the first cueing condition, an asterisk was presented at the location of the fixation cross (= centre cue condition), and the target configuration was presented above or below the centre of the screen, with equal probability. In the second cueing condition, two asterisks were presented (= double cue condition); the two asterisks were presented at the fixed locations of 1.1° of visual angle above and below the centre of the screen. Since the cue appeared 500 ms before target onset (see Figure 1A), the cue provided information on the timing of the target stimulus. In the third cueing condition, an asterisk was presented at the future location of the target stimulus above or below the centre of the screen (= spatial cue condition). In this case, participants were informed both on the timing and on the location of the target configuration. In the fourth cueing condition, no cue was given, and, as a consequence, participants had neither information on the timing nor on the location of the upcoming target symbol.

The attention network test consisted of one training block with 24 trials and three test blocks with 94 trials each. After the first and second blocks, participants took a break of a few minutes, before starting the next block of the attention network test. A single trial consisted of the following: during a variable interval (VI, see Figure 1A), ranging from 400–1,600 ms, a fixation cross was presented in the middle of the screen. Then, depending on the cue condition, a cue could be presented for 100 ms. Thereafter, a central fixation cross was presented for 400 ms, followed by the target stimulus, which was presented for 1,700 ms, or shorter if a response was given within 1,700 ms. Finally, a fixation cross was presented during a variable delay. The length of this delay was determined by subtracting the RT plus 400 ms from the constant trial duration that was 3,500 ms (see Figure 1A). All 12 combinations of cueing (4) and target (3) conditions were presented in random order within each block. Both RT and ES were measured.

Attention networks calculations and analyses

For each participant, all reaction times (RT) of a specific condition, outside the range of the mean RT $\pm$ 4 standard deviations of that specific condition, and RTs shorter than 100 ms were excluded from analysis. Then, the average RT for each of the 12 conditions (4 cue conditions $\times$ 3 target conditions) was recalculated. Determination of the network effects was based on these RT data. Error scores (ES; percentage of incorrect

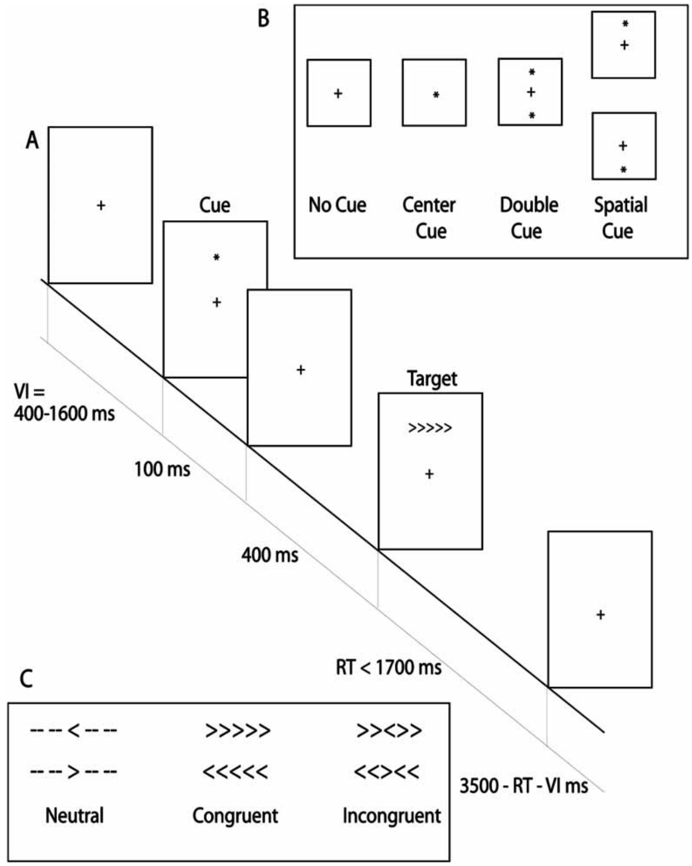

Figure 1. *Attentional network test paradigm. (A) During a variable interval (VI = 400–1,600 ms) a central fixation cross is presented, and the participant is instructed to look at it. Then a cue can be presented for 100 ms. (B) The four cue conditions are shown: no cue, central cue, double cue, and spatial cue. After presentation of the cue, a central fixation cross is shown for 400 ms, followed by the target stimulus. (C) The three different target configurations are shown: the neutral, congruent, and incongruent target configurations. The target is visible until the participant responds with a maximum of 1,700 ms. If reaction time (RT) is shorter than 1,700 ms, the stimulus is replaced by the central fixation cross.*

