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Title: **The effects of 8-weeks Mindfulness-Based Stress Reduction program on cognitive control: an EEG study**

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## Abstract

**Objectives**

Mindfulness practice can enhance different aspects of attentional functions, such as the ability to sustain the attentional focus over time. However, it is still unclear whether this practice might indeed impact higher cognitive functions, such as control mechanisms that allow the appropriate and flexible allocation of attentional resources. In this longitudinal study, changes associated with a Mindfulness-Based Stress Reduction (MBSR) program were investigated, with a focus on proactive and reactive cognitive control mechanisms, namely, the ability to maintain task-relevant information and to prepare in advance the response and the ability to promptly adjust overlearned behaviors in response to conflicting stimuli.

**Methods**

Two groups of participants took part in the study: 26 participants who completed a formal MBSR training (mean age = 43 years, females = 21) and 23 participants who performed a control training (mean age = 47.2 years, females = 20). They were tested on a modified AX-Continuous Performance Task (AX-CPT), before and after 8 training weeks. The electroencephalographic (EEG) signal was recorded during task execution, and amplitude modulations of event-related potentials (ERPs) associated with cues and probes were examined.

**Results**

After the training, the MBSR group exhibited a significant reduction of errors on high conflicting trials. Concurrently, the Contingent Negative Variation (CNV), an index of anticipatory processes, elicited by task cues became more pronounced in post-training session in the MBSR group only. In addition, an attenuated probe-locked N2 amplitude and an increased P3a component emerged.

**Conclusion**

Taken together, the electrophysiological and behavioral results suggest that the mindfulness practice enhanced the ability to implement both proactive and reactive cognitive control processes.



**Keywords:** Meditation; Cognitive Control; AX-CPT; Event-related Potentials; Mindfulness Based Stress Reduction Program; Proactive Control Strategy



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Mindfulness has been conceptualized as an attentional regulatory training which aims to calm and stabilize mind while cultivating an open and non-elaborating attitude toward one's own experience (Lutz, Slagter, Dunne & Davidson, 2008; Malinowski, 2013). In recent years, the study of the cognitive effects of mindfulness practice is receiving a growing interest. However, there is no clear consensus about the exact cognitive processes that are involved in and shaped by this meditation practice. Recently, some interesting attempts have been made to create a coherent theoretical framework regarding the neurocognitive processes underlying mindfulness (e.g., Raffone et al., 2019). A large body of research has shown mindfulness-related effects on attentional processes, such as selective and sustained attention, as well as on executive functions, such as inhibition (for reviews see Chiesa, Calati & Serretti, 2011; Gallant, 2016; Lutz et al., 2008). However, little research has been devoted to investigate the neural dynamics underpinning these changes (see Tang, Hölzel & Posner, 2015 for a review).

A functional magnetic resonance study showed an increase of the hemodynamic brain activity in the orbitofrontal cortex during a body mental rotation task, after a 8-week mindfulness training (Tomasino, Campanella & Fabbro, 2016). Another longitudinal study found a cortical thickness increase in the right insula and in the somatosensory cortex after a 8-week Mindfulness Based Stress Reduction (MBSR) training (Santarnecchi et al., 2014). Interestingly, this increase correlated with a decrease in psychological indices associated to alexithymia, worry, anxiety and depression. Group differences in the right insula, and specifically a stronger functional coupling of this area with the lateral prefrontal cortex, were also found in a cross-sectional study comparing MBSR practitioners to a naive group (Farb et al., 2007). This effect was interpreted as a change in self-referential processes. Overall, neuroimaging findings have suggested that mindfulness training might impact brain structures and their functioning.

Similarly, electroencephalographic (EEG) evidence has accounted for meditation-related effects on brain activity (see Cahn & Polich, 2006 for an extensive review). For instance, Moore, Gruber, Derose and Malinowski (2012) compared the EEG markers of executive functions of a group of participants in a 8-week MBSR program with a waiting list control group. To this end, the classical Color-Word Stroop task was administered, which requires to inihibit a dominant automatized process (e.g., reading a word) in favor of a task-relevant but weaker one (e.g., naming the font color of the word). At the behavioral level, no differential changes were found between meditation and control group. In constrast, a significant effect of mindfulness practice emerged in two event-related potential (ERP) components, that is, the N2 and P3, over occipito-parietal and parietal scalp sites, respectively. Interestingly, the P3 amplitude decreased when evoked by incongruent stimuli. This finding was interpreted as less demanding allocation of attentional resources to monitor conflicting stimulus-response (S-R) associations, in the meditation group only (Moore et al., 2012). A meditation-related effect on a more anterior P3 component (i.e., the P3a) was also observed in a cross-sectional study employing a passive three-stimulus oddball task (Cahn & Polich, 2009). The smaller P3a amplitude elicited by novel stimuli was interpreted as a relative disengagement of the exogenous/stimulus-driven orienting system, since the system became more internally directed and less responsive to unexpected task-unrelated changes. A meditation-related benefit on the ability to allocate attentional resources was also observed in a study by Slagter et al.(2007), which employed the attentional blink paradigm to assess the effects of a 3-months meditation retreat. In this study, the group of meditators exhibited an improved detection of the target stimulus when the P3 evoked by the preceding stimulus was attenuated. This evidence suggested that meditation training resulted in more efficient deployment of attentional resource allocation over time, in accordance with task requirements (Slagter et al., 2007).

Another ERP component that was found to be modulated by meditation practice is the Contingent Negative Variation (CNV; Walter, 1964). This potential is typically observed over fronto-central scalp sites and shows a negative going waveform and a slow development. Its peculiarity is that it shows up in anticipation of the onset of target stimuli and its amplitude increases (i.e., becomes more negative) when these targets are task-relevant. Specifically, the CNV is evoked by cue stimuli that announce upcoming probe stimuli and reflects expectancy and preparatory processes (see Mento, 2013 for an extensive review). Two studies, comparing meditators with different length of experience in Trascendental Meditation (TM) and different frequency of self-reported transcendental experiences, reported more negative CNV amplitude over central scalp sites in more experienced meditators (Travis, Tecce, Arenander & Wallace, 2002; Travis, Tecce & Guttman, 2000). Interestingly, when a distracting task was presented (i.e., a short-term memory task), the disruption of the typical CNV development (distraction effect) was higher in less experienced meditators, compared to more experienced ones (Travis et al., 2000). Unfortunately, so far collected evidence concerning the CNV index is limited to cross-sectional designs; longitudinal evidence is needed in order to make more compelling inferences about the relation between meditation practice and observed changes in preparatory processes between meditators and non-meditators (Moore et al., 2012).

Taken together, the ERP findings suggest that meditation practice influences cognitive control functions. Namely, the abilities to allocate attentional resources to task-relevant information over time, to suppress task unrelated information, and to engage preparatory processes are affected. According to the Dual Mechanism of Cognitive Control (DMC), theorized by Braver, Gray & Burgess (2007), cognitive control includes a set of attentional and executive processes that allow individuals to flexibly adapt responses to task demands, emphasizing goal-directed behaviors over habituation and dominant response. Specifically, an efficient cognitive control results from a dynamic interaction between two qualitatively distinct mechanisms, that is, proactive and reactive cognitive control mechanisms (Braver et al., 2007; Braver, 2012). Proactive cognitive control mechanisms includes future-oriented “early-selection” processes, which allow to actively maintain contextual information prior to the occurrence of the demanding events, in order to prepare the response. These preparatory processes bias successive cognitive processing and affect task performance (e.g., memory, perception and action). Reactive cognitive control is instead intended as a past-oriented, “late-correction” process, activated *just-in-time* by target stimuli, to detect and solve interference, when required.

Recently, cognitive control mechanisms have been investigated, such as in people who participated to a Mindfulness-Based Stress Reduction program (MBSR; Kabat-Zinn, 1990), a structured and standardized intervention. In that study (Li, Liu, Zhang, Liu & Wei, 2018), the AX – *Continuous Performance Task* (AX-CPT) paradigm was used. This paradigm tests the dynamic interaction between proactive and reactive cognitive control mechanisms (e.g., Dias, Foxe & Javitt, 2003; Gonthier, Macnamara, Chow, Conway & Braver, 2016; Morales, Yudes, Gómez-Ariza & Bajo, 2015; Richmond, Redick, & Braver, 2015). The task requires to respond to probe stimuli according to the preceding cue stimuli. The study by Li et al. (2018) showed a shift toward the use of more proactive control processes in the treated group. However, no significant interactions emerged when comparing the MBCT with a waiting list control group. Moreover, a follow-up assessment of participants who completed the mindfulness intervention was missing. Therefore, the study was not robust enough to draw firm conclusions about the effectiveness of mindfulness training on cognitive control mechanisms.  Another recent study documented an association between either higher mindfulness traits, as tested by a self-report questionnaire, or a brief mindfulness intervention, and a better balance between the proactive and reactive control systems (Chang, Kuo, Huang & Lin, 2017). Unfortunately, only behavioral measures have been examined. Unlike most of the previous literature, we complemented behavioral data with electrophysiological measures, in order to elucidate the degree of change of these two interacting control processes, both behaviorally and neurally, after a structured mindfulness practice. Specifically, we examined the electrophysiological responses (ERPs) to cue and probe stimuli during the execution of an AX-CPT in a group of MBSR trainees and in a group of age- and education-matched control participants, who underwent a Pilates training. Both groups were tested before and after a 8-week training.

