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The EEG spectral properties of meditation and mind wandering differ between experienced meditators and novices

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ABSTRACT

Previous literature suggests that individuals with meditation training become less distracted during meditation practice. In this study, we assess whether putative differences in the subjective experience of meditation between meditators and non-meditators are reflected in EEG spectral modulations. For this purpose, we recorded electroencephalography (EEG) during rest and two breath focus meditations (with and without experience sampling) in a group of 29 adult participants with more than 3 years of meditation experience and a control group of 29 participants without any meditation experience. Experience sampling in one of the meditation conditions allowed us to disentangle periods of breath focus from mind wandering (i.e. moments of distraction driven by task-irrelevant thoughts) during meditation practice. Overall, meditators reported a greater level of focus and reduced mind wandering during meditation practice than controls. In line with these reports, EEG spectral modulations associated with meditation and mind wandering also differed significantly between meditators and controls. While meditators (but not controls) showed a significant decrease in individual alpha frequency / amplitude and a steeper 1/f slope during meditation relative to rest, controls (but not meditators) showed a relative increase in individual alpha amplitude during mind wandering relative to breath focus periods. Together, our results show that the subjective experience of meditation and mind wandering differs between meditators and novices and that this is reflected in oscillatory and non-oscillatory properties of EEG.

1. Introduction

In an important part of meditation traditions, practitioners are instructed to focus on an object of meditation (e.g. breathing, body sensations) and to bring the attention back to the present moment whenever self-generated thoughts (i.e. mind wandering) occur (Analayo, 2019; Kabat-Zinn, 2006; Krishnamurti, 2002; Matko and Sedlmeier, 2019). Interestingly, it has been shown that experienced meditators from different traditions report less mind wandering frequency than novices during meditation practice (Brandmeyer and Delorme, 2018) and other cognitive tasks (Mrazek et al., 2012, 2013). In addition, trained meditators are thought to experience less engagement with mind wandering episodes in the context of meditation practice (i.e. they would tend to 'observe thoughts' instead of 'attaching to them') (Krishnamurti, 2002; Lutz et al., 2015; Pagnoni et al., 2008; Petitmengin et al., 2017). Hence, previous literature suggests that the subjective experience of meditation differs between trained meditators and novices and that this is related to mind wandering.

Despite Electroencephalography (EEG) has been widely used to study the neural correlates of meditative states and mind wandering in both experienced practitioners and novices, the obtained results remain highly inconsistent. Most of previous studies have focused on the amplitude of neural oscillations in the alpha range (∼ 7–14 Hz), which is thought to reflect functional inhibition in the cortex (Bonnefond and Jensen, 2012; Hanslmayr et al., 2019; Klimesch et al., 2007). When compared to resting state, meditative states have been associated with both increased (for review see Lee et al., 2018; Lomas et al., 2015) and decreased (Aftanas and Golocheikine, 2001; Amihai and Kozhevnikov, 2014; Lehmann et al., 2012) amplitude of alpha oscillations, without a clear distinction between experienced meditators and novices. Similarly, the relationship between the amplitude of alpha oscillations and mind wandering is still debated. Although some studies have associated mind wandering during meditation to a relative decrease in alpha amplitude (in both experienced practitioners and novices) (Braboszcz and Delorme, 2011; Brandmeyer and Delorme, 2018; Rodriguez-Larios and Alaerts, 2020; van Son et al., 2019), the opposite pattern of results has been found in other cognitive tasks (Boudewyn and Carter, 2018; Compton et al., 2019; Gouraud et al., 2021; Groot et al., 2021; Jin et al., 2019, 2020).

There are at least two factors that could explain the lack of consistency regarding the EEG oscillatory correlates of mind wandering

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and meditative states. On the one hand, it has been suggested that the alpha power decrease associated with mind wandering during meditation practice could be related drowsiness (Rodriguez-Larios and Alaerts, 2020) instead of mind wandering *per se*. In this regard, no previous study has assessed whether the EEG correlates of drowsiness and mind wandering during meditation actually differ. On the other hand, the analytical approach adopted in previous studies could have also contributed to the lack of consensus in the literature. In this way, previous studies often estimated alpha power by defining its frequency band *a priori* (e.g. 8–12 Hz). This approach may however severely hinder consistency (e.g. in some studies alpha is divided in two sub-bands; Aftanas and Golocheikine, 2001, 2002; Saggar et al., 2012) and does not take into account inter-individual differences in alpha peak frequency (Klimesch, 1999). In addition, previous studies did not control for possible modulations of non-oscillatory components of the EEG signal such as the slope of the 1/f trend of the EEG spectrum, which is known to conflate power estimations (see Donoghue et al., 2021; Donoghue et al., 2020; Kosciessa et al., 2020).

Although no previous study has investigated changes in the slope of the 1/f trend of the EEG spectrum in relation to meditation practice, previous literature suggests that this parameter could be of functional relevance in this context. The slope of the 1/f trend is thought to be reflective of excitation-inhibition balance (E:I ratio) in the brain (a steeper slope is associated with greater synaptic inhibition) (Gao et al., 2017). In human EEG, the 1/f trend has been linked to arousal and cognitive load (Kosciessa et al., 2021; Lendner et al., 2020; Voytek et al., 2015b; Waschke et al., 2021). Since both arousal and cognitive load are thought to be altered during meditation practice (Hinterberger et al., 2014; Rodriguez-Larios et al., 2020; Vago and Zeidan, 2016), it can be expected that the 1/f slope of the EEG signal would also be modulated. Given this expected change and the fact that previous studies did not control for possible changes in the aperiodic component of EEG to estimate oscillatory power, it is possible that the previously reported oscillatory power changes associated to meditation and mind wandering are reflecting changes in the slope of the 1/f trend.