responses) of the 12 conditions were calculated by dividing the number of incorrect responses by the total number of responses for the specific condition and multiplying this number by 100.

To calculate the alerting network effect mean RT and ES of the double cue condition were subtracted from the mean RT and ES of the no cue condition. In such a way, the potentially beneficial effect of an alerting cue on RT and ES was probed. The orienting network effect was calculated by subtraction of the mean RT and ES of the responses in the spatial cue condition from the mean RT and ES of the responses in the centre cue condition. This allowed us to probe the beneficial effect of spatial information, in addition to timing information. The executive network effect was calculated by subtracting the mean RT and ES in the congruent target condition from the mean RT and ES in the incongruent target condition. In this way, the advantage of congruence over incongruence in the target condition was determined. Mean RT and ES of the three target conditions were averaged to calculate the orienting and alerting network effects, whereas mean RT and ES of the four cueing conditions were averaged to calculate the executive network effect. Normalized network effects were determined by dividing the raw network effect by the mean of the two conditions involved in the calculation of the network effect: raw effect, R = RTA−RTB; normalized effect, N = R/[(RTA + RTB)/2], with RT_x representing mean RT for condition *x*.[3]

In all tests, we verified the normal distribution of data. When a normal distribution was violated, we used nonparametric tests. The specific test is described in each case. In all other cases we have used paired *t* tests to investigate whether meditators differed from their matched controls. In those cases, where the hypothesis was very specific, as to the differences of responses of both groups for the orienting and executive network scores, a one-tailed paired *t* test was used.

General behavioural analyses

In order to analyse differences between meditators and their matched controls on overall RT and ES data, two paired tests were run. Grand mean RT/ES data of each participant were used in these tests.

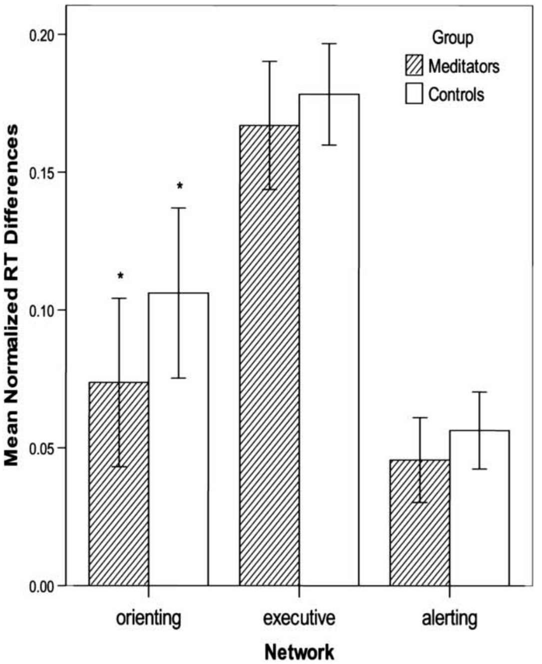

Figure 2. *Mean normalized reaction time (RT) difference scores for all three networks. A significant difference between the results of the meditators and controls exists in the orienting network (*$p < .05$*). No significant difference was found for the executive and alerting networks. Error bars indicate 95% confidence intervals.*

Results

Attention networks analyses

A one-tailed paired *t* test on normalized RT network data revealed no significant difference between meditators and controls in the executive network, $t(19) = -0.779$, $p = .22$. However, a significant difference in the orienting network $t(19) = -1.746$, $p < .05$ (see Figure 2 and Footnote 3) was observed.

