This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier’s archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright
Mindfulness meditation associated with alterations in bottom-up processing: Psychophysiological evidence for reduced reactivity

Paul A.M. van den Hurk a,b, Barbara H. Janssena, Fabio Giommi a, Henk P. Barendregta, Stan C. Gielena,b

a Radboud University Nijmegen, Faculty of Science, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands
b Radboud University Nijmegen, Donders Institute for Brain, Cognition and Behaviour, Geert Grooteplein 21, 6525 EZ Nijmegen, The Netherlands

Article history:
Received 13 May 2010
Received in revised form 5 July 2010
Accepted 6 July 2010
Available online 13 July 2010

Keywords:
Bottom-up processing
Intersensory facilitation
Mental training
Mindfulness meditation
Start/React effect

Abstract

Mental training by meditation has been related to changes in high-level cognitive functions that involve top-down processing. The aim of this study was to investigate whether the practice of meditation is also related to alterations in low-level, bottom-up processing. Therefore, intersensory facilitation (IF) effects in a group of mindfulness meditators (MM) were compared to IF effects in an age- and gender-matched control group. Smaller and even absent IF effects were found in the MM group, which suggests that changes in bottom-up processing are associated with MM. Furthermore, reduced interference of a visual warning stimulus with the IF effects was found, which suggests an improved allocation of attentional resources in mindfulness meditators, even across modalities.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

In recent years there has been a significant increase in research on the effects of meditation on brain and behavior (Davidson et al., 2003; Kabat-Zinn, 2003; Moore and Malinowski, 2009; Slagter et al., 2007; van den Hurk et al., 2010). Among other findings, meditation has been associated with improvements in attentional processing (Lutz et al., 2009; van den Hurk et al., 2010) and better resource allocation (Slagter et al., 2007). One of the most consistent findings has been better executive attention as shown by improved performance of meditators in Stroop-like tasks (Chan and Woollacott, 2007; Moore and Malinowski, 2009; van den Hurk et al., 2010). The improvement in executive attention points to a greater ability of meditators to inhibit incorrect responses and suggests a reduction in reactivity due to improved top-down control. Actually, many, if not all, research findings on meditation related effects have been limited to high-level, top-down processing. To our knowledge, only in a recent study by Vastergaard-Poulsen et al. (2009), have differences between meditators and non-meditators in low-level brain structures been investigated. An increase in gray matter density in the medulla oblongata, a brain region in the lower brain stem, was found in meditators. Thus, the aim of our study was to investigate whether also functional differences in low-level, bottom-up processing are associated with meditation.

One well-known phenomenon that is considered to reflect bottom-up processing is intersensory facilitation (IF) (Kirchner and Colonius, 2005). IF stands for the reduction in reaction time (RT) to a stimulus presented in one modality when it is accompanied, close in time, by the presentation of a stimulus in another modality (Keuss et al., 1990; Kirchner and Colonius, 2005; Schmidt et al., 1984; Stoffels et al., 1985). For example, Keuss et al. (1990) demonstrated that non-informative sounds (auditory accessories) of low to moderate intensity facilitate RT to a visual stimulus. Even more, they showed that visual choice reactions become faster with increasing intensity of the auditory accessory, which is remarkable since the auditory stimulus does not provide any information about the correct response. Interestingly, the latter finding on IF effects by Keuss et al. (1990) bears a close resemblance to the Start/React Effect (SRE), i.e., the fact that high intensity, startle inducing auditory stimuli (high intensity accessory) can speed up simple as well as choice visual RT in comparison with auditory stimuli of moderate intensity (Oude Nijhuis et al., 2007; Vallis-Sole et al., 1995). In addition to RT facilitation as observed in IF, the SRE has been associated with increases in speed and acceleration of movement (Siegmund et al., 2001). Contrary to previous research findings, which suggested that the SRE is the result of startle, recent studies provided compelling evidence for the view that the SRE reflects stimulus-intensity facilitatory effects (Carlsen et al., 2007; Lipp et al., 2006). As such, the SRE might be considered as a specific case of IF with auditory accessories of moderate and high intensity, of which the latter have high potential to elicit a startle response.