The choice of a standardized structured intervention overcomes a widely discussed limitation of the meditation literature, which is the great heterogeneity of the meditation practices included in the same investigation (Chiesa & Malinowski, 2011). Indeed, both ancient Buddhist meditation, such as Vipassana, Zen and Transcendental Meditation, and modern Mindfulness-based intervention, such as the MBSR (Kabat-Zinn, 1990) and Mindfulness-Based Cognitive Therapy (MBCT; Segal, Williams & Teasdale, 2002), are commonly referred to with the general term of "Mindfulness meditation practice"; however, they largely differ in the way mindfulness is conceptualized and practiced (Chiesa & Malinowski, 2011). The use of the MBSR program clearly defines the generalizability of the findings, facilitates replication, and makes the comparison among studies more reliable.

Pilates trainees were selected as control participants in order to assess non MBSR-specific learning effects. Indeed, the involvement of an active group allowed us to address another important issue, which concerns the choice of an adequate control group. In the meditation literature, the use of an active control group is usually preferred against the widely used passive or waiting list control group, in order to attenuate group biases related to motivational levels (MacCoon, MacLean, Davidson, Saron & Lutz, 2014). Our control participants were engaged in a regular physical training, that is, the practice of Pilates, during 8 weeks. This training is similar to Hatha Yoga in the emphasis that is given on performing correct and harmonious movements, which must be healthy and enjoyable, in contrast with body overtraining (Hoffman & Gabel, 2015). However, there is not any explicit instruction about achieving a mindful state, characterized by self-regulation of attention on present moment experience, typical of the MBSR training (Kabat-Zinn, 1990).

Given previous findings, we expected that the MBSR practice, but not the Pilates one, shall lead to significant changes on behavioral performance and, more importantly, on the associated neural processes. We hypothesized the mindfulness training to modulate some key ERP components, namely, the CNV elicited by cue stimuli, which is linked with an enhanced implementation of proactive cognitive control processes, and the N2 and P3a components elicited by probe stimuli, which are linked with an enhanced implementation of reactive control mechanisms.

## Methods

### Participants

Overall, 29 participants were recruited from 8-week MBSR training course promoted by a local center conducted by instructors certified by the Center for Mindfulness in Medicine, Health Care and Society of the University of Massachusetts (Medical School). Twenty-six participants were included in final statistical analyses, since they completed the training and both pre- and post-training experimental sessions (mean age = 43.6 years, SD = 11.3, range = 26-60 years; mean education = 16.6 years, SD = 2.9; females = 21). Based on Edinburgh Handedness Inventory (EHI; Oldfield, 1971), 23 were right handed (EHI range = 55-100), 2 were mixed right handed (EHI score = 15 and 45, respectively), and one was left handed (EHI score = - 70).

For the Pilates control group, 25 participants were recruited from training classes conducted by local centers specialized in physical well-being and health care. Twenty-three of them regularly attended the Pilates training for 8 weeks, completed both pre- and post-training experimental sessions and were included in the final statistical analyses (mean age = 47.2 years, SD = 11.9, range = 28-67; mean education = 15.5, SD = 3.7; females = 20). Based on the EHI questionnaire, 19 were right handed (EHI range = 60-100), 2 were mixed right handed (EHI score = 45 and 50, respectively), and 2 were left handed (EHI score = -70 and -80, respectively). The two groups did not differ in terms of age ($t(47) = 1.58$, $p = .12$), education level ($t(47) = 1.04$, $p = .30$), and handedness ($t(47) = .05$, $p = .96$).

All participants signed consent forms prior to testing and received a reimbursement of 10 euros soon after each experimental session. The study was approved by the local Ethical Committee in agreement with Helsinki declaration.

## Procedure

Both groups underwent the same procedure. Specifically, all participants performed two identical experimental sessions about 8 weeks apart. At the beginning of each experimental session, a 64-channel EEG cap was mounted and participants were instructed about the task. At the end of each session, they were invited to fill in self-report mindfulness questionnaires.

### *Measures*

Three self-report questionnaires were administered to assess daily subjective experience of mindful states. The questionnaires allowed us to evaluate the level of “dispositional mindfulness”. We expected an increase of scores on all questionnaires in the MBSR group after the training.

### *Mindfulness Attention and Awarness Scale (MAAS)*

The Mindfulness Attention and Awareness Scale (MAAS) is a self-report questionnaire developed to assess individual differences in the frequency of mindful states (Brown & Ryan, 2003; Veneziani & Voci, 2014). The scale is based on a single-factor structure and consists of 15-items that measure the tendency to be attentive and aware of present experience in day to day circumstances.

### *Cognitive Affective Mindfulness Scale-Revised (CAMS-R)*

The Cognitive and Affective Mindfulness Scale-Revised (CAMS-R) is a self-report questionnaire (12-items) developed to assess “attitudes and approaches toward internal experiences of emotions and thoughts” in the general population

(Feldman, Hayes, Kumar, Greeson & Laurenceau, 2007; Veneziani & Voci, 2015). The CAMS-R is based on a broad conceptualization of mindfulness that captures not only a particular type of attention and awareness, such as the MAAS questionnaire, but also attitudinal components related to mindfulness, such as acceptance and non-judgmental attitude.

***Five Facets Mindfulness Questionnaire (FFMQ)***

The Five Facets Mindfulness Questionnaire (FFMQ) consists in 39 items that assess five scales of mindfulness: (1) non reactivity to inner experience (Non reacting), (2) observing/attending/noticing to sensations/feelings/thoughts (Observe), (3) acting with awareness/automatic pilot/concentration/non-distraction (Acting with awareness), (4) describing/labelling with words (Describe), and (5) non judging of experience (Non judging) (Giovannini et al., 2014; Baer, Smith, Hopkins, Krietemeyer & Toney, 2006).

***The AX-Continuous Performance Task (AX-CPT)***

The task consisted in the presentation of pairs of letters (i.e., a cue and a probe). The letters were delivered one at a time. Participants were asked to respond to each letter by pressing one of two buttons (‘z’ or ‘m’), with the index finger of either hand. They were instructed that the target pair was “AX” and that the response to this target requires to press the left button with the left index finger at the onset of the first letter (i.e., the “A”), and to press the right button with the right index finger at the onset of the second letter (i.e., the “X”). To any other pair of letters, they were asked to respond by pressing the left button with the left index finger at the onset of the first letter and by pressing again the left button at the onset of the second letter. Left and right response keys were counterbalanced across participants. Overall, four trial types (i.e., pairs of letters) were included in the task: the “AX” trials, the A-nonX trials (“AY”), the nonA-X trials (“BX”), and nonA-nonX trials (“BY”). In contrast to traditional AX-CPT, an equal number of A trials and B trials were delivered (Richmond, Redich & Braver, 2015). Specifically, the proportion of trials was as follows: 37.5% AX, 12.5% AY, 12.5% BX, and 37.5% BY. Within a block, the frequency of A and B cues was equated (50/50 vs. 80/20 in the traditional version), allowing us to control for cue validity across trials (here the 75% of A-cues anticipated an X probe, and 75% of B-cues anticipated an Y probe) and for potential confounding factors related to the infrequency/novelty of B cues. As a consequence, the frequency of each probe type was the same as well (i.e., 50% of trials contained an X-probe, and 50% of trials contained an Y-probe). In that way, a greater emphasis was placed on cue information (see Richmond et al., 2015). No information about probability of AX pairs was provided; therefore, participants were not induced to implement a specific proactive strategy.

All stimuli were black (about 2 × 2.3 cm) and centrally displayed on a silver background, on a 19’’ screen (1024 × 768 pixel resolution). The task was performed in an acoustically and electrically isolated booth for EEG signal acquisition. The cue letter could be either the letter A (A-cue) or the letter C, D, F, H, M, N, P, U, O (B-cue); the probe letter could be either the letter X (X-probe) or the letters B, E, G, L, Q, R, S, V, J, W (Y-probe).