A one-tailed paired *t* test on ES network data showed no significant difference in the orienting network $t(19) = 1.185$, $p = .13$, whereas a trend towards significance was observed in the executive network, $t(19) = -1.560$, $p = .07$ (see Figure 3). This trend could be explained by the fact that meditators make significantly fewer errors in the incongruent target condition, $Z(80) = -2.403$, $p < .05$ (see Figure 4; nonparametric Wilcoxon Signed Ranks Test was used to compare ES of each cue condition of each meditator in the incongruent target condition with the corresponding ES of a matched control; this yields a distribution of 80 (4 cue × 20 participants) paired data points). No significant differences were observed in both the congruent, $Z(80) = -1.004$, $p = .316$, and neutral target condition, $Z(80) = -1.060$, $p = .289$ (analyses performed here are similar to the incongruent condition analysis). Presumably, we are dealing with floor effects in these two target conditions, as ES approach 0% (see Figure 4).

In conclusion, meditators showed a significantly smaller orienting network effect on RT

[3] Normalized network data were calculated by dividing the absolute network effect by the mean RT of the two conditions used to calculate the network effect. See Wang et al. (2005) for similar analyses of RT network scores.

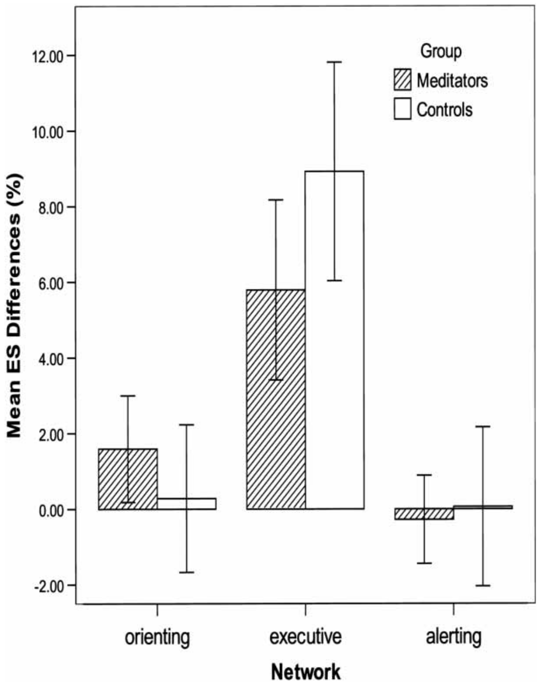

Figure 3. *Mean error score (ES; %) for all three networks. A trend towards a significant difference between the results of the meditators and controls is observed in the executive attention network. No significant difference was found for the orienting and alerting networks. Error bars indicate 95% confidence intervals.*

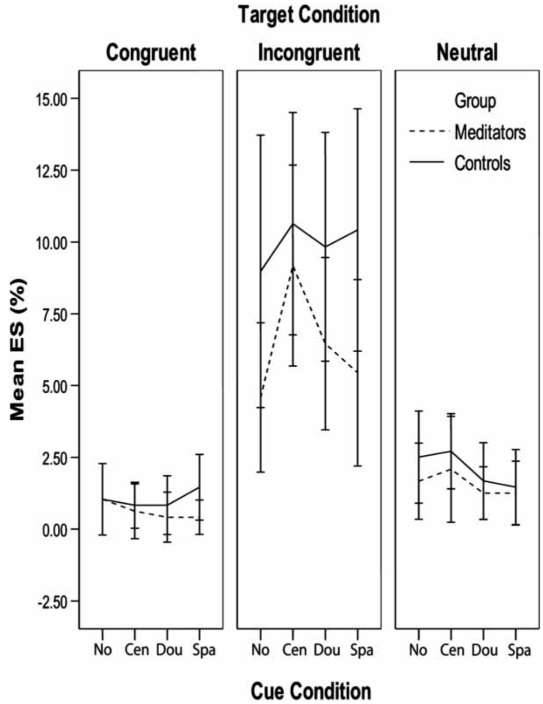

Figure 4. *Mean error score (ES; %) for meditators (dashed line) and controls (solid line) in all 12 (4 cue × 3 target) conditions. Meditators make fewer errors than controls. This effect is most obvious in the incongruent condition. Error bars indicate 95% confidence intervals.*

data than did controls. And a trend towards significance in the same direction on ES data in the executive network was observed.