In this study, we aimed to assess whether the EEG correlates of meditative states and mind wandering differ between experienced meditators and novices. We recorded EEG during rest, an uninterrupted breath focus meditation and an interrupted breath focus meditation (with experience sampling) in a group of experienced meditation practitioners ($N = 29$) and a control group without any previous meditation experience ($N = 29$). In order to provide a comprehensive description of mind-wandering/meditation-related EEG modulations, we investigated four parameters of interest: i) EEG power (2–30 Hz) without an *a priori* definition of frequency bands, ii) the slope of the 1/f trend, iii) individual alpha power (after controlling for the 1/f trend) and iv) individual alpha frequency (after controlling for the 1/f trend). Hence, unlike previous studies, we disentangled oscillatory from non-oscillatory EEG activity and controlled for interindividual differences in alpha peak. In addition, we used the same four parameters to assess the EEG correlates of drowsiness during meditation practice and potential differences between experienced meditators and novices.

2. Methods

2.1. Participants

A total of 63 participants were recruited through social media and by directly contacting different meditation centers throughout Belgium. 5 participants had to be excluded due to technical problems during data acquisition. From the remaining 58 participants, 29 participants (12 males) had at least three years of experience with meditation practices (mean = 9.79 years; SD = 7.11) (i.e. meditators group). Meditators often reported to have experience with more than one meditation tradition. The three most reported traditions were Mindfulness (20 subjects), Zen (8 subjects) and Vipassana (9 subjects). The other 29 participants (14 males) had no previous experience with meditation practices (i.e. control group). The group of meditators and controls did not differ significantly in age (meditators, mean = 47.31, SD = 11.21; controls, mean = 47.13, SD = 13.93) (t-value (28) = 0.05; p-value = 0.95), gender (14 vs 12 males; t-value (28) = −0.52; p-value = 0.60) or level of education (t-value (23) = −1.64; p-value = 0.10). Note that the level of education was quantified as: 1 = professional training, 2 = University degree, 3 = PhD degree. Informed consent forms and study design were approved by the Social and Societal Ethics Committee (SMEC) of KU Leuven, in accordance with the Declaration of Helsinki (dossier no. G-2019 09 1747). Participants were compensated for their participation with 8 € per hour in addition to travel costs.

2.2. Design and task

EEG recordings were performed during three different conditions: rest (5 min), meditation (10 min) and meditation with probe-caught experience sampling (~ 60 min) (for overview see **Fig. 1A**). The experimental instructions were given in Dutch or English. During rest, participants were instructed to close their eyes, try to not to fall asleep, move as little as possible and let their minds wander in thought. For the meditation condition, the following instructions were used: *'Sit in a comfortable posture that embodies dignity, keeping the spine straight and letting your shoulders drop. Close your eyes and allow your attention to gently align to the sensation of breathing. You can focus on the part of your body where you feel your breath most clearly (for example: nostrils, belly, chest…). Every time you notice that your mind has wandered off your breath, notice what it was that carried you away, and then gently bring your attention back to the sensations associated with your breath'* (Kabat-Zinn, 1990). In the meditation with experience sampling condition, participants were asked to follow the instructions appearing on a computer screen. First, they were asked to close their eyes and focus on their breath. After a period of 30 to 90 s, participants were presented with a bell sound and were required to open their eyes and report with a keyboard whether they were 1) focusing on their breath, 2) distracted by thoughts or 3) distracted by something else (sound, discomfort or other) (see **Fig. 1D** for depiction). Regardless of the answer to the first question, participants had to report in the two following questions (scored on 7-point scales) their level of confidence on the previous question (ranging from 'not confident at all' (1) to 'completely confident' (7)) and their level of drowsiness (from 'completely awake' (1) to 'falling asleep' (7)). Then, some extra follow-up questions (also on 7-point scales) were asked depending on the answer to the first question. If participants answered 'focusing on the breath' in the first question, they were asked an extra question about the level of attention to the breathing (from 'only superficially' (1) to 'full attention' (7)). If participants answered 'distracted by thoughts' in the first question, they were asked three extra questions about the level of engagement in the thought (from 'mostly observing' (1) to 'fully engaged' (7)) and the level of visual and auditory components in the thought (from 'not visual/auditory at all' (1) to 'completely visual/auditory' (7)). Lastly, if participants answered 'distracted by something else' in the first question, they were asked in an extra question about what distracted them (three options: external sound, feeling of pain discomfort or something else). Participants performed a total of 40 trials in approximately 60 min.

2.3. EEG data acquisition

Electroencephalography (EEG) recordings were performed using a Nexus-32 system and BioTrace software (V2018A1) (Mind Media, The Netherlands). Continuous EEG was recorded with a 19-electrode cap (plus two reference electrodes and one ground electrode) positioned according to the 10–20 system (see **Fig. 1A**). Vertical (VEOG) and horizontal (HEOG) eye movements were recorded by placing pre-gelled foam electrodes (Kendall, Germany) above and below the left eye (VEOG) and next to the left and right eye (HEOG) (sampling rate of 2048 Hz). Skin abrasion and electrode paste (Nuprep) were used to reduce the electrode