Participants completed a total of 6 blocks that lasted about five minutes each. Each block contained a sequence of 64 trials, comprising 24 AX, 8 AY, 8 BX, and 24 BY trials presented in random order. The stimulus timing was as follows:

both the cue and the probe letter were on the screen for 300 ms and a fixation cross was displayed for 1700 ms between the two. From the probe offset to the successive cue, a jittered inter-trial interval (ITI) randomly changing from 2000 to 3000 ms was inserted, during which a string of three fixation crosses was displayed. Rest breaks were offered at the end of each block.

Before starting the experimental task, participants performed a short practice session (15 trials) in order to familiarize with it. If less than 11 responses were correct, they repeated the practice (overall, this was the case only for two participants that repeated the practice once). Stimulus presentation and response collection were controlled by E-Prime 2.0 software (Schneider, Eschman & Zuccolotto, 2002).

***EEG recording and preprocessing***

The EEG signal was recorded using an EEG portable system (Brain Products, Munich, Germany), connected to 64 sintered Ag/AgCl ring electrodes mounted on an elastic cap (EASYCAP GmbH, Germany), according to the extended 10-20 system (Jasper, 1958). Reference and ground channels were located over FCz and AFz, respectively. Impedance values were kept below 5 kΩ. Raw data were band-pass filtered between 0.016-250 Hz, and digitized at a 500 Hz sampling rate.

The data preprocessing was performed using EEGLAB (v. 13.4.4b, Delorme & Makeig, 2004), an open source toolbox for EEG analysis implemented in MATLAB (v. R2017b). Firstly, a low-pass filter was applied, using the windowed sinc FIR filter method (Kaiser window type), with a cut-off frequency of 35 Hz and a transition bandwidth of 10 Hz (Widmann, Schröger & Maess, 2015). Then, a high-pass filter was applied (cut-off frequency= 0.125 Hz, transition bandwidth= 0.25 Hz), in order to remove slow drifts. The continuous EEG signal was initially segmented in epochs ranging from 1500 ms before to 5300 ms after cue onset. An Independent Component Analysis (ICA) was run, based on an extended Infomax algorithm. The resulting ICA components were visually scrutinized basically to identify and remove ocular movements and muscle artefacts. For the cue-locked ERP analysis, epochs were segmented from 500 ms before to 3000 ms after cue onset and the signal was baseline-corrected using the average amplitude in the 500-ms time window before cue onset. For the probe-locked ERP analysis, epochs were segmented from 200 ms before to 1000 after probe onset and the signal was baseline-corrected using the 200-ms time window before probe onset.

The epochs associated with missing and incorrected responses were removed. An automatic detection of artifactual and/or outlier epochs was performed, by applying four criteria (see Delorme, Sejnowski & Makeig, 2007): i) -100/+100 µV as extreme amplitude values threshold; ii) drifts larger than ±50 µV and $R^2$> 0.3 for the linear trend test; iii) SD > 7 (for each channel) and SD > 4 (for all channels) from the mean probability distribution of amplitude values across epochs for the improbability test; iv) SD > 7 (for each channel) and SD > 4 (for all channels) from the kurtosis of the probability distribution. Epochs containing data points exceeding these criteria were excluded from further analyses. Table 1 summarizes the number of epochs included in the analyses, for each condition. Finally, data were re-referenced to the average of all electrodes, with the exception of the vertical EOG channel.

## Data analysis

### ***Questionnaire data***

A 2 (Session: pre- vs. post-training) × 2 (Group: MBSR vs. Control) mixed ANOVA was performed for each questionnaire score. Least Significant Difference (LSD) post-hoc tests were used in order to interpret significant effects and partial $\eta^2$ to estimate effect size.

### ***Behavioral data***

Error rates and response times (RTs) were examined. Trials containing omissions or anticipations (RTs ≤100 ms), either to the cue or to the probe, or incorrect responses to the cue, were removed. Error rates were computed in terms of incorrect responses to probes (i.e., false alarms). In order to adjust for floor effects, a correction was applied to error rates equal to 0, which were replaced by 0.5/(total number of trials + 1). The total number of trials was n= 144 for the AX and BY trials, and n= 48 for the AY and BX trials. Raw RTs were log-transformed to improve normality. Then, RTs exceeding 3 standard deviations above the mean, computed for each participant and condition separately, were removed. A 2 (Session: pre- vs. post-training, within-subjects factor) × 4 (Trial type: AX, AY, BX and BY, within-subjects factor) × 2 (Group: MBSR vs. Control, between-subjects factor) mixed ANOVA was performed on RTs. LSD post-hoc tests were used in order to clarify significant effects and *partial* $\eta^2$ to estimate effect size.

To estimate the amount of proactive control, additional behavioral indices were computed by comparing performance across trial types, specifically, *d'*-context, A-cue bias and Proactive Behavioral Index (PBI; Barch et al., 2001; Braver, Paxton, Locke & Barch, 2009; Gonthier et al., 2016; Richmond et al., 2015). The first two indices, *d'* context and A-cue bias, correspond to *d-prime* and *c criterion* respectively, as described in the Signal Detection Theory (Stanislaw & Todorov, 1999). The *d'*-context index was calculated as the difference between hits on AX trials and false alarms on BX trials. Hits were calculated as the proportion of correct trials (correct response to both cue and probe). A correction was applied when hits matched total trials, as follows: (total number of trials – 0.5)/(total number of trials + 1). Hit and false alarm values were then z-transformed. Therefore, the *d'*-context was computed as follows: Z (hits on AX trials) – Z (false alarms on BX trials). This measure reflects the ability of participants to use contextual information from the cue to drive the response to the probe. The A-cue bias was calculated on hits on AX trials and false alarms on AY trials, as follows: Z(correct hits on AX trials) + Z(errors on AY trials)/2. This index represents the tendency to make a target response after an A-cue regardless of the probe identity. The PBI was calculated both in terms of error rates and RTs, as (AY – BX)/(AY + BX). A positive PBI is given by more errors/longer RTs on AY trials compared to BX trials and reflects a higher proactive control engagement; a negative PBI value is given by more errors/longer RTs on BX trials compared to AY trials and reflects a higher reactive control engagement.

The statistical analysis on error rates and proactive control indices was performed by means of non-parametric tests, since data distribution did not meet the normality assumption, as tested via Shapiro-Wilk Normality test (all *ps*$< 0.05$). The Wilcoxon Signed Rank test for paired data was applied on each trial type in order to assess the pre/post-training effects in each group and session, separately. The Mann-Whitney tests for unpaired data were performed to assess group differences in each session and trial type, separately. Since multiple tests were performed, False Discovery Rate (FDR) correction was applied to correct *p*-values (Benjamini & Hochberg, 1995).

### *Event-Related Potential (ERP) data*

One participant from each group was excluded from the ERP analyses due to insufficient data quality (excessive eye movements and muscular artefacts, which could not be reliably removed by the ICA algorithm and the automatic artefact rejection procedure). The final sample consisted of 25 participants in the MBSR group and 22 participants in the control group.

First of all, the amplitude of potentials evoked by cues (cue-locked ERPs) was analyzed to investigate pre/post-training effects. Specifically, the CNV amplitude was examined in a 500-ms time window immediately preceding the probe onset, over midline fronto-central electrode sites (FCz and Fz collapsed), where it was expected to reach the maximum amplitude (Boksem, Meijman & Lorist, 2006; Dias et al., 2003; Ng, Tobin & Penney, 2011; Tarantino et al., 2010). The mean amplitude over a time window of 500 ms preceding the probe onset was extracted for each trial. Trials containing A-cue (AX, AY) and trials containing B-cue (BX, BY) were then averaged. The mean CNV amplitude values were submitted to a 2 (Session: pre- vs. post-training) × 2 (Cue type: A vs. B cue) × 2 (Group: MBSR vs. Control) mixed ANOVA.

Secondly, the amplitude of potentials evoked by the probe letters (probe-locked ERPs) was analyzed. Specifically, the anterior N2 and P3a components were examined. The N2 is a fronto-central negative potential, peaking around 200-300 ms after a target stimulus; it reflects conflict monitoring and is especially pronounced in tasks requiring high cognitive control costs, such as the Stroop task (Donkers & Van Boxtel, 2004; Eimer, 1993; Folstein & Van Petten, 2008; Larson, Clayson & Clawson, 2014). The P3a is a positive deflection characterized by a fronto-central scalp distribution, peaking around 300-500 ms post stimulus; it is mainly involved in context-updating and attentional resource allocation (Hämmerer, Li, Müller & Lindenberger, 2010; Polich, 2007). We extracted mean ERP amplitude over a 200-300 ms time window after probe onset, and over a 300-400 ms time window after probe onset, in order to examine the anterior N2 and P3a components, respectively. Both the N2 and the P3a amplitudes were extracted from midline centro-frontal electrode sites (FCz, Cz), where they are maximally expressed. Mean amplitude values were submitted to a 4 (Trial type: AX, AY, BX, BY) × 2 (Session: pre- vs. post-training) × 2 (Group: MBSR vs. Control) mixed ANOVA.