General behavioural analyses

A trend towards a significant difference between groups on grand mean RT data was observed, $t(19) = -2.008$, $p = .059$. Mindfulness meditators generally tended to respond slower (see Figure 5).

Also a trend towards a significant difference between groups on grand mean ES data was observed, $t(19) = -1.824$, $p = .084$. Mindfulness meditators generally tended to respond more accurately (see Figure 4).

At first, one is tempted to explain these behavioural differences by referring to the well-known trade-off function between speed and accuracy in behavioural experiments (Posner, 1978). If so, meditators would simply have put more emphasis on accuracy (i.e., smaller ES), accepting longer RTs, and would therefore show a speed–accuracy distribution that could be obtained by extrapolation from the distribution of controls. Instead, a different, *vertically* shifted speed–accuracy distribution would imply a difference in the efficiency/functioning of attentional processing (see Figure 6).

Overall attentional processing efficiency

RT-bin analysis. In order to investigate which of these two explanations fits our data, we divided the whole RT time range of both meditators and controls in small time windows. Within each time window, the responses of both groups can be regarded as "equally" fast. For all windows, the total number of correct and incorrect responses

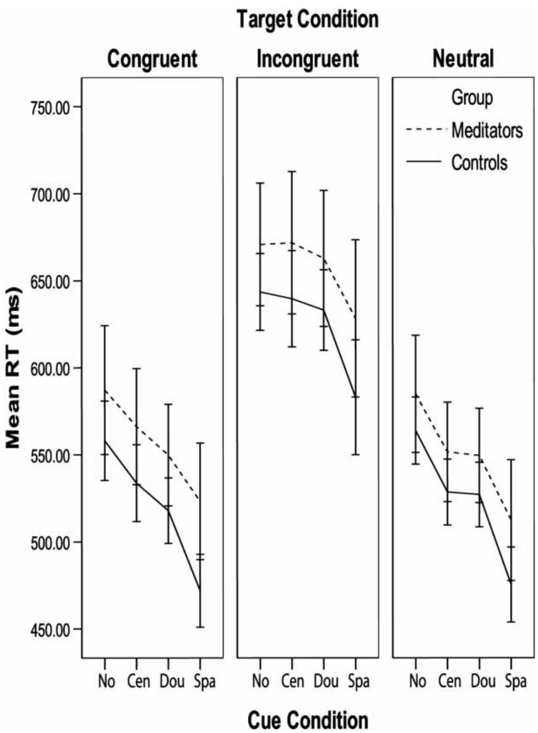

Figure 5. *Mean reaction time (RT; ms) for meditators (dashed line) and controls (solid line) in all 12 (4 cue × 3 target) conditions. Meditators have longer RTs than controls. Error bars indicate 95% confidence intervals.*

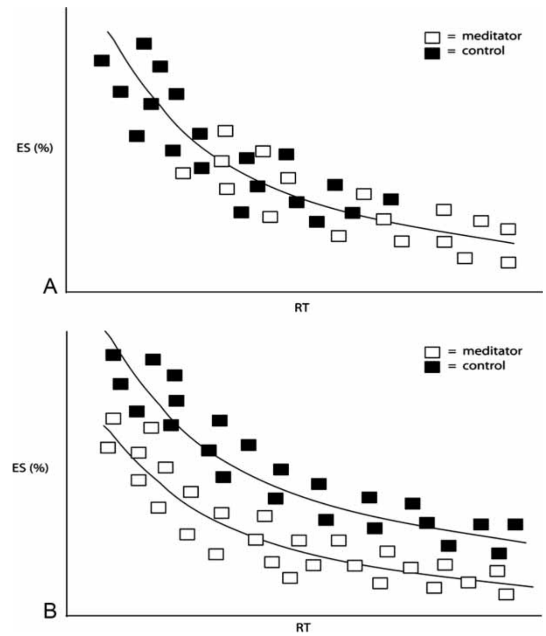

Figure 6. *Two hypothetical data distributions: (A) Meditators opted for a different strategy: longer reaction time (RT) and lower error score (ES). Distribution of meditators can be obtained by extrapolation of data of controls. (B) Meditators differ in efficiency of attentional processing: They show a vertically shifted distribution—that is, with identical RT meditators have lower ES. In this case, meditators would have a different distribution, which cannot be obtained by extrapolation.*