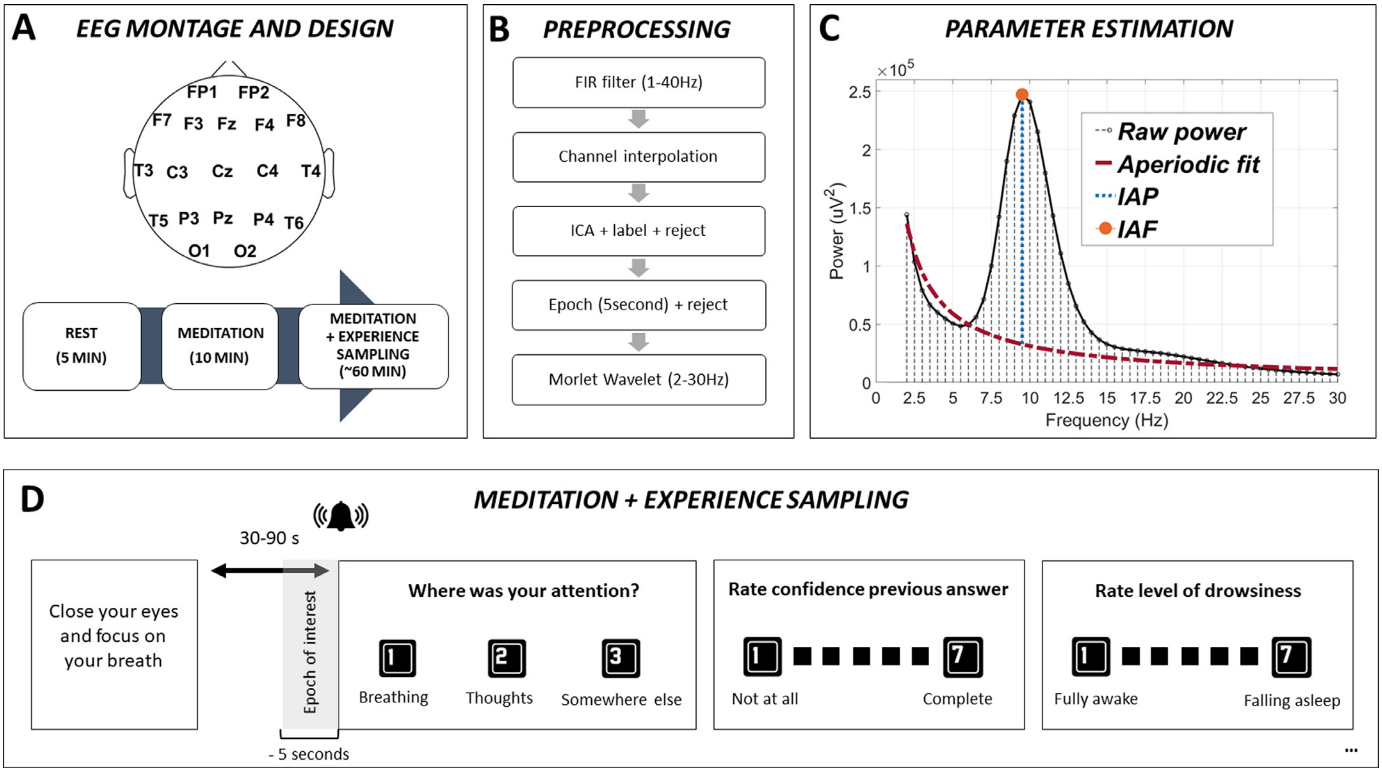

Fig. 1. Design, EEG parameter estimation and task. A) Depiction of EEG montage and design. 19-channels EEG was acquired during three experimental conditions (rest, meditation and meditation with experience sampling) in a group of experienced meditators and a control group. B) Depiction of the pre-processing steps including: Finite impulse response (FIR) filter, channel interpolation, Independent Component Analysis (ICA), epoching and Morlet wavelet transform. C) Estimation of raw power, aperiodic fit (based on 1/f slope in log-log space), individual alpha power (IAP) and individual alpha frequency (IAF). D) Illustration of the meditation condition with experience sampling task. Participants were asked to close their eyes and focus on their breath. At random intervals between 30 and 90 s participants heard a bell sound and they were asked to report the location of their attentional focus (breathing, thoughts or something else). Then, several follow-up questions were asked for a better characterization of their experience (confidence, drowsiness…etc.). Participants performed 40 trials in ~60 min. Only the 5 s before the bell sound (epoch of interest; see gray area) were used for further EEG analysis.

impedances during the recordings. The EEG signal was amplified using a unipolar amplifier with a sampling rate of 512 Hz. In the meditation with experience sampling condition, EEG recordings were synchronized to E-prime 2.0 using the Nexus trigger interface (Mind Media).

2.4. EEG analysis

Pre-processing was performed in MATLAB R2020b using custom scripts and EEGLAB (version 2019) functions (Delorme & Makeig, 2004) (see Fig. 1**B** for overview). EEG data were first filtered between 1 and 40 Hz (function *pop_eegfiltnew*). Then noisy electrodes were detected automatically (function *clean_channels*) and interpolated (spherical interpolation implemented in function *pop_interp*). A mean of 1.40 channels (SD = 1.20) were interpolated. Then EEG data were re-referenced to the common average and independent component analysis (ICA) (function *pop_runica*) was performed. An automatic component rejection algorithm (i.e. *IClabel*) was employed to discard components associated with muscle activity, eye movements, heart activity or channel noise (Pion-Tonachini et al., 2019). In addition, components with an absolute correlation with EOG channels higher than 0.6 were also discarded. The mean number of rejected components was 1.37 (SD = 1.01). Data was then epoched in 5 second epochs (note that in the meditation condition with experience sampling these 5 s corresponded to the 5 s before the bell sound; see Fig. 1**D**). Epochs with an absolute amplitude higher than 100 μV were excluded (mean percentage of epochs rejected = 4.5%; SD = 6.07). Note that for the experience sampling task (interrupted meditation), we obtained an average of 37.5 (SD = 3.73) clean trials per participant. For the comparison of the uninterrupted meditation and rest conditions, only the last 5 min of the uninterrupted meditation condition were considered (originally 10 min long) to make the number of epochs equal to the rest condition (5 min long).