The research findings of reduced reactivity due to improved high-level, top-down processing led us to the hypothesis that meditation
might be related to reduced (re)activity in low-level, bottom-up processing. In order to test this first hypothesis, a group with extensive mindfulness meditation (MM) experience was compared to an age- and gender-matched control group on IF effects in a visual choice reaction time task involving head rotations. The level of IF was indexed by the size of the SRE in the following outcome parameters: onset latency of head rotation, onset latency of EMG activity in neck muscles, peak angular velocity of head rotation and peak angular acceleration of head rotation. A reduction in (re)activity in bottom-up processing would be revealed by attenuated IF effects. In other words, for each of the outcome parameters a smaller SRE in the MM group was expected. In addition, since previous literature showed that a visual warning stimulus seems to draw attention away from the auditory modality and, as a corollary, reduces the influence of auditory stimuli (Lipp et al., 2000; Schicatano and Blumenthal, 1998), we wanted to test the second hypothesis that, due to an improved deployment of attentional resources in the group of meditators (Slagter et al., 2007; van den Hurk et al., 2010), the IF effects are less affected by an interfering visual warning stimulus in this group. For this reason, trials with and without a visual warning stimulus were presented and the condition without an interfering visual warning was considered the default condition in which to study the IF effects.

2. Methods

2.1. Ethical approval

The experiment was done in accordance with the standards of the Declaration of Helsinki and was approved by the local ethical committee, i.e., Central Committee on Research on Human Subjects (CCMO) region Arnhem/Nijmegen. All subjects gave written informed consent before start of the experiment. They were paid 15 euros for participation in the experiment and received a refund of their travel expenses.

2.2. Subjects

Thirteen experienced mindfulness meditators and thirteen healthy controls, matched on age and gender, participated in this study. The matching was done in such a way that for each mediator a control subject with the same gender and the same age ±3 years was selected. Each group consisted of 8 males and 5 females. The mean age of the meditators was 46 (SD = 14) years, with a range of 28–64 years. The mean age of the controls was 45 (SD = 16) years, with a range of 26–67 years. The meditators had a mean MM experience of 14 (SD = 11) years, with a range of 2–36 years. The controls did not have any meditation experience.

2.3. Experimental setup

During the experiment, subjects sat in a dark room in front of a projection screen with a width of 2.70 m and a height of 2.00 m at a distance of 80 cm (between the tip of the nose and the screen). Prior to the experiment, three axes were defined relative to the subject as x-axis (anterior–posterior), y-axis (left–right) and z-axis (up–down). All measured positions refer to this coordinate system. The position of the cyclopean eye of the subject was aligned with a fixation cross that was presented right in front of the subject at the center of the screen. Subjects were strapped to the chair with two seatbelts running from the shoulders to the hips in order to ensure that only head rotations could be made. Spatial cues (white circles with diameter of 5 cm) were projected either 8° to the left or to the right on the y-axis from the centrally projected fixation cross. The target stimuli were white circles (diameter = 12 cm), printed on black, A4-sized paper, positioned 60° to the left and right on the y-axis from the subjects’ center (see Fig. 1 for a schematic overview of the experimental setup). The fixed locations of the central fixation cross and target stimuli ensured similar head rotations across conditions and subjects.

2.3.1. Choice reaction time task

Subjects were instructed to rotate their head as fast as possible from the central fixation cross to the target stimulus when a spatial cue was presented. A spatial cue presented to either the left or right of the central fixation cross instructed the subjects to rotate their head to the left or right target stimulus, respectively. Spatial cues were presented on an equal (50%–50%) basis for left and right targets. In warning trials the central fixation cross turned from white into a red color, signaling the subjects that the spatial cue would appear within 1 to 3 s. In trials without a warning stimulus (no-warning trials) the central fixation cross did not change color. Warning and no-warning trials were randomly presented on a 50%–50% basis (see Fig. 2 for a schematic overview of warning and no-warning trials). High intensity (HI) acoustic stimuli were presented in one-third of all trials to reduce habituation to this stimulus and moderate intensity (MI) stimuli were presented in the remaining trials. All combinations of left versus right rotation, warning versus no-warning, and HI versus MI acoustic stimuli yielded 8 different types of trials that were presented in a pseudo-random order. Before the start of the actual experiment, five practice trials were presented, including one HI trial. The actual experiment consisted of six blocks of 24 trials giving a total of 144 trials (72 warming and 72 no-warming trials). The whole experiment lasted for about 30 min. In between blocks subjects were given time to pause and could indicate the start of the next block when they felt ready.