The Spearman correlation analysis was also performed, on the whole data sample, between ERP component's amplitude, behavioral data, AX-CPT indices and questionnaire scores in order to explore possible relationships between these measures. The FDR correction was applied to correct for multiple comparisions.

All statistical analyses were performed using the IBM SPSS software (release 23).

# Results

### Mindfulness Questionnaires

Tables 2 and 3 show mean scores for each self-report mindfulness questionnaire, and the relative inferential statistics testing the effect of experimental Session and Group. All questionnaire scores but the CAMS showed a significant Group × Session interaction. The post-hoc tests revealed significantly higher MAAS and FFMQ scores in the post- compared to the pre-training session for the MBSR group [$t(24) = 4.40$, $p < .001$, Cohen's $d = .87$, and $t(24) = 5.92$, $p < .001$, Cohen's $d = .94$, respectively]. The analysis of each FFMQ subscale revealed a significant score increase in the MBSR group only, for all dimensions. No training effects were observed in the CAMS-R scores (all *ps* > .11).

### Behavioral results

Figure 1 illustrates the percentage of error rates for each trial type before and after the training. Based on the Wilcoxon Signed Rank test for paired data, only participants who underwent the MBSR training exhibited significantly fewer errors on AY trials [$mean_{pre} = 4.82\%$ (SD = 4.07), $mean_{post} = 2.67\%$ (SD = 2.21); Z = -3.16, $p = .002$], and on BX trials [$mean_{pre} = 2.59\%$ (SD = 2.16), $mean_{post} = 1.31\%$ (SD = .69); Z = -2.77, $p = .006$] after the training. No training effect was observed in the control group. However, based on Mann-Whitney tests, the control group exhibited significantly lower error rates on AY trials both before and after the training compared to the MBSR group (Z = 2.78, $p = .005$ and Z = 2.54, $p = .011$, respectively).

Figure 2 illustrates mean RTs for each trial type, before and after the training. As expected, a main effect of Trial type [$F(1,47) = 109.06$, $p < .0001$, partial $\eta^2 = .70$] was found, which revealed that RTs significantly differed across Trial types ($RT_{AY} > RT_{AX} > RT_{BX} > RT_{BY}$, all *ps* < .03). Moreover, significant Session × Group [$F(1,47) = 5.93$, $p = .018$, partial $\eta^2 = .11$] and Session × Trial type interactions [$F(1,47) = 4.32$, $p = .006$, partial $\eta^2 = .08$] emerged. Post-hoc tests showed shorter RTs in the post- compared to pre-training session for the Control group ($p = .015$). Additionally, irrespective of group, participants were faster in responding to trials containing B cues in post- compared to pre-training session (all *ps* < .0001), whereas no Session effect was found for the A cue trials (all *ps* > .077).

Wilcoxon Signed Rank tests were performed on behavioral indices, namely the *d'*-context, the A-cue bias and the PBI (both on errors and on log-RTs). Table 4 summarizes the mean scores for each behavioral index, as a function of group and experimental session. First of all, the effect of training was assessed in each group separately. Statistical analyses showed more positive PBI-RT values in post-training session for the control group (Z = 2.98, $p = .003$). All other comparisons did not survive the FDR correction. Group differences on indices, in both pre- and post-training sessions, were submitted to multiple Mann-Whitney tests. No comparison survived the significance correction.

In order to explore possible relationships between behavioral data and questionnaire scores, non-parametric Spearman correlation analyses were performed, regardless of the group. In terms of error rates, in pre-training session a negative correlation between MAAS score and errors on AY trials [$\rho(47) = -.399$, $p = .005$] and a negative correlation between CAMS score and error on AY trials [$\rho(47) = -.423$, $p = .002$] emerged. This means that participants with higher values of "mindfulness", as measured by the self-report questionnaires, exhibited a higher accuracy on AY trials. Neither the analysis on RTs nor the analysis on behavioral indices yielded significant results (according to the

FDR correction). In post-training session, the negative correlation between the MAAS score and the AY error rate was maintained [$\rho(47) = -.535$, $p < .001$]. Moreover, a negative correlation between the MAAS score and the PBI, both in terms of accuracy [$\rho(47) = -.536$, $p < .001$] and RTs [$\rho(47) = -.450$, $p < .002$] emerged. This means that participants with a higher "mindfulness" score on the self-report questionnaire exhibited higher accuracy on AY trials both in terms of errors and RTs; in other word, in post-training session AY trials exerted less interference in individuals with higher mindulness.

**ERP data: cue-locked analysis**

We first computed cue-locked analysis in order to evaluate mindfulness-related effects on proactive control processes. Figure 3 shows ERP waveforms locked to A-cue (a) and B-cue (b), and the topographical distribution of ERPs during the 500 ms interval before probe onset. The MBSR is represented on the top-right (c), whereas the control group on the bottom-right (d). As expected, a slow negative potential developed after the cue onset (CNV), which increased in amplitude throughout the cue-to-probe delay, in anticipation of the probe, and reached maximal (negative) amplitude values over fronto-central sites. As one can see, the CNV evoked after A-cues was steeper in post- compared to pre-training session, in the MBSR group only. This effect was not observed in the control group.

The 2 (Cue type) × 2 (Session) × 2 (Group) ANOVA contrasting the CNV amplitude in A-cue and B-cue trials during the 500-ms time window preceding probe onset, over Fz and FCz electrodes, yielded a significant main effect of Cue type [$F(1,45) = 66.47$, $p < .0001$, partial $\eta^2 = .59$]. This effect demonstrated that the CNV amplitude after A-cue was larger than after B-cue, irrespective of group and session. Neither a main effect of Session nor a main effect of Group was observed [$F(1,45) = 2.59$, $p = .115$; $F(1,45) = .825$, $p = .369$, respectively]. A significant Session × Group interaction [$F(1,45)=7.11$, $p=.011$, partial $\eta^2=.14$] and a significant Cue type × Session interaction [$F(1,45) = 6.64$, $p = .013$, partial $\eta^2 = .13$] were found. The post-hoc analysis of the Session × Group interaction revealed that only the MBSR group showed a training effect, namely a more negative CNV amplitude in post-training session [$mean_{pre} = -1.28$ μV (SD = 1.50); $mean_{post} = -1.60$ μV (SD = 2.15); $p = .003$], whereas the control group did not [$mean_{pre} = -1.25$ μV (SD = 1.09); $mean_{post} = -1.17$ μV (SD = 1.10); $p = .472$]. The post-hoc analyses of the Cue type × Session interaction revealed that only the CNV amplitude in the A-cue trials was affected by the training. Namely, only the CNV evoked by the A-cue was larger (more negative) in the post-training session. A marginally significant three-way interaction between Cue type × Group × Session [$F(1,45) = 4.03$, $p = .051$, partial $\eta^2 = .08$] suggested that the MBSR training affected CNV amplitude in A-cue trials only, namely, the amplitude of the CNV showed more negative values in post- compared to pre-training session in the MBSR group in A-cue trials ($p = .001$), whereas it did not differ in all other comparisons (all $ps > .159$).

In order to understand the behavioral counterpart of the CNV, Spearman correlation analyses with behavioral data were performed. Specifically, the CNV amplitude was correlated with error rates, RTs, behavioral indices and questionnaire scores, on the whole participants' sample, for each trial type and for pre- and post-training sessions, separately. In pre-training session, the CNV amplitude evoked by A-cues was positively correlated with RTs on all trial types [AX: $\rho(45) = .404$, $p = .005$; AY: $\rho(45) = .382$, $p = .008$; BX: $\rho(45) = .430$, $p = .003$; BY: $\rho(45) = .410$, $p = .004$]. To be noted that the CNV is a negative component, thus the positive correlation means that a more negative CNV amplitude is associated to shorter RTs. Significant correlations did not emerge between the CNV on B-cue trials and RTs ($p$= .286). Interestingly, a significant negative correlation between A-cue locked CNV and the A-cue bias emerged [$\rho(45) = -.405$, $p = .005$]. Furthermore, the CNV amplitude on A trials negatively correlated with PBI index, both in terms of error rates [$\rho(45) = -.419$, $p = .003$] and RTs [$\rho(45) = -.351$, $p = .016$].

Similarly, in post-training session, the CNV amplitude evoked by A cues was positively correlated with RTs on AX trials [$\rho(45) = .405$, $p = .005$], BX trials [$\rho(45) = .388$, $p = .007$], and BY trials [$\rho(45) = .407$, $p = .005$]. Negative correlations were also found with PBI index [PBI-errors: $\rho(45) = -.550$, $p < .001$; PBI-RTs: $\rho(45) = -.373$, $p = .010$]. All these correlations survived FDR correction for multiple comparisons. No significant correlations were found with questionnaire scores.