The frequency spectrum between 2 and 30 Hz (0.5 Hz resolution) of each epoch was obtained using Morlet wavelet transform with a wave number of 6 cycles (as implemented in the function *BOSC_tf*; see Whitten et al., 2011). Note that EEG activity at higher and lower frequencies were not initially included in the analysis to avoid noise from different non-neural sources (Voytek et al., 2010, 2015a; Yuval-Greenberg et al., 2008). Four parameters of interest were extracted from the frequency spectrum of each electrode: power at each frequency (without removal of 1/f trend), 1/f trend slope, individual alpha power (IAP) (after removal of the 1/f trend) and individual alpha frequency (IAF) (after removal of the 1/f trend) (see Fig. 1**C** for depiction).

Power at each frequency was extracted by squaring the real component (amplitude) of the convolution between the EEG signal and a family of wavelets. The 1/f slope of the spectrum was estimated by fitting a straight line in log–log space to the EEG frequency spectrum (excluding the 7 – 14 Hz range containing the alpha peak) using the *robustfit* function in MATLAB (for similar approaches see Caplan et al., 2015; Kosciessa et al., 2020; Watrous et al., 2018; Whitten et al., 2011). Note that throughout the manuscript we use the term 'steeper' when the 1/f slope becomes more negative (higher exponent) and 'flatter' when the 1/f slope becomes more positive (lower exponent). The mean goodness of fit (R^2) for the 1/f line fits across electrodes, conditions and subjects was 0.76 (SD = 0.24). In order to estimate individual alpha, a find local maxima algorithm (function *findpeaks* in MATLAB R2020b) was employed to find a peak between 7 and 14 Hz above the estimation of the 1/f trend. Then, the amplitude of this peak relative to the 1/f trend (individual alpha power; IAP) and its frequency (individual alpha frequency; IAF) was calculated.

The parameter estimation was performed in the average spectrum (across epochs/trials) when comparing different conditions (i.e. meditation vs rest; mind wandering vs breath focus) and in an epoch by epoch basis to assess correlations within subjects (i.e. relation between drowsiness and each of the estimated parameters across different trials).

The average spectrum in the meditation with experience sampling condition (last 5 s before the bell sound) was estimated by performing a weighted average of the spectrum of different epochs, so epochs with a greater confidence rate had a greater weight in the average spectrum. The rationale behind this approach is to minimize the influence of epochs in which subjects are not sure about their state (breath focus or mind wandering) in the estimation of each EEG dependent variable (Rodriguez-Larios and Alaerts, 2020). Note that the reported results did not change qualitatively when averaging trials without considering confidence reports (i.e. no weighting).

2.5. Statistical analysis

A cluster-based permutation statistical method (Maris and Oostenveld, 2007) was adopted to assess the significance of condition-related differences and trial by trial correlations in each EEG dependent variable. This statistical method controls for the type I error rate arising from multiple comparisons using a non-parametric Montecarlo randomization. First, cluster-level test statistics are estimated in the original data (comparing subjects between conditions or correlations against zero) and in several shuffled versions of the data (i.e. 10,000 random partitions). Cluster-level test-statistics are defined as the sum of t-values with the same sign across adjacent electrodes and/or frequencies that are above a specified threshold (i.e. 97.5th quantile of a T-distribution). Then, the cluster-level statistics from the original data and the null distribution emerging from the random partitions are compared. Cluster-corrected p-values are defined as the proportion of random partitions whose cluster-level test statistic exceeded the one obtained in the original (non-shuffled) data. Significance level for the cluster permutation test was set to 0.025 (corresponding to a false alarm rate of 0.05 in a two-sided test) (Maris and Oostenveld, 2007). Paired-samples *t*-test was chosen as the test statistic to compare conditions (meditation vs rest and mind wandering vs breath focus), independent samples *t*-test was used to compare condition-related differences (% change) between groups (meditators vs controls). For trial by trial correlations (relation between drowsiness in each dependent variable), Pearson r-values were estimated per subject and one sample *t*-test was used to assess the significance of the obtained r-values at group level. In addition to the obtained cluster statistics, effect size is reported across electrodes and/or frequencies through Cohen's d estimate (Nakagawa and Cuthill, 2009). In order to assess the robustness of our results, a Repeated Measures ANOVA (SPSS implementation) was also performed with Condition/Electrodes as within subject factors and Group as a between subject factor. The Greenhouse-Geisser method was used to correct for the lack of sphericity. Note that this later analysis was only performed for IAF, IAP and 1/f slope estimates.

For the behavioural data, we decided to perform non-parametric tests that do not assume normality. Specifically, Wilcoxon rank sum test was employed to compare scores between groups and Wilcoxon signed rank test was used to compare scores within subjects (both implemented in MATLAB R2020b).

3. Results

3.1. Self-reports during meditation with experience sampling

On average, participants reported to be focusing on their breath in 63.69% of the trials (SD = 16.07), distracted by thoughts in 23.57% of the trials (SD = 11.88) and distracted by something else in 14.62% of the trials (SD = 8.97). For the statistical analysis we focused on 'breath focus' and 'distracted by thoughts' (i.e. mind wandering) trials.

Wilcoxon signed rank tests showed that, relative to the control group, meditators reported a significantly higher proportion of 'breath focus' trials (z-value = 4.46; p <0.001) (see top panel Fig. 2**A**) and a significantly lower proportion of 'distracted by thoughts' trials (z-value = −3.01; p = 0.0026) (see top panel of Fig. 2**B**). In addition, Wilcoxon rank sum tests revealed that the meditators group (relative to controls) reported a significantly higher mean level of attention in breath focus trials (z-value = 3.40, p < 0.001) (Fig. 2**A** bottom panel) and a lower mean level of engagement in mind wandering trials (z-value = −1.87, p = 0.06) (non-significant) (Fig. 2**B** bottom panel). Generally, reports of drowsiness were low in both meditators (mean = 1.92; SD = 1.02) and controls (mean = 2.14; SD = 1.08) and no significant differences between groups were evident (z-value = −1.4315, p = 0.15). Also, no significant group differences were revealed for ratings of confidence (z-value = 0.82, p = 0.40), visualization (z-value = 0.08, p = 0.93) or auditory components of mind wandering episodes (z-value = 1.35, p = 0.17).