and also the total number of responses of each of the two groups were calculated. Then, the percentage of incorrect responses for each group was determined within each time window. This yields one data point (percentage of incorrect responses) for each group for each time bin. These data points of all time bins of each group render a distribution of error percentage scores for that specific group.

This analysis was repeated with time windows of 20, 40, and 60 ms, respectively, in order to check the robustness of the result. Only time windows in which, at the group level, more than 30 responses were given were included. Then, the error percentage distribution of the meditators was compared to the error percentage distribution of the controls (see Figure 7). Irrespective of the size of the time window, a Wilcoxon Signed Rank test revealed a significantly different speed–accuracy distribution of meditators from that of controls $Z(10) = -2.090$, $p < .05$; $Z(13) = -2.510$, $p < .05$; $Z(23) = -2.728$, $p < .01$ (for 60-, 40-, and 20-ms time windows, respectively). For all three time windows, the distribution of error percentages included at least 94.6% of all data from both the control and the meditator group. This means that these results are based on a large amount of overlapping RT data (see Figure 8 for RT distributions of both groups). Thus, considering the fact that meditators appear more accurate with equal RT, this result suggests a higher efficiency in attentional processing in mindfulness meditators.

Logistic regression analysis. Another way of looking at both RT and ES and a possible different

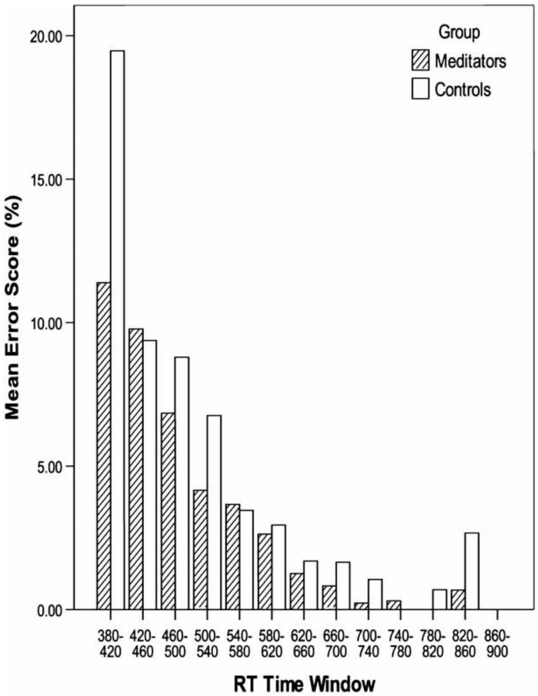

Figure 7. *Mean error score (ES; %) for meditators (dashed bars) and controls (white bars) for reaction times (RTs) within a window of 40 ms in the range between 380 and 900 ms. Meditators make significantly fewer errors than controls for responses with the same RT.*

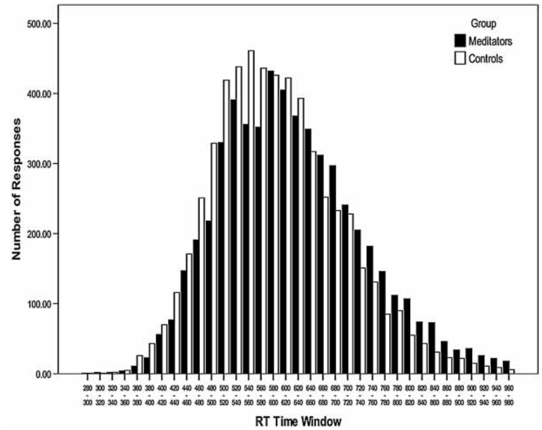

Figure 8. *Distribution of reaction times (RTs) for meditators (black) and controls (white). Notice the large overlap of the distributions. In general, meditators tend to have slightly longer RTs than controls.*