**ERP data: probe-locked analysis**

Figure 4 represents the grand average of ERPs evoked by the probe letter in each trial type, over FCz-Cz electrodes (collapsed). Mean amplitude was extracted in the 200-300 ms time window for the analysis of the N2 component and in the 300-400 ms time window for the analysis of the P3a component. The 4 (Trial: AX, AY, BX, BY) × 2 (Session: pre-, post-training) × 2 (Group: MBSR, Control) mixed ANOVA revealed a main effect of Trial type on N2 amplitude [$F(3,45) = 50.07$, $p < .0001$, partial $\eta^2 = .52$], which was less pronounced (i.e., more positive) on AX compared to AY, BX and BY trials (all *ps* < .0001), and on AY and BX trials compared to BY trials (both *ps* < .001). We did not observe either a main effect of Group [$F(1,45) = .12$, $p = .733$] or a main effect of Session [$F(1,45)= .34$, $p= .563$]. A significant Session × Group interaction [$F(1,45) = 9.45$, p = .003, partial $\eta^2 = .17$] revealed less pronounced N2 amplitude in the post- compared to the pre-training session in the MBSR group [$mean_{pre}$ = .16 μV (SD = 1.26); $mean_{post}$ = .59 μV (SD = 1.48); $p = .010$] and not in the control group [$mean_{pre}$ = .33 μV (SD = .92); $mean_{post}$= 0.04 μV (SD = .98); $p = .094$].

The 4 (Trial: AX, AY, BX, BY) × 2 (Session: pre-, post-training) × 2 (Group: MBSR, Control) mixed ANOVA on P3a amplitude revealed a main effect of Trial [$F(3,45) = 73.43$, $p< .0001$, partial $\eta^2 = .62$], which reflected a larger amplitude on AY trials compared to AX, BX and BY trials (all *ps*<.011) and on AX trials compared to BX and BY trials (all *ps* < .0001). Moreover, a significant main effect of Session was found [$F(1,45) = 6.87$, $p = .012$, partial $\eta^2 = .13$]. Irrespective of group and trial type, the P3a component in post-training session exhibited larger amplitude compared to the pre-training session [$mean_{pre}$ = 1.62 μV (SD = 1.81) ; $mean_{post}$= 2.07 μV (SD = 2.13)]. Whereas, a main effect of Group did not emerge [$F(1,45) = 3.31$, $p = .075$]. A marginally significant Session × Group interaction [$F(1,45)= 4.05$, p= .050, partial $\eta^2$= .08] denoted a more positive P3a amplitude in the post- compared to pre-training session in the MBSR group [$mean_{pre}$ = 2.05 μV (SD = 1.90); $mean_{post}$= 2.84 μV (SD = 2.26); $p = .001$], but not in the control group [$mean_{pre}$ = 1.19 μV (SD = 1.89); $mean_{post}$= 1.29 μV (SD = 1.98); $p = .677$].

The correlation analysis performed between N2 amplitude and behavioral and questionnaire indices did not yield significant results. On the other hand, the P3a amplitude negatively correlated with RTs, in all trial types and in both pre- [AX: $\rho(45) = -.434$, $p = .002$; AY: ρ(45) = -.308, p = .035; BX: $\rho(45) = -.381$, $p = .008$; BY: $\rho(45) = -.453$, $p = .001$] and post-training sessions [AX: $\rho(45) = -.366$, $p = .011$; AY: ρ(45) = -.303, p = .038; BX: $\rho(45) = -.414$, $p = .004$; BY: $\rho(45) = -.416$, $p = .004$]. This is in line with the traditional literature (Polich et al., 2007). Interestingly, the P3a amplitude in BX trials positively correlated with the PBI index in pre- [$\rho(45) = .440$, $p = .002$] and post-training sessions [$\rho(45) = .425$, $p = .003$]. Moreover, the P3a amplitude in AX trials significantly correlated with the A-cue bias [$\rho(45) = .347$, $p = .017$]. This means that also probe-related neural activity was associated with behavioral indices that have been usually interpreted as proactive.

## Discussion

The present study was aimed to elucidate the effects of mindfulness-based meditation training (MBSR) on cognitive control processes, within the theoretical framework of the Dual Mechanism of cognitive control (Braver et al., 2007). In particular, we investigated potential effects of an 8-week training on the dynamic interplay between two functionally distinct control systems, the proactive and the reactive system, by complementing behavioural data with electrophysiological measures. Based on previous evidence on cognitive benefits of meditation practice (e.g., Lutz et al., 2008; 2009; MacLean et al., 2010; Moore et al., 2012; Slagter et al., 2007), we hypothesized that the training would enhance the participants' ability to implement proactive cognitive control, which allows to actively maintain contextual information prior to the occurrence of target events and to strategically allocate attention in order to improve the target response. Additionally, we explored the training effect on reactive cognitive control, which is instead intended as a past-oriented mechanism, activated *just-in-time* by target stimuli to detect and solve interference in unexpected stimuli. To this aim, a modified version of the traditional AX-CPT paradigm was administered to a group of MBSR trainees and to a control group of Pilates trainees (Gonthier et al., 2016; Richmond et al., 2015). Both behavioral and ERP data were examined. The main findings consisted in a reduction of errors specifically on more conflicting trials (i.e., AY and BX trials) and in an amplitude increase of anticipatory and preparatory ERP correlates (i.e., the CNV), in post-training session of the MBSR group only, as discussed in detail below. An amplitude modulation of reactive ERP components (i.e., the probe-locked N2 and P3a) was also observed in post-training session of the MBSR group.

Compared to pre-training session, after the 8-week mindfulness training participants exhibited a significant reduction of error percentages, both on AY and BX trial types. This specific accuracy enhancement might be interpreted as reflecting a more efficient balance between proactive and reactive control processes (Gonthier et al., 2016). Indeed, relative to other trial types, AY and BX trials are associated with higher proactive and reactive control costs. Given the probability distribution of trials, the occurrence of an Y-probe after an A-cue (AY trials) is unexpected, therefore it requires a prompt correction of an already prepared response. On the other hand, the occurrence of an X-probe after a B-cue (BX trials) might activate a wrong target response if participants had not prepared in advance the response and had not maintained the cue context. Therefore, higher accuracy on AY and BX trials reflects an efficient adaptation of proactive and reactive control processes. In brief, from a behavioral point of view, the MBSR group showed a more efficient balance between the proactive and reactive control processes post-training, which facilitates a flexible adaptation to environmental requirements.

On the other hand, control participants exhibited an overall reduction of RTs in post-training session. When examining the PBI index calculated on RTs, a significant improvement in post-training session relative to pre-training session emerged in the control group. A closer look at the data revealed that this effect was driven by a significant RT decrease on BX trials, rather than on AY trials. This effect might be interpreted as reflecting a diminished interference of task-relevant but non-target stimuli, that is, improved reactive control processes in the Pilates group.

In order to better understand the neurofunctional origin of this pattern of behavioral results, we analyzed the simultaneous brain activity monitored through EEG. A significantly larger negative potential was evoked by the cue stimuli (i.e., more negative CNV amplitude) in the MBSR group during post-training session relative to pre-training session (see Figure 3a). The control group did not show CNV changes after the training. As already discussed in the Introduction, the CNV is a negative deflection that develops between a cue stimulus and an upcoming target; it reflects central processes of anticipatory attention and response preparation (Boksem et al., 2006; Gomez, Marco & Grau, 2003; Gaillard, 1977). The more pronounced CNV amplitude exhibited by MBSR participants likely reflected an increased employment of proactive cognitive control processes after the 8-week MBSR training compared to the control group. This result is consistent with the findings reported in the cross-sectional study of Travis et al. (2000; 2002), in which a larger CNV was elicited after a cue in more trained meditators compared to a control group. The authors interpreted the CNV effect as an increase of the arousal level and a better allocation of attentional resources with increasing frequency of meditation practice (Travis et al., 2000).

During mindfulness meditation one needs to monitor moment-by-moment the focus of attention on an intended object (e.g., the breathing), detecting distractors (e.g., interfering thoughts, sensations, emotions), disengaging attention from them, and (re)directing attention to the original object (Lutz et al., 2008; Malinowski, 2013). The present behavioral and EEG findings suggest that this extensive training on focusing and sustaining attention might have contributed in improving higher cognitive control processes, such as proactive control. Moreover, they suggest that attentional control abilities trained during mindfulness training might have generalized to other contexts and tasks, such as in the experimental setting of our study.