3.2. EEG spectral modulations during meditation relative to rest

We used cluster permutations statistics (see statistical analysis) to compare each of our EEG dependent variables (power at each frequency, 1/f slope, IAP and IAF; see Fig. 1**C**) between conditions (meditation vs rest; paired samples *t*-test) and condition-related modulations (% change) between groups (meditators vs controls; independent samples *t*-test). In addition, we assessed the robustness of our results by performing a Repeated Measures ANOVA with IAF, IAP and 1/f slope estimates (see Supplementary materials).

Raw power. Experienced meditators showed a significant power decrease in the alpha/beta range (9 - 30 Hz; widespread across electrodes) during meditation relative to rest ($t_{cluster} = -881.37$; $p_{cluster} < 0.001$; d = 0.70) (see Fig. 3**D**). In contrast, the control group showed a non-significant high-beta (21 - 30 Hz) power increase in fronto-central electrodes during meditation ($t_{cluster} = 91.86$; $p_{cluster} = 0.084$; d = 0.51) (see Fig. 3**E**). A comparison of meditation-related changes between groups revealed that meditators showed a significantly more pronounced power decrease in the alpha/beta range (9–30 Hz) ($t_{cluster} = -666.56$; $p_{cluster} = 0.004$; d = 0.52) than controls (see Fig. 3**F**).

Individual alpha power and frequency. Experienced meditators showed significant decrease in IAF in frontal electrodes ($t_{cluster} = -5.42$; $p_{cluster} = 0.021$; d = 0.71) and significant decrease in IAP in parietal electrodes ($t_{cluster} = -14.89$; $p_{cluster} = 0.010$; d = 0.56) during meditation relative to rest (see left and middle panels in Fig. 3**G**). Instead, the control group showed a non-significant IAF increase in central electrodes ($t_{cluster} = 4.42$; $p_{cluster} = 0.039$; d = 0.48) during meditation (see left and middle panels in Fig. 3**H**). A comparison of meditation-related changes between groups revealed non-significant differences in IAP ($t_{cluster} = -2.29$; $p_{cluster} = 0.072$; d = 0.42) and IAF ($t_{cluster1} = -2.49$; $p_{cluster1} = 0.093$; $t_{cluster2} = -2.47$; $p_{cluster2} = 0.096$; d = 0.70) (see left and middle panels in Fig. 3**I**).

1/f slope. Experienced meditators showed a non-significant increase in the steepness of the 1/f slope (i.e. more negative values) during meditation relative to rest ($t_{cluster} = -4.23$; $p_{cluster} = 0.057$; d = 0.45) (see right panel in Fig. 3**G**). On the contrary, controls showed a non-significant flattening (more positive values) of the 1/f slope during meditation relative to rest ($t_{cluster} = 2.54$; $p_{cluster} = 0.10$; d = 0.47) (see right panel in Fig. 3**H**). Hence, groups differed significantly in meditation-related changes in the 1/f slope (i.e. steeper during meditation relative to rest for meditators and flatter during meditation relative to rest for novices) ($t_{cluster} = -7.76$; $p_{cluster} = 0.016$; d = 0.85) (see right panel in Fig. 3**I**). Note that the results were qualitatively similar when estimating the 1/f slope in broader frequency ranges (i.e., 2–35 Hz, 2–40 Hz).