speed–accuracy distribution between groups is the following. One could see RT as a predictor of the probability to give a correct response, where the probability of a correct response increases with longer RT (a view inspired by the well-known speed–accuracy trade-off). Next, group membership could also be important for the probability of a correct response. Now, if only RT would appear to be a predictor of the probability of a correct response, only a difference between the two groups in the performance strategy could explain our general behavioural results. However, if, on top of the predictive value of RT, group membership would also appear predictive on the probability of a correct response, intrinsic differences between groups in attentional processing must be present.

In order to distinguish between these two possible explanations for the observed differences between meditators and controls in RT and ES, we used a hierarchical logistic regression analysis. The type of response (correct vs. incorrect) was designated as the dependent variable, and RT and group membership (meditator vs. control) were entered as predictors (RT in Block 1 and group in Block 2). Interestingly, group membership appeared a significant predictor in addition to RT: $\beta\text{RT} = -.009$, $p < .001$, $\exp(B) = 0.991$; $\beta\text{group} = .284$, $p < .01$, $\exp(B) = 1.329$. This result points to an intrinsic difference between meditators and controls in attentional processing. Therefore, results cannot be explained by "just" referring to a difference in performance strategy between the two groups, but rather reflect a more efficient use of resources by the meditators, since meditators perform more accurately when identical RTs are considered.

Discussion

Attention networks analysis

In this study experienced mindfulness meditators showed a better orienting of attention than their matched controls, as reflected by lower scores on the orienting network. This decrease was present in RT data, but not in ES data (see Figures 2 and 3).

Our interpretation of this smaller orienting network effect as reflecting a more flexible orienting of attention is based on the remark made by Fan and Posner: "For the orienting condition we generally assume that larger orienting times arise because of a difficulty in disengaging from the centre cue, where no target appears" (Fan & Posner, 2004, p. 212). Thus, it seems that meditators already perform closer to their optimum in the centre cue condition, since additional spatial information does not seem to reduce their RT to the same extent as in controls. However, one cannot completely rule out the possibility that meditators just cannot benefit as much as controls from additional spatial information, which should then be due to some orienting attention impairment(s). In our view, the presence of such a large number of participants having orienting attention impairments in the meditator group, to produce such a systematic shift from the control group, would be quite unlikely.

It seems more plausible that mindfulness meditators, in general, show a more flexible orienting network. This is because an important instruction during the practice of mindfulness meditation is to continue to successively detach–attach–detach attention to all objects passing by in the receptive fields, thereby presumably improving the flexibility of the orienting of attention. Jha et al. recently noted that "the practice of repeatedly engaging, disengaging and moving, instantiates the orienting or 'shift' operation of attention" (Jha et al., 2007; Posner & Badgaiyan, 1998; Posner & Gilbert, 1999)—that is, a statement that supports our interpretation.

Besides the better orienting of attention, also a trend towards a significantly better executive attention was revealed in our study, as meditators showed smaller executive network ES. No difference in executive attention was found considering RT data. The trend in the executive network can be explained by the fact that controls make significantly more errors in the incongruent condition (see Figure 4). Notably, the incongruent target condition appears to be the only target condition in which the results of the two groups are significantly different from each other considering ES; we are probably dealing with floor effects in the other two target conditions, as ES approaches 0% (see Figure 4) in both groups. Similar floor effects have also been obtained by Fan et al. (2002).

It is of interest that we found a better orienting and a better executive attention as this had not been found in the study by Jha et al. (2007; who found no difference in the orienting of attention). This difference might be explained by the fact that in the present study more experienced meditators were tested and that there was a better match between meditators and control participants.