The positive correlation observed between A-locked CNV amplitude and RTs revealed that faster responses to probes were preceded by larger CNV. This effect is consistent with a vast literature showing that increased CNV amplitude is associated to performance improvement on speed (e.g., Boksem et al., 2006; Travis et al., 2000). Interestingly, the A-cue evoked CNV amplitude correlated with RTs on both A-trials and B-trials. This finding suggests that individuals who relied on anticipatory control strategies on A trials boosted performance on B trials as well. The negative correlation observed between A-locked CNV amplitude and both A-cue bias and PBI (in terms of errors as well as RTs) further supported the evidence that CNV amplitude reflects the preferential implementation of proactive cognitive control processes.

The probe-locked data revealed additional interesting results about mindfulness-related effects on more transient and reactive processes, activated by the probe. In the AX-CPT paradigm, AY trials are expected to exhibit higher N2 amplitude compared to AX, BX and BY trials, since whenever an A-cue appeared participants were prompted to make a target response (*Go Local Context*), and if a Y-probe is then displayed, a response-conflict arises (Dias et al., 2003; Hämmerer et al., 2010; Morales et al., 2015). In the present study, we observed a reduction of the frontal N2 (more positivity) at probe onset in post- compared to pre-training session in the MBSR group only. This N2 amplitude reduction might be the result of facilitated implementation of probe-related control processes and suggests an increased ability to manage response conflict. The N2 amplitude reduction that we observed seems in contrast with the findings of a previous study also investigating the longitudinal effects of MBSR training on attentional functions (Moore et al., 2012). Indeed, the authors found a more negative N2 amplitude after the 8-week training. There are however noteworthy differences with respect to our study. In the study of Moore et al. (2012), the verbal Stroop task was used, and the main finding was a post-training increase of posterior N2 amplitude (more negativity) irrespective of stimulus congruency. Therefore, it could be the case that this component did not reflect the implementation of control mechanisms, but rather an increased activation of task relevant cortical areas (namely, enhanced stimulus processing when attending to the color of the word), as suggested by the authors.

The probe-locked analysis revealed an increase in P3a amplitude in the post- compared to pre-training session, in all trial types. The marginally significant Session × Group interaction suggests that this effect was specific for the MBSR group. Apparently, this result contrasts previous findings in a passive oddball task, showing diminished P3a amplitude (Cahn & Polich, 2009). Nevetheless, in AX-CPT paradigms, a larger probe-locked P3a denotes a better inihibition of prepotent responses (Morales et al., 2015). Furthermore, a larger probe-locked P3 amplitude in similar cue-probe paradigms (such as task-switching) has been interpreted as reflecting the reactivation of task context and the amount of attentional resources devoted to overcome the conflict induced by the overlearned S-R mapping (Brydges & Barceló, 2018; Tarantino, Mazzonetto & Vallesi, 2016). Taken together, the modulation of the N2 and P3a components in post- compared to pre-training session suggests that the MBSR group implemented more efficient reactive cognitive control mechanisms as well.

Remarkably, participants in the MBSR training group only exhibited significantly higher scores on the self-report questionnaires in post-training session, namely on the total FFMQ score and on all the five relative sub-scales (i.e., Observing, Describing, Act with awareness, Non-judging and Non-reacting). The FFMQ increase after the MBSR training suggests a stronger openness to experience, higher emotional intelligence and self-compassion, as well as a decrease in neuroticism, thought suppression and alexithymia (Baer et al., 2006). Additionally, we observed a significant improvement of the total MAAS score, which captures the tendency to be attentive and aware in the day to day circumstances. Previous studies found that the MAAS score positively correlates with emotional intelligence and openness to experience, and with a number of well-being measures, such as the PANAS (Positive Affect Negative Affect Scale), that is a subjective emotional well-being scale (Brown & Ryan, 2003).

Correlational analyses between behavioral indices and questionnaire scores revealed that individuals that reported subjective experience of mindfulness more frequently exhibited lower error rates on AY trials. In addition, a negative correlation between MAAS score and PBI (calculated on both errors and RTs) showed decreased interference of AY trials compared to BX ones in “more mindful” individuals. Overall, in post-training session participants with higher self-reported mindfulness scores exhibited a more efficient use of contextual information, with lower costs on more demanding trials (e.g., AY).

It is worth noting the reduction of RTs on BX trials in the Pilates group and the main effect of Session on N2 and P3a amplitudes. This evidence suggests that the the control group benefitted of training as well, but only in the reactive components of control processes. This is in line with studies showing the favorable influence of regular physical activity on cognitive processing (e.g., Voss et al., 2013).

In summary, the study shows that the abilities trained during mindfulness meditation practice (such as sustaining the attentional focus on a chosen object and reporting, whenever necessary, attention back to the object) generalize to higher cognitive functions. One of the strengths of this study is that neural changes were examined together with behavioral data, in a highly controlled experimental setting. Furthermore, a structured mindfulness intervention

(MBSR) was investigated, characterized by a standard program, worldwide conducted in roughly the same way (see Kabat-Zinn, 1990, for an extensive description of the training). This choice was important to reduce the enormous heterogeneity of meditation practices and to improve study replicability. An additional strength of our study consists in the choice of an active control group. This aspect guaranteed that pre- vs. post-training differences could be selectively attributed to mindfulness practice itself, rather than to general training effect, and contributed to overcome a main limitation in the meditation literature, which concerns the inclusion of passive or waiting list control groups (MacCoon et al., 2014; Marcus, O'Connell, Norris, & Sawaqdeh, 2014). Lastly, the inclusion of a group of participants actively engaged and motivated in the Pilates training allowed us to control for possible biases due to differences in expectancies between groups. Indeed, both groups were characterized by i) the expectation that the training will succeed; ii) experiential exercises made in group (sharing of experience); iii) the emphasis that is given on the benefits of the training on physical and psychological well-being. Importantly, all participants were informed that the aim of the study was to explore the cognitive benefits related to practices addressed to individual psychological and physical well-being, which applies to both trainings. On the other hand, we should cautiously consider that the Pilates training was not as structured as the MBSR training. To conclude, the study results provide behavioral as well as neural evidence that the MBSR training improves the implementation of both proactive and reactive cognitive control processes. Specifically, this type of training influences anticipatory and sustained processes, which act in preparation to future predictable events. Moreover, it boosts the ability to promptly adjust planned responses in reaction to unexpected events. Overall, the study suggests that the training may act on neural plasticity and modulate cortical functioning.

## Limitations and future directions

Among the limits of our study, we may point out the fact that this was a quasi-experiment, as we did not randomly assign the participants to the two groups (mindfulness vs. pilates) starting from the same general population, but they were already self-selected for the type of training of their choice before volunteering. This makes it difficult to totally discard the possibility that intrinsic pre-existing differences between the two groups (e.g., personality aspects, motivation, expectations, etc.) might at least partially have influenced the results. Moreover, the relatively low sample sizes and the differences in structure and daily schedule between the two trainings could have counfonded the comparison between groups. Future studies should try to overcome these shortcomings.

A better understanding of the cognitive benefits associated with the mindfulness practice would help to further improve its clinical applicability, especially in those populations characterized by control impairments, including some developmental disorders.

## Compliance with Ethical Standards

### Ethical approval

This study was approved by the Bioethical Committee of the Azienda Ospedaliera of Padova (Prot. N. 2758P) and was conducted according to the guidelines of the Declaration of Helsinki (World Medical Association, 2013).

### Conflict of Interest

The authors declare that they have no conflict of interests.

### Informed Consent

Informed consent was obtained from all individual participants included in the study.

## Author Contributions

FI and VT: designed and executed the study, performed the data analysis, and wrote the paper. CC: collaborated with the design and editing of the final manuscript. AV: supervised all research steps, wrote and revised the manuscipt.