2.3.2. Acoustic stimuli

Acoustic stimuli with a duration of 300 ms were used. The onset of the acoustic stimuli was simultaneous with the onset of the spatial cues as in previous studies (Keuss et al., 1990; Oude Nijhuis et al., 2007). HI (MI) acoustic stimuli were presented with an intensity of 107 (67) dB measured at the location of the subjects head with a Bruel & Kjaer measuring amplifier type 2610. Two acoustic stimuli with frequencies of 2000 and 2500 Hz were randomly used in order to prevent habituation effects to the stimulus. The acoustic stimuli were sent out by a SM10 loudspeaker located 1.5 m directly behind the subject, similarly as in Carlsen et al. (2007). In this way, the acoustic stimulus did not provide any spatial information about the target position. See also Oude Nijhuis et al. (2007), who showed that the location of the acoustic stimulus source did not affect the response. Timing of the fixation cross, the visual cues and the auditory stimuli as

![Fig. 1. Experimental setup. Posterior schematic overview of the experimental setup showing a subject sitting in the chair in front of the screen. Spatial cues are indicated by SC. The visual target stimuli are indicated by T. In each trial, a spatial cue was presented either to the left or to the right of the subject, signaling the subject to make a head rotation to either the left or right target stimulus, respectively.](image-url)
well as the trigger to start the data acquisition was arranged using Presentation software (Neurobehavioral Systems Inc., Albany, USA).

2.4. Data acquisition and analysis

We determined onset time of i) head rotation and ii) EMG activity in the left and right SCM muscles relative to the onset time of the visual spatial cue as two parameters that index the SRE. In addition, since Siegmund et al. (2001) showed that peak angular velocity and acceleration are increased by HI auditory stimuli, these parameters were also considered as probes of the SRE. All data were analyzed using customized Matlab programs (The Mathworks Inc., Natick, MA, USA).

Because of technical problems, not all trials could be used for data analysis in three control subjects. For these subjects, the number of trials was reduced to 46, 47 and 53 no-warning trials and 53, 59 and 60 warning trials, respectively. The scores for these subjects were very similar to the results for the other subjects in the control group.

2.4.1. Kinematic analysis of head rotation

An infrared light emitting diode (IRED) was mounted on a headband at the right frontal side of the subject’s head to measure head movements (see Fig. 1). An Optotrak 3020 motion analysis system (Northern Digital Inc., Waterloo, Canada), consisting of three cameras, tracked the position of the IRED with an accuracy of 0.1 mm or better in all directions. The Optotrak system was mounted on the ceiling above the subject at a distance of approximately 2 m from the seated subject, tilted downward at an angle of 30° relative to the ceiling. All measured positions of the IRED in this manuscript refer to the coordinate system fixed to the subject, as described in Section 2.3. Angular velocity data were obtained by differentiation of the head-position data and were smoothed by a first order Savitsky-Golay (1964) filter. Differentiation of velocity data yielded angular acceleration data. Recordings started 200 ms pre-stimulus (baseline) in sweeps of 2000 ms with a sample rate of 500 Hz. The onset latency of head rotation was determined directly from the acceleration data. Onset values outside the range of the mean ± 3 standard deviations (<1% of onset values) for a specific condition were considered as outliers and excluded from analysis. Error trials, in which the subjects responded by head rotations in the wrong direction or made no head rotation, were excluded from kinematic as well as EMG analyses. The mean differences in onset, peak angular velocity and peak angular acceleration of head rotation between the HI and MI conditions were defined as SREs on kinematics of head rotation, according to Oude Nijhuis et al. (2007).