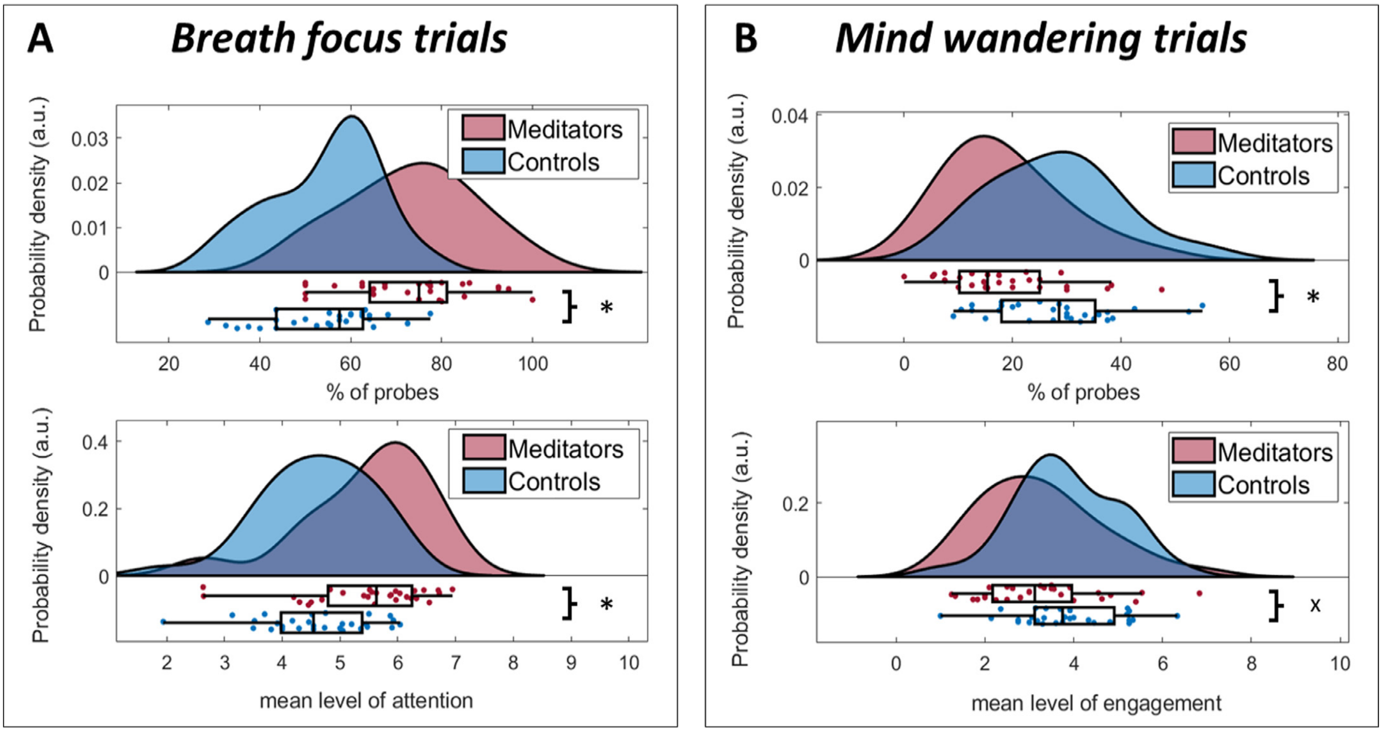

Fig. 2. Self-reports during meditation with experience sampling. Individual data points and probability density distributions depicting the percentage of breath focus trials (A, top panel), the percentage of mind wandering trials (B, top panel), the mean level of attention in breath focus trials (A, bottom panel) and the mean level of engagement in mind wandering trials (B, bottom panel) for meditators (red) and control (blue) groups. Asterisks indicate significance (i.e. $p<0.05$) and 'x' indicates statistical tendency ($p<0.1$).

In summary, experienced meditators and controls differed significantly in meditation-related EEG spectral changes. Specifically, only experienced meditators showed reduced power in the alpha/beta band, reduced individual alpha power/frequency, and a steeper 1/f slope during meditation relative to rest. However, group differences in condition-related modulations only reached statistical significance for the 1/f slope estimate. Note that Repeated Measures ANOVA showed a qualitatively similar pattern of results (see Supplementary Figure 1&2).

3.3. EEG spectral modulations during mind wandering relative to breath focus

We used the same cluster permutation procedure to compare each of our EEG dependent variables (power at each frequency, 1/f slope, IAP and IAF; see Fig. 1**C**) between mind wandering and breath focus periods identified during the meditation with experience sampling condition (see Fig. 1**D**). Like in the previous section, we also compared condition-related changes in each of our dependent variables between meditators and the control group. In addition, we assessed the robustness of our results by performing a Repeated Measures ANOVA with IAF, IAP and 1/f slope estimates (see Supplementary Materials).

Raw power. Experienced meditators showed a non-significant decrease in theta band power (3 - 6 Hz) in frontal electrodes during mind wandering relative to breath focus ($t_{cluster} = 67.72$; $p_{cluster} = 0.078$; $d = 0.68$) (see Fig. 4**D**). In contrast, controls showed a significant increase in alpha/beta (10.5 - 25 Hz) power during mind wandering across electrodes ($t_{cluster} = 485.32$; $p_{cluster} = 0.0064$; $d = 0.62$) (see Fig. 4**E**). Significant differences between groups in mind wandering-related changes were found in both theta and alpha/beta bands (3–25 Hz range) ($t_{cluster} = -1192.99$; $p_{cluster} = 0.0017$; $d = 0.84$) (see Fig. 4**F**).

Individual alpha power and frequency. Only the control group showed a significant increase of IAP in frontal electrodes during mind wandering relative to breath focus ($t_{cluster} = 9.03$; $p_{cluster} = 0.019$; $d = 0.44$) (see left panel in Fig. 4**H**). However, group differences in mind wandering-related IAP modulations did not reach statistical significance ($p_{cluster} > 0.1$).

1/f slope. Experienced meditators showed a non-significant flattening (more positive value) of the 1/f slope in a left frontal electrode in mind wandering relative to breath focus conditions ($t_{cluster} = 2.62$; $p_{cluster} = 0.097$; $d = 0.49$) (see right panel in Fig. 4**G**) while no differences were found in controls ($p_{cluster} > 0.1$). A non-significant group difference was also found in the same electrode ($t_{cluster} = 2.56$; $p_{cluster} = 0.092$; $d = 0.68$) (see right panel in Fig. 4**I**).

In summary, experienced meditators and controls differed significantly in mind wandering-related EEG spectral changes. Specifically, controls (but not meditators) showed a significant increase in IAP and alpha/beta power during mind wandering relative to breath focus. Note that Repeated Measures ANOVA showed a qualitatively similar pattern of results for IAP modulations (see Supplementary Figure 3).

3.4. EEG spectral modulations associated with drowsiness

In addition to condition-related differences, we assessed the relationship between trial-by-trial variations in each of our dependent variables and trial-by-trial variations in self-reported drowsiness during meditation practice. For this purpose, Spearman rank order correlations were estimated for each of the dependent variables (power at each frequency, 1/f slope, IAP and IAF; see Fig. 1**C**) per electrode and subject. Then, we assessed the significance of these correlations at group level using the described cluster permutation test (Maris and Oostenveld, 2007) against zero (one sample *t*-test). In addition, we assessed potential group differences in the obtained correlations using the same cluster permutation test. We also performed a Repeated Measures ANOVA with IAF, IAP and 1/f slope estimates in order to assess the robustness of the results (see Supplementary materials).