**TABLES**

**Table 1** Mean and standard deviation (in brackets) of the number of event-related potential (ERP) epochs after artifact rejection and removal of missing and incorrect responses.

| | MBSR group | | | | Control group | | | |
|---|---|---|---|---|---|---|---|---|
| | AX tot=144 | AY tot=48 | BX tot=48 | BY tot=144 | AX tot=144 | AY tot=48 | BX tot=48 | BY tot=144 |
| **Pre-training** | 136.6 (4.9) | 44.3 (2.8) | 45.0 (2.6) | 137.9 (5.7) | 140.3 (5.1) | 46.7 (1.5) | 46.6 (1.9) | 141.8 (5.6) |
| **Post-training** | 137.6 (4.2) | 45.7 (2.2) | 45.6 (1.7) | 139.2 (2.8) | 138.8 (2.7) | 46.0 (55.0) | 45.4 (1.4) | 139.2 (1.4) |

**Table 2** Mean and standard deviation (in brackets) of the mean scores on the Mindfulness-Attention Awareness Scale (MAAS), on the Cognitive and Affective Mindfulness Scale-Revised (CAMS-R), on the Five Facets Mindfulness Questionnaire (FFMQ), and on its five subscales: Non-Reactivity (FFMQ-NR), Observing (FFMQ-O), Acting with awareness (FFMQ-A), Describing (FFMQ-D) and Non-judging (FFMQ-NJ).

| | MBSR group | | Control group | |
|---|---|---|---|---|
| | Pre-training | Post-training | Pre-training | Post-training |
| MAAS | 3.46 (.86) | 4.03 (.67) | 4.20 (.53) | 4.17 (.51) |
| CAMS-R | 2.54 (.29) | 2.65 (.31) | 2.76 (.31) | 2.76 (.29) |
| FFMQ-total | 3.06 (.66) | 3.53 (.44) | 3.54 (.40) | 3.54 (.46) |
| FFMQ-NR | 2.66 (.73) | 3.18 (.48) | 3.00 (.60) | 2.92 (.58) |
| FFMQ-O | 3.00 (.82) | 3.60 (.50) | 3.57 (.70) | 3.64 (.67) |
| FFMQ-A | 2.87 (.67) | 3.40 (.62) | 3.78 (.68) | 3.86 (.52) |
| FFMQ-D | 3.33 (.73) | 3.63 (.84) | 3.73 (.88) | 3.68 (.94) |
| FFMQ-NJ | 3.24 (.92) | 3.83 (.72) | 3.44 (.80) | 3.55 (.79) |

**Table 3** Inferential statistics overview for each self-report mindfulness questionnaire score (average). We report the effects for Session factor (pre- vs. post-8 weeks training), Group factor (MBSR vs. Control group), and Session by Group interaction. Only the significant post-hoc tests were reported. They showed an increase in the questionnaire scores (namely a training effect) in the MBSR group. ns = p > .05

| | Session | | | Group | | | Session × Group interaction | | | Post-hoc tests |
|---|---|---|---|---|---|---|---|---|---|---|
| | *F* | *p* | partial eta$^2$ | *F* | *p* | partial eta$^2$ | *F* | *p* | partial eta$^2$ | Session |
| MAAS | 8.63 | .005 | .17 | 6.06 | .018 | .13 | 18.22 | <.001 | .30 | $MBSR_{post} > MBSR_{pre}$ |
| CAMS-R | 2.22 | ns | .05 | 2.66 | ns | .06 | 0.89 | ns | .02 | - |
| FFMQ-total | 12.71 | <.001 | .23 | 2.86 | ns | .06 | 12.32 | <.001 | .22 | $MBSR_{post} > MBSR_{pre}$ |
| FFMQ-NR | 6.65 | .013 | .14 | 0.08 | ns | .001 | 9.1 | .004 | .18 | $MBSR_{post} > MBSR_{pre}$ |
| FFMQ-O | 10.46 | .002 | .20 | 2.52 | ns | .06 | 11.54 | .001 | .21 | $MBSR_{post} > MBSR_{pre}$ |
| FFMQ-A | 17.7* | <.001 | .31 | 13.70 | <.001 | .24 | 7.30 | .009 | .15 | $MBSR_{post} > MBSR_{pre}$ |
| FFMQ-D | 4.68 | .036 | .10 | 1.74 | ns | .04 | 6.24 | .016 | .13 | $MBSR_{post} > MBSR_{pre}$ |
| FFMQ-NJ | 12.33 | .001 | .23 | 0.09 | ns | .002 | 5.00 | .03 | .11 | $MBSR_{post} > MBSR_{pre}$ |

**Table 4** Mean and standard deviation (in brackets) for the AX-CPT measures, as a function of group and experimental session.

| | MBSR group | | Control group | |
|---|---|---|---|---|
| | Pre-training | Post-training | Pre-training | Post training |
| *d'*-context | 4.19 (0.47) | 4.43 (0.32) | 4.37 (0.32) | 4.46 (0.38) |
| A-cue bias | 0.16 (0.15) | 0.09 (0.18) | 0.05 (0.14) | 0.040 (0.10) |
| PBI-errors | 0.22 (0.47) | 0.19 (0.38) | 0.09 (0.39) | 0.01 (0.31) |
| PBI-RTs | 0.02 (0.02) | 0.02 (0.02) | 0.02 (0.16) | 0.03 (0.02) |

**FIGURES**

***Fig. 1*** *Mean percentage of error rates for each trial type, depending on the Pre-training (dark grey) and Post-training (light grey) sessions. Error bars represent standard errors of the mean. Asterisks indicate significant differences (p < .05). MBSR group is represented on the left panel (a) and the control group on the right one (b).*

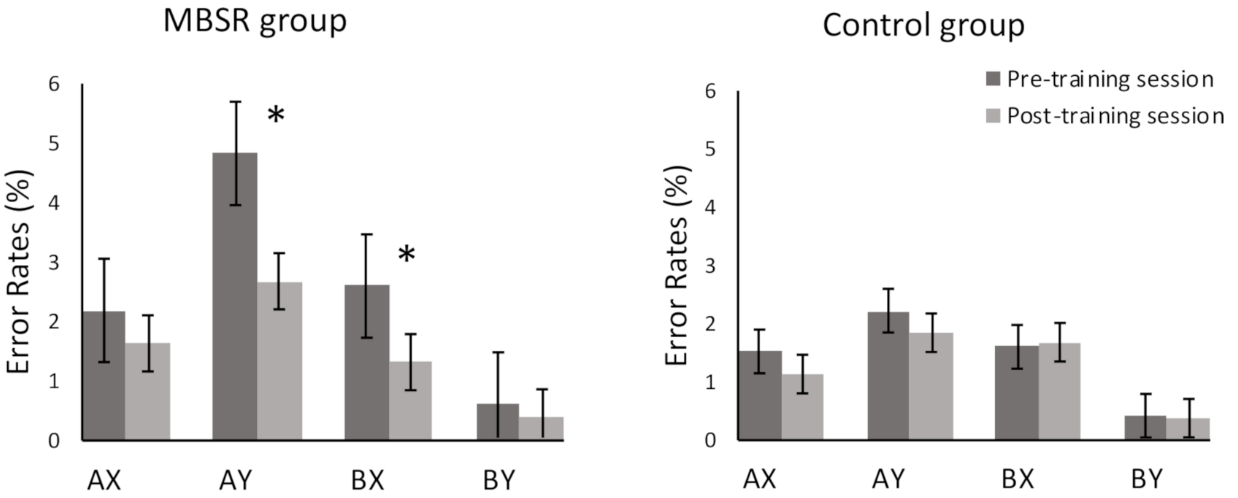



***Fig. 2*** *Mean Response Times (RTs, in ms) for each trial type, depending on the Pre-training (dark grey) and Post-training (light grey) sessions. Error bars represent standard errors of the mean. MBSR group is represented on the left panel (a) and the control group on the right one (b).*

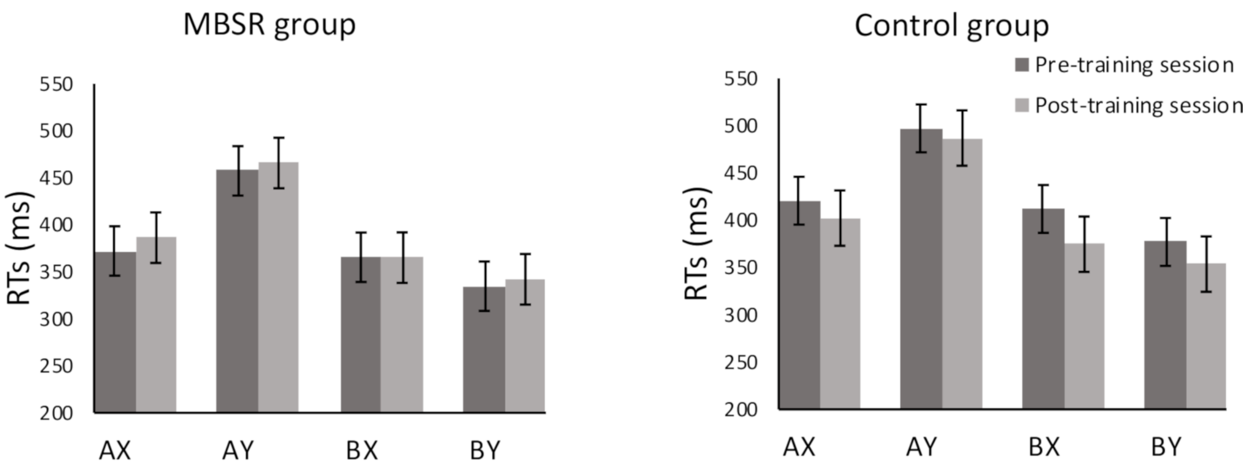


***Fig. 3*** *In the left panels, grand average Event-related Potential (ERP) waveforms in A-cue (a) and B-cue (b) trials are depicted. ERPs are time-locked to the cue onset (0 ms); probe onset is at 2000 ms. FCz and Fz electrodes are collapsed. A negative component (the Contingent Negative Variation, CNV) emerges in anticipation of probe onset in A-cue trials only. The shaded area represents the standard error of the mean. In the right panels, topographical maps of the post-pre training difference in ERP amplitude in the MBSR group (c) and control group (d) are represented. The amplitude difference is extracted from 1500 to 2000 ms relative to A-cues onset. The fronto-central distribution of the post-pre amplitude difference can be appreciated in the MBSR group only.*