2.4.2. EMG

Electromyographic activity was measured in both the left and right SCMs using Ag–AgCl electrodes. The electrodes were placed 3 cm below the mastoid process and 3 cm above the collarbone on the SCM. A reference electrode was placed on the upper verbra. EMG signals were recorded for 2 s, starting 200 ms before the spatial cue and auditory stimulus onset, with a sampling rate of 500 Hz. After pre-amplification, the EMG signal was passed through an analog band-pass filter (with low-pass frequency of 150 Hz and high-pass frequency of 10 Hz), converted to a digital signal and finally stored on a computer.

In an off-line analysis, this digital EMG signal was first rectified and then smoothed with a Savitsky-Golay filter (frame size 31 and polynomial order 2). For each trial the EMG activity onset was determined in the agonist muscle. The onset was defined as the first time point in a trial after which the threshold value was exceeded for 50 consecutive milliseconds. This threshold value was calculated by adding 3 standard deviations to the mean of the EMG in the baseline period of the trial preceding stimulus onset. All automatically determined onset latencies were visually inspected and adjusted when the algorithm did not find the correct onset latency. Onset values outside the range of the mean onset ± 3 standard deviations (<1% of onset values) for a specific condition were considered as outliers and were excluded from the analysis. The mean difference in the onset of EMG activity between the HI and MI conditions was defined as the SRE on EMG activity, according to Oude Nijhuis et al. (2007).

2.5. Statistical analyses

Because of the skewed distributions of onset, velocity and acceleration data, data were log-transformed before running statistical analyses. A similar statistical procedure was followed for scores on all outcome parameters. Three within-subject factors were distinguished: warning condition (WC; warning versus no-warning), stimulus intensity (SI; HI versus MI) and mindfulness meditation experience (MM; yes versus no). MM was considered a within-subject factor because control subjects were strictly matched to meditators on age and gender. More specifically, for each meditator a specific control subject, with a comparable age (±3 years) and the same gender, was selected. In this way, subject-pairs were formed and two related – instead of two independent – samples were obtained. At the group level, outliers were defined as parameter values that deviated from the nearest quartile by more than 1.5 times the interquartile range. These outlier values were excluded from analysis together with the corresponding score of the matched subject in the mental training or control group (see Table 1).
In order to test our hypothesis that mental training by MM is associated with a smaller SRE, we first tested whether a significant SRE was present in both groups in the no-warning condition with a paired-samples t test. A significant SRE in the control group would provide evidence for the validity of the design of our study in producing the phenomenon of interest, i.e., the SRE. In addition, the presence of a significant SRE in both groups seemed a precondition for a meaningful comparison. If a significant SRE were present in both groups, then our hypothesis – that the mental training by MM is associated with a smaller SRE – would be tested by a one-sided paired t test.

If a significant SRE would be present in both groups in the no-warning condition, the interaction term between warning and SI condition would be probed for both groups, indicating the size of the interfering effect of a visual warning stimulus. When both groups would show significant interference, a meaningful comparison could be made with respect to the size of the interference by probing the three-way WC×SI×MM interaction.

### 2.6. Baseline EMG activity

In order to check whether baseline EMG activity affected the scores on the outcome parameters, we tested whether baseline EMG activity was related to scores on outcome parameters. For each trial the area under the curve (AUC) of the last 100 ms baseline period before the spatial cue was determined for both the left and right SCMs. Since no lateraled differences in baseline EMG activity were to be expected – because the test was a choice reaction time task – AUCs of left and right SCMs were added for each single trial to obtain the total AUC. Trials were then categorized as either warning or no-warning trials. Trials were defined as outliers if the total AUC of that trial exceeded the mean total AUC for that condition ± three standard deviations. These outlier trials (∼1% of all trials) were excluded from analysis. Then, the mean total AUC for the warning and the no-warning conditions was determined from the remaining trials for each subject. Because of the skewed distributions group AUC data were log-transformed. At the group level, outliers in the log-transformed AUC data were defined as values with a distance from the nearest quartile greater than 1.5 times the interquartile range and no outliers were found. The EMG data of one meditator could not be analyzed due to technical problems. We tested whether baseline EMG activity was related to scores on the outcome parameters using the correlation between baseline EMG activity and scores on outcome parameters. For each outcome parameter, separate correlation analyses were run for the warning and no-warning conditions to test whether baseline EMG activity in that condition was related to scores on the outcome parameter in either the MI or HI condition.