Raw power. Drowsiness was positively correlated to theta/low-alpha band power (3 – 8 Hz) in both experienced meditators ($t_{cluster} = 138.10$; $p_{cluster} = 0.059$; $d = 0.80$) (see Fig. 5**D**) and controls ($t_{cluster} = 399.10$;

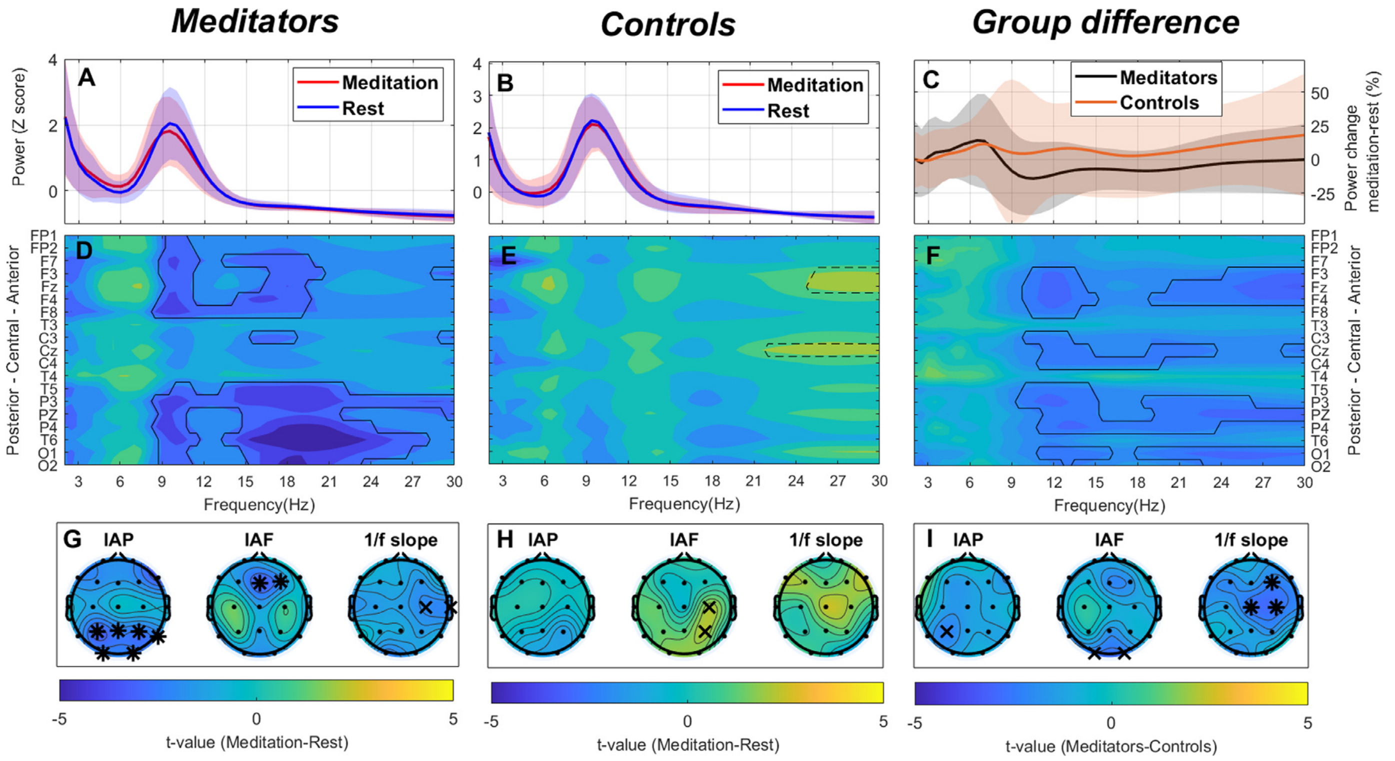

Fig. 3. EEG spectral modulations associated to the uninterrupted meditation in meditators and control groups. A-B) Average power spectrum (solid line) and standard deviation (shaded) in the 2–30 Hz range (across electrodes) during meditation (red) and rest (blue) in meditators (A) and the control (B) group. The power spectrum was z-scored (relative power) for visualization purposes. C) Mean power change (solid line) and standard deviation (shaded) in the 2–30 Hz frequency range (% change from rest; across electrodes) in meditators (black) and controls (orange). D-E) Matrix depicting the t-values resulting from comparing power at each frequency (x-axis; 2–30 Hz) and electrode (y-axis) between conditions (meditation vs rest) in the meditators (D) and control (E) group. The colours code for the direction of the differences between conditions (yellow = higher in meditation; blue = higher in rest). F) Matrix of t-values resulting from comparing power at each frequency (x-axis; 2–30 Hz) and electrode (y-axis) between groups during meditation. The colours code for the direction of the differences between groups (yellow = higher in meditators; blue = higher in controls). In all matrices, solid contours indicate significance at $p<0.025$ while dotted contours indicate statistical tendency ($p<0.1$). G-I) Topographical plots depicting differences in individual alpha power (IAP), individual alpha frequency (IAF) and the slope of the 1/f trend between conditions in each group (panel G for meditators and panel H for controls) and between groups (panel I). The colours code for the direction of the differences is the same as in the t-value matrices. Asterisks indicate statistical significance at $p<0.025$ whilst the symbol ‘x’ indicates non-significant differences (p-values between 0.025 and 0.1).

$p_{cluster} = 0.016$; $d = 1.09$) (see Fig. 5E). However, this correlation was statistically significant in controls only. No significant differences were found between groups ($p_{cluster} > 0.1$).

Individual alpha power and frequency. Drowsiness was negatively correlated to IAF in both experienced meditators ($t_{cluster} = -14.74$; $p_{cluster} = 0.004$; $d = 0.69$) (see middle panel in Fig. 5G) and controls ($t_{cluster} = -15.98$; $p_{cluster} = 0.006$; $d = 0.65$) (see middle panel in Fig. 5H). No other differences were found.

1/f slope. A steeper 1/f slope was associated with increased drowsiness in controls ($t_{cluster} = -5.19$; $p_{cluster} = 0.04$; $d = 0.58$) although this correlation did not reach statistical significance according to the chosen α level (i.e. $p<0.025$) (see Fig. 5H right panel). No correlations were found in meditators and no differences were identified between groups ($p_{cluster} > 0.1$).