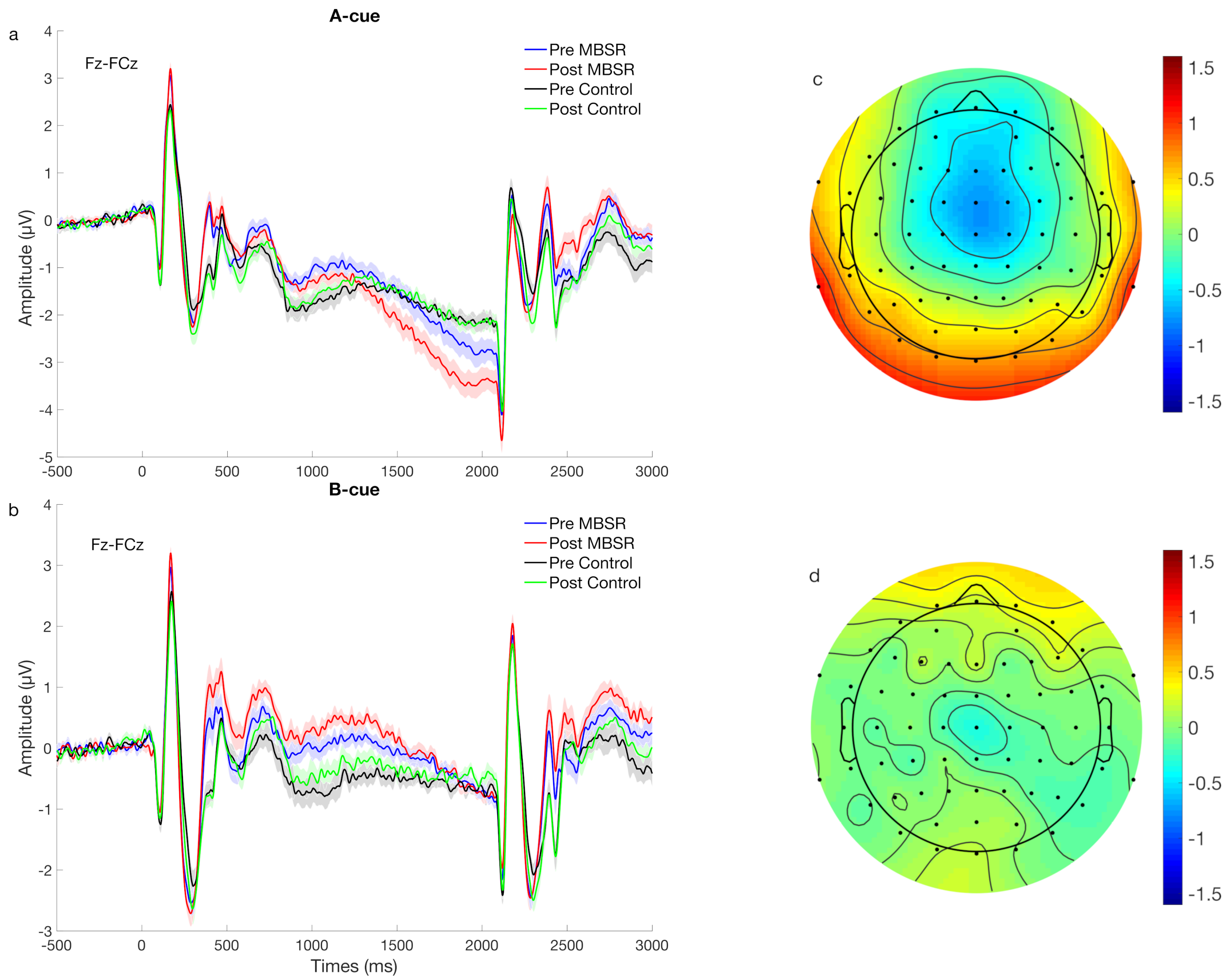
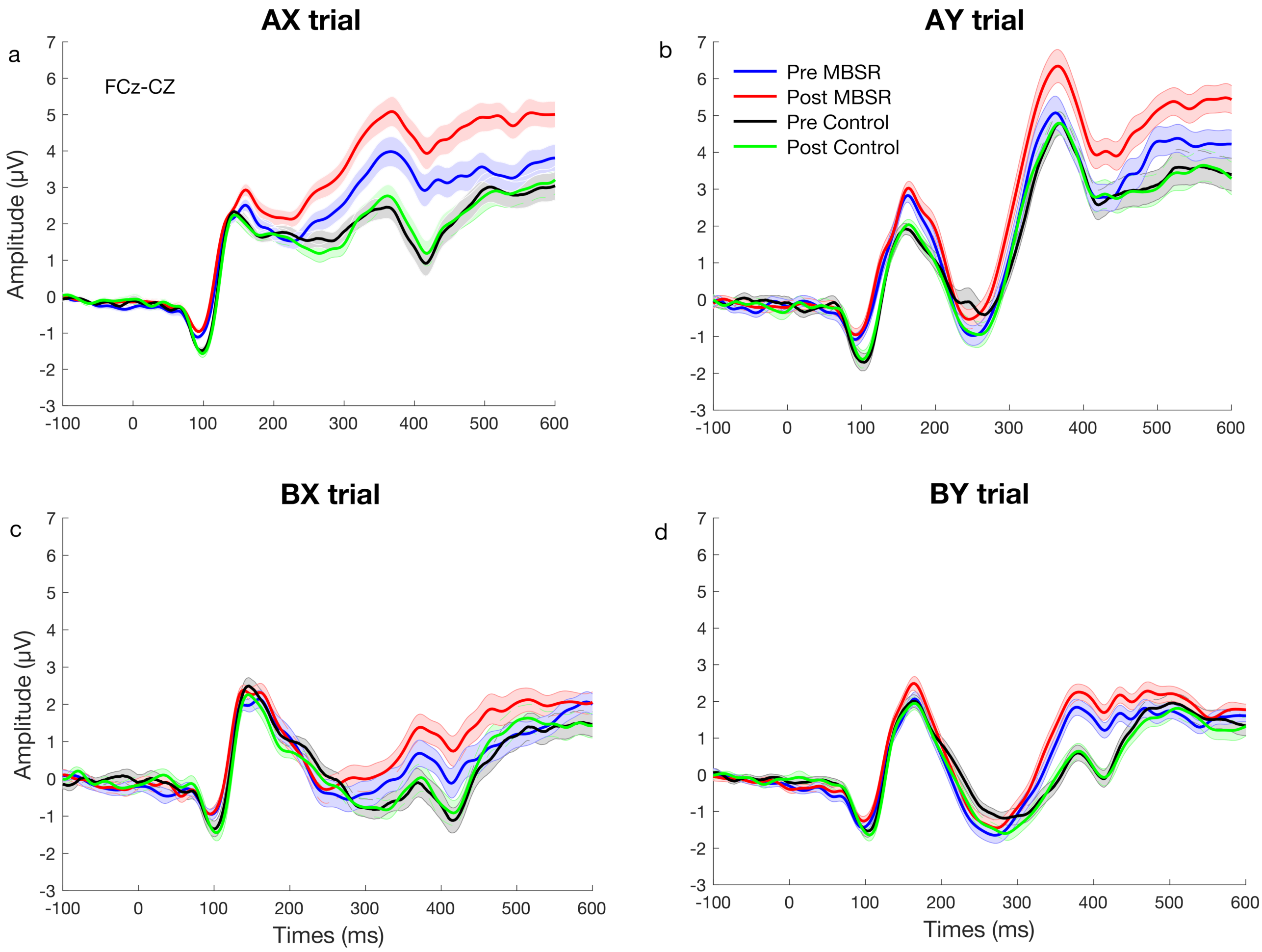


***Fig. 4*** *Grand average of the ERPs time-locked to the probe (0 ms). All trial types are represented, namely clock-wise from the top-left: AX (a), AY (b), BX (c) and BY (d) trials. The standard error of the mean is represented as shaded error bars. ERPs in the two groups and the two sessions are represented in different colors. FCz and Cz electrodes are collapsed. The N2 mean amplitude was extracted from the 200-300 ms post-probe time window, whereas the P3a mean amplitude was extracted from the 300-400 ms post-probe time window.*



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