### 2.7. Response errors

For each subject and condition the percentage of trials with incorrect responses was determined. Incorrect responses were defined as (initial) head rotations in the wrong direction or the absence of a clear head rotation. Repeated-measures ANOVA with incorrect response data was run with factors WC, SI and MM to test main and interaction effects. This additional analysis was run to test whether groups differed in response accuracy across conditions.

### 2.8. Number of startle responses

For each subject and condition we determined the percentage of trials with startle activity. According to Carlsen et al. (2007), EMG activity in SCM was classified as startle if the onset occurred within 120 ms following stimulus onset. Repeated-measures ANOVA with startle activity data was run with factors WC, SI and MM to test main and interaction effects. This additional analysis was run to test what extent differences on outcome parameters reflected effects of startle or rather IF effects.

### 3. Results

#### 3.1. Onset latency of head rotation

Fig. 3 shows the average over all movement trials for the EMG activity of the right SCM (top panel), left SCM (middle panel) and the absolute value of head displacement (lower panel) for the HI responses (solid line) and for MI responses (dashed line) for a control subject. Fig. 3 illustrates that HI responses have clearly shorter onset latencies than responses to visual stimuli with an accompanying MI acoustic stimulus, which is in agreement with the findings of Nijhuis et al. (2007). These qualitative results will be analyzed more quantitatively below.

The quantitative differences for head rotation onset latencies of both groups are shown in Fig. 4. In the no-warning condition, both groups showed a significant SRE, F(1,11) = 16.24, p < 0.01, η² = 0.60 with a mean reduction of 20.7 (SD = 16.4) ms in onset time for the mental training group and F(1,11) = 14.98, p = 0.01, η² = 0.58 with a mean reduction of 33.2 (SD = 26.1) ms for controls (see Table 1). The difference in the size of the SRE between groups approached the level of significance, t(11) = −1.74, p = 0.06, suggesting a smaller SRE in the mental training group.

<table>
<thead>
<tr>
<th>Outcome parameter</th>
<th>Mental training</th>
<th>No warning</th>
<th>Warning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Condition</td>
<td>MI</td>
<td>HI</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HRO</td>
<td>Yes</td>
<td>196.6 (41.4)</td>
<td>175.9 (51.3)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>180.7 (50.2)</td>
<td>147.5 (52.5)</td>
</tr>
<tr>
<td>PAV</td>
<td>Yes</td>
<td>3.4 (1.8)</td>
<td>3.6 (2.5)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>4.1 (0.5)</td>
<td>4.5 (0.4)</td>
</tr>
<tr>
<td>PAA</td>
<td>Yes</td>
<td>38.2 (23.3)</td>
<td>45.9 (39.5)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>38.1 (11.1)</td>
<td>42.2 (11.5)</td>
</tr>
<tr>
<td>EO</td>
<td>Yes</td>
<td>177.4 (42.2)</td>
<td>156.1 (34.8)</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>161.7 (49.3)</td>
<td>128.6 (47.2)</td>
</tr>
</tbody>
</table>

Due to outlier rejection, data of 1, 3, 1 and 1 subject-pairs were deleted from the analysis of HRO, PAV, PAA and EO data, respectively.

*p < .01, †p < .05, ‡p < .10.

Table 1

Overview of scores of both groups in all experimental conditions on all outcome parameters. Scores represent group means and standard deviations are placed between parentheses.
In summary, the mental training group showed i) a trend towards a significantly smaller SRE than the control group, and ii) no interfering effect of a visual warning stimulus with the SRE, contrary to the results for the control group. These results seem to provide support for both our hypotheses.

3.2. Peak angular velocity of head rotation

For the no-warning condition a significant SRE was found in the group of controls, $F(1,9) = 15.05$, $p < 0.01$, $\eta^2 = 0.63$ with a mean increase of 0.4 (SD = 0.3) rad per second in angular velocity, whereas no significant SRE was found for the mental training group ($p > 0.85$).

In the control group a significant WC×SI interaction was observed, $F(1,9) = 9.4$, $p < 0.05$, $\eta^2 = 0.51$. Also in the warning condition the control group showed a significant SRE, $F(1,9) = 5.79$, $p < 0.05$, $\eta^2 = 0.39$, but the mean increase in peak angular velocity was smaller (0.234 (SD = 0.3) rad per second) than for the no-warning condition.