Over the past years, several studies have related the functioning of the executive network to the functioning of the orienting network (Callejas et al., 2005; Callejas et al., 2004; Funes & Lupianez, 2003). The orienting network appears to exert a positive influence on the executive attention network, as the flanker effect is reduced in spatially cued trials in comparison to uncued trials (Callejas et al., 2005; Callejas et al., 2004). Considering this positive interaction, the better executive attention in the meditators can partially be explained by the better functioning of their orienting network. In addition, meditators also might profit from an increased ability to focus attention to the relevant information embedded in the target condition, while ignoring or detaching faster from the irrelevant information signalled by the target configuration.

Better executive attention in meditators has also been reported by Jha et al. (2007) and Chan and Woollacott (2007). Chan and Woollacott explained the effect of meditation on attention by referring to the possibility of an increased ability to focus attention and an improved inhibition of automatic responses (for example, inhibiting the shift of attention to distracting externally generated stimuli or internally generated thoughts) in favour of the desired response (remaining focused on the desired object or task). This explanation is similar to our interpretation given above.

As there is a large body of neuropsychological literature showing that (impaired) executive attention is the key element for self-regulation of cognition and emotion (Fernandez-Duque, Baird, & Posner, 2000; Posner & Rothbart, 1998; Tang et al., 2007), it would be interesting for future studies to explore possible changes in orienting and executive attention, induced by mindfulness meditation, in clinical populations. As attentional biases in information processing have been demonstrated to be important in patients with anxiety and depression (Williams, Watts, MacLeod, & Mathews, 1997), the effectiveness of mindfulness-meditation-based practices might be mediated by improvements in attentional processing, especially in executive attention.

Overall analysis of attentional processing

If we consider the grand mean RT and ES, the attention network test allows a distinction between the performance of meditators and controls at a more general and integrated level of attentional processing, as meditators appeared to have systematically longer RT and, at the same time, showed a systematic increase in accuracy (decrease in ES) as compared to controls (see Figures 4 and 5). These systematic shifts across almost all conditions cannot be explained, in our view, by specific changes limited to the alerting, orienting or executive component of attention. They can better be explained as the result of a more general and persistent change in attentional processing, which requires an integrated analysis.

At first sight, one could interpret the differences in RT and ES as a good example of the well known speed–accuracy trade-off effect (Posner, 1978). In that case, the differences could be explained by the fact that meditators take more time to respond and consequently become more accurate. This result by itself would already be of interest, showing mindfulness meditation to be related to a systematic change in the performance strategy for such a low-level task.

Alternatively, the differences could actually reflect a higher "efficiency" in attentional processing in the mindfulness meditation group. We would like to refer to the term "efficiency" when we want to take into consideration the overall performance on this attention task—that is, to consider both RT and ES at the same time. In our view, these two performance dimensions together are very informative on the efficiency in the use of mental resources, as the efficiency in functioning of a mental operation is reflected by scores on both these dimensions.

Without any additional analyses, no inference could be made to distinguish the performance of meditators from that of controls, considering the efficiency of attentional processing. To introduce a measure of efficiency in which both RT and ES are considered, we opted for the strategy to analyse ES for responses with the same RT (see RT-bin analysis and logistic regression analysis in the Results section for details).

Both the RT-bin analysis and logistic regression analysis showed meditators to be more accurate when identical RTs are considered. This gripping result, in our view, reflects a general increase in efficiency in attentional processing in meditators (see Figure 7). As such, it provides evidence for the suggestion by Chan and Woollacott (2007) that mindfulness meditation enhances one's general performance on attentional tasks.

Conclusions

We have found that (a) meditators show a significant better orienting of attention and a trend towards a significantly better executive attention and that (b) meditators show a significantly higher degree of attentional processing efficiency than controls.

The present study can be considered as an answer to Posner's observation that "training of attention either explicitly or implicitly is sometimes a part of the school curriculum, but additional studies are needed to determine exactly how and when attention training can best be accomplished and its long-lasting importance" (Posner & Rothbart, 2007, p. 13).

Despite of our study being cross-sectional, our results seem to point to the possibility to train our attentional system through an extensive mental training, known as mindfulness meditation, in order to obtain a systematic and sustained betterment in attentional processing as compared to normal functioning.

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