The absence of a SRE for peak angular velocity in the mental training group is in line with our first hypothesis that mental training is associated with a smaller SRE. This result excluded the possibility to test our second hypothesis that the SRE in the mental training group would be less affected by a visual warning stimulus. Interference of the visual warning stimulus with the SRE was found in the control group.

3.3. Peak angular acceleration of head rotation

For the group of controls a significant SRE was found, $F(1,11) = 12.73$, $p < 0.01$, $\eta^2 = 0.54$ for the no-warning condition with a mean increase of 7.12 (SD = 7.5) rad/s² in peak angular acceleration, whereas no significant SRE was found for the mental training group ($p > 0.75$).

For the group of controls no significant WC×SI interaction was observed ($p > 0.15$).

Thus, similarly to the peak angular velocity results, the complete absence of a SRE for peak angular acceleration in the mental training group seems to confirm our first hypothesis. This result, however, did not allow us to test our second hypothesis. For the group of controls, no significant interfering effect of the warning stimulus was seen.

3.4. Onset latency of EMG activity

For the no-warning condition, both groups showed a significant SRE for onset of EMG activity with a mean reduction of 21.3 (SD = 15.6) ms in onset time for the mental training group, $F(1,10) = 16.48$, $p < 0.01$, $\eta^2 = 0.62$ and a mean reduction of 33.1 (SD = 25.3) ms in onset time for the control group, $F(1,10) = 15.66$, $p < 0.01$, $\eta^2 = 0.61$. The difference in the size of the SRE between groups approached the level of significance ($p = 0.05$), which suggests that the mental training is related to a smaller SRE.

In the group with mental training a trend towards a significant WC×SI interaction was observed ($p = 0.05$) and in the control group a significant interaction was seen, $F(1,10) = 5.27$, $p < 0.05$, $\eta^2 = 0.35$. In the warning condition, the mental training group showed a trend towards a significant SRE ($p = 0.08$) with a mean reduction of 8.6 (14.8) ms, whereas no SRE was present in the control group. The WC×SI×MM interaction was not significant ($p = 0.3$).

In summary, the trend towards a significantly smaller SRE in the mental training group provided support for our first hypothesis. The non-significant WC×SI×MM interaction did not provide support for our second hypothesis that the mental training is associated with a smaller effect of a visual warning stimulus.
3.5. Mean baseline EMG activity

The correlation analyses showed that, neither in the no-warning nor in the warning condition, mean baseline EMG activity was related to scores on any of the outcome parameters in the MI or HI condition (all p-values ≥ 0.10). This result implies that differences between groups in scores on outcome parameters cannot be explained by differences in baseline EMG activity.

3.6. Response errors

With repeated-measures ANOVA only the main effect of SI was found, F(1,10) = 16.86, p = 0.01, η² = 0.63, with a higher percentage of trials with incorrect responses in the HI versus the MI condition. No main effects for WC and MM or interaction effects were found. Response error percentages for both groups are shown in Table 2, specified for each condition.

3.7. Number of startle responses

With repeated-measures ANOVA only the main effect of SI was found, F(1,11) = 6.37, p < 0.05, η² = 0.37, with a higher percentage of trials with startle activity in the HI than in the MI condition. No main effects for WC and MM or interaction effects were found. Percentages of trials with startle activity for both groups are shown in Table 3, specified for each condition.

4. Discussion

The main results of this study are that the MM group showed no significant SRE for peak angular velocity and peak angular acceleration of head rotation and a trend towards a significantly smaller SRE for onset latency of head rotation and onset latency of EMG activity. Furthermore, the MM group revealed no interference of a visual warning stimulus with the SRE for head rotation onset. Age and gender-matched control subjects showed i) a significant SRE for all outcome parameters and ii) interference with the SRE by a visual warning stimulus for three out of the four outcome parameters.

4.1. Mindfulness meditation and attenuated IF effects

The results of our study support the first hypothesis that MM is related to attenuated IF effects, as shown by the smaller or even absent SREs in the MM group. Because scores on outcome parameters were not probed in the absence of an auditory accessory in our study, the scores (obtained from a bimodal condition in which both a visual spatial cue and an auditory accessory were presented), could not be compared to scores in a unimodal condition, which is not affected by IF effects. However, inspired by the argument of Keuss et al. (1990), we opted for testing IF effects by presenting auditory accessories (of different intensities) in all trials. Keuss et al. (1990) stated that “RT is considered to be not so much a function of the particular stimulus presented but of that stimulus in relation to other possible stimulus events. Consequently, the subtraction method – subtracting scores of unimodal (catch) trials from bimodal (intersensory) trials to estimate the (additional) intersensory effect – may overestimate the size of the intersensory effect”. (Keuss et al., 1990, p. 44). In line with this reasoning, the bimodal MI condition in our study can be considered as a proper reference condition for the bimodal HI condition, in order to determine the size of IF effects.

Considering the fact that IF is considered to reflect involuntary, automatic processing (Kirchner and Colonius, 2005; Schmidt et al., 1984), it seems striking to find an attenuation in IF to be related to MM. To our knowledge, this study is the first study that relates MM to functional alterations in low-level, bottom-up processing and suggests that the potential of mental training by meditation is not limited to changes at high-level top-down processing. Interestingly, in a recent study, Vestergaard-Poulsen et al. (2009) found structural differences between meditators and control subjects in a low-level brain stem structure. More specifically, in meditators an increase in gray matter density in the medulla oblongata was seen, a region known to be involved in relaying sensory inputs from the body and in respiratory and cardiac control. Their findings together with related findings – increases in vagal tone and lower cortisol levels in meditators – were suggested by Vestergaard-Poulsen et al. to be a possible mechanism for the finding that regular practice of meditation can induce increased resistance to stressful stimuli, increased attentional skills and the increased sense of calmness commonly reported by meditation practitioners. Our results of reduced IF and interference effects seem to fit strikingly well into this pattern of research findings on meditation related effects.

The differences in IF effects could not be explained by the amount of baseline EMG activity as correlation analyses showed that scores on outcome parameters were not related to baseline EMG activity. Also the number of response errors could not explain the differences in IF effects, as no differences in the amount of response errors between the MM and control group were observed. Noteworthy, the finding of an increase in the percentage of response errors in the HI condition versus the MI condition adds further evidence to the general view that 70 to 80 dB marks the limit above which performance deteriorates (Keuss et al., 1990). Interestingly, our results seem to provide additional evidence for a dissociation between startle and the SRE (Carlson et al., 2007; Lipp et al., 2006), as groups showed differences in the SRE, but not in the number of trials with startle activity. A possible cause for the absence of differences in startle activity might be the relatively small number of startle responses that were observed, which could reflect a floor effect that excludes the possibility to differentiate between groups. Since the different processing stages of the visual spatial cue were not manipulated in the current experiment, the exact locus of the difference in IF effects between groups could not be determined. According to what seems to be the most suitable view to explain IF effects, i.e., the preparation-enhancement view, the auditory accessory has an alerting or arousing role that may alter processing in a number of stages (Schmidt et al., 1984). Thus, it would be interesting for further research to investigate which specific processing stage(s) are affected by MM, resulting in the attenuated IF effects.

Table 2
Overview of response error percentages for both groups specified for all conditions. Scores represent group means and standard deviations are placed between parentheses. MI = moderate intensity accessory, HI = high intensity accessory.

<table>
<thead>
<tr>
<th>Mental training</th>
<th>No warning</th>
<th>Warning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MI</td>
<td>HI</td>
</tr>
<tr>
<td>Yes</td>
<td>0.6 (1.0)</td>
<td>3.4 (4.1)</td>
</tr>
<tr>
<td>No</td>
<td>2.4 (2.6)</td>
<td>5.5 (8.4)</td>
</tr>
</tbody>
</table>

Table 3
Overview of fraction of trials (%) with startle activity for both groups specified for all conditions. Scores represent group means and standard deviations are placed between parentheses. MI = moderate intensity accessory, HI = high intensity accessory.

<table>
<thead>
<tr>
<th>Mental training</th>
<th>No warning</th>
<th>Warning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Condition</td>
<td>MI</td>
</tr>
<tr>
<td>Yes</td>
<td>13.2 (6.0)</td>
<td>15.3 (4.8)</td>
</tr>
<tr>
<td>No</td>
<td>15.5 (6.3)</td>
<td>18.8 (7.5)</td>
</tr>
</tbody>
</table>
4.2. Interference of visual warning stimulus

The pronounced interfering role of the visual warning stimulus with the SRE in the control group has a strong resemblance to the effect of a visual warning stimulus on the acoustic startle response (Schicatano and Blumenthal, 1998; Anthony et al., 1978; Anthony and Graham, 1985; Simons and Zelson, 1985). The study by Schicatano and Blumenthal (1998) showed that attention being directed to a visual search task during presentation of an acoustic startle stimulus was associated with a decrease in startle amplitude and probability, and with an increase in startle latency. Schicatano and Blumenthal stated that “these findings support previous research by showing that the attentional modulation of startle is sensitive to the attended modality, such that the startle reflex is larger when the modality of the startle stimulus and attended stimulus match compared to when they do not match” (Schicatano and Blumenthal, 1998, p. 149). This interpretation by Schicatano and Blumenthal is in line with the interpretation given by Lipp et al. (2000) who stated that “the enhanced startle magnitude facilitation in the modality match condition may reflect an attentional mechanism that facilitates the processing of all stimuli presented in an attended modality, inhibiting processing in an ignored modality, or results in both” (Lipp et al., 2000, p. 63). In addition, Lipp et al. (2000) stated that “such a modality-specific attentional mechanism may affect stimulus processing at a very early stage, by, for instance, changing the threshold of sensory receptors” (Lipp et al., 2000, p. 63). Thus, it seems likely that the interference of the visual warning stimulus with the SRE in the control group of our study can be explained by the ability of the visual stimulus to draw attention to the visual modality and, in doing so, away from the auditory modality, which results in an attenuated effect of the auditory accessory. At this point it is interesting to consider the less pronounced interfering role of the visual warning stimulus in the MM group, as no interference with the SRE for head rotation onset latency and only a trend towards a significant interference for onset of EMG activity were found. This reduced interference in the MM group suggests that mental training by MM is related to a better distribution of attentional resources, not only within one modality, but even across the visual and auditory modalities. As such, these results seem to extend the view of Slagter et al. (2007) and van den Hurk et al. (2010) – who associated MM with a better control over visual attentional resources and greater efficiency in visual attention processing, respectively – from intra-modality to inter-modality improvements in the deployment of attentional resources.

4.3. Limitations of the current study

Because of the cross-sectional design of the current study, we have to be careful to conclude that the observed differences in IF effects and attentional resource allocation in the MM group are due to the mental training per se. Pre-existing differences between groups, that actually predict whether one is likely to start with a MM practice, might underlie the differences between groups, rather than the MM practice itself. Future longitudinal research could resolve this issue by investigating whether a period of mental training (by MM) actually induces changes in IF effects.

All subjects in the MM group of this study have experience with Vipassana meditation (2–36 years), which is also known as mindfulness meditation. Vipassana meditation consists of both concentration meditation (focused attention: FA) and mindfulness meditation (open monitoring: OM). FA is generally considered to be the base of the practice (that is trained first), upon which the ability of OM is cultivated. Thus, all subjects have experience with both FA and OM meditations and it seems very difficult to get a reliable estimate of the respective contribution of the two different forms as they appear to become more and more intertwined along the practice. In our view, in order to differentiate between FA and OM effects, it might be interesting for future research to investigate whether mediators with only FA experience reveal a similar pattern of results.

5. Conclusions

In this study, MM was related to attenuated IF effects as shown by smaller or even absent SREs for outcome parameters in a choice reaction time task involving head rotations. This finding suggests that mental training by MM affects low-level, bottom-up processing. Further research is needed to determine which specific neuronal processing stages are affected by MM to result in reduced reactivity in bottom-up processing. In addition, the less pronounced interfering role of a visual warning stimulus with the SRE suggests that MM is related to a better, more widespread allocation of attentional resources, even across modalities.

References