In summary, drowsiness during meditation practice was significantly associated with reduced individual alpha peak frequency in both meditators and controls. In line with these results, a main effect of condition in IAF was identified through Repeated Measures ANOVA (see Supplementary Figure 4). In addition, increases in theta/alpha power were also associated with drowsiness, although this comparison only reached statistical significance in the control group.

4. Discussion

This study assessed whether the EEG correlates of meditative states and mind wandering differ significantly between experienced meditators and novices. We compared meditation/mind wandering-related EEG spectral modulations between a group of experienced meditators and a control group without any meditation experience. Our results show that group differences in the experience of meditation (i.e. reduced mind wandering frequency / engagement and greater focus in experienced practitioners) are accompanied by group differences in meditation/mind wandering-related EEG spectral modulations. On the one hand, meditators (but not controls) showed a power decrease in alpha/beta band power, a decrease in individual alpha frequency and a steeper 1/f slope during an uninterrupted breath focus meditation practice relative to rest. On the other hand, experience sampling during meditation revealed that controls (but not meditators) showed a significant increase in alpha/beta power during mind wandering relative to periods of breath focus.

Our results are in line with other studies reporting a relative decrease in alpha power (Aftanas and Golocheikine, 2001; Amihai and Kozhevnikov, 2014; Lehmann et al., 2012) and frequency (Aftanas and Golocheikine, 2002; Irrmischer et al., 2018; Rodriguez-Larios et al., 2020; Saggar et al., 2012; Takahashi et al., 2005; Yamamoto et al., 2006) during meditation relative to rest. However, it is important to underline that previous literature reviews have concluded that meditation is most commonly associated with relative increases in alpha power when compared to rest and other control conditions (Lee et al., 2018; Lomas et al., 2015). In this way, it is possible that this inconsistency relates to the fact that previous reviews included different meditation techniques (e.g. mantra recitation, visualizations…etc.) that could have differential ef-

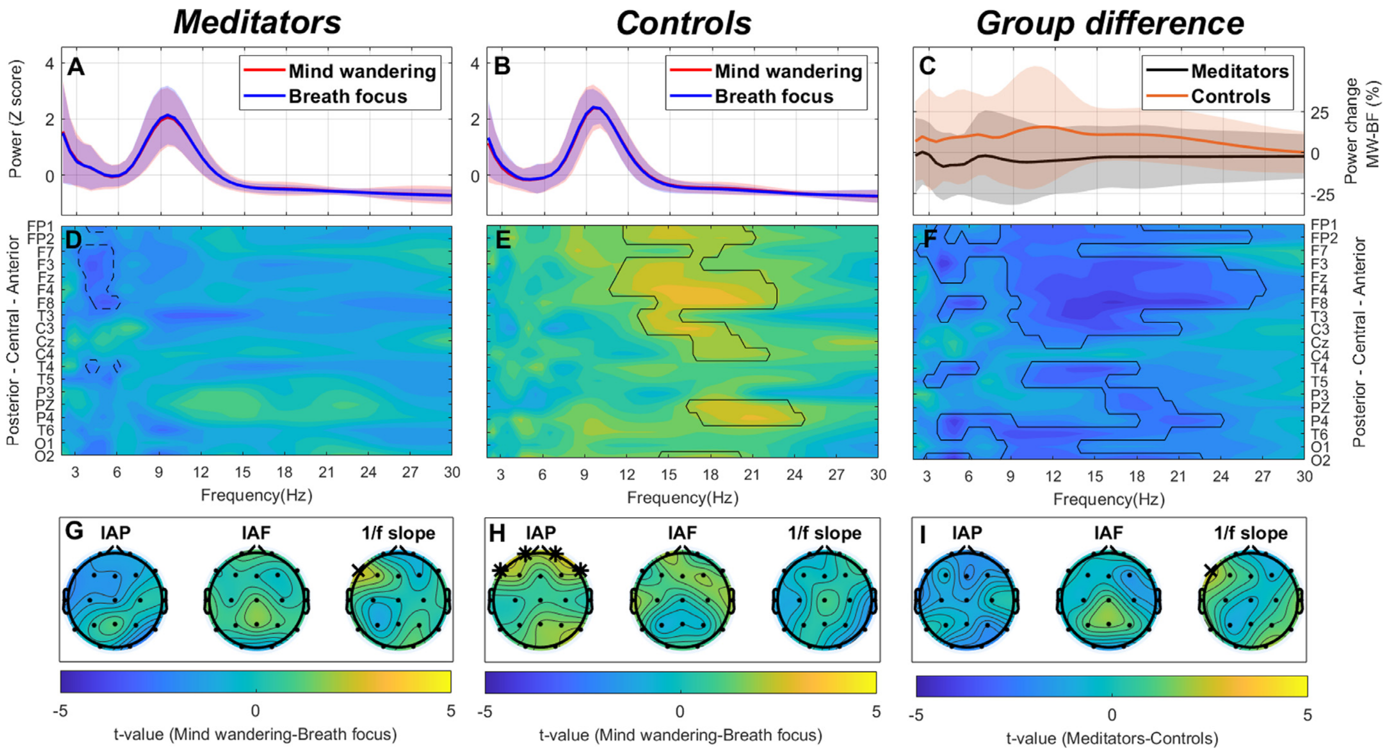

Fig. 4. EEG spectral modulations associated to periods of mind wandering relative to periods breath focus in meditators and control groups. A-B) Average power spectrum (solid line) and standard deviation (shaded) in the 2–30 Hz range across electrodes during mind wandering (red) and breath focus (blue) in meditators (A) and control (B) groups. The power spectrum was z-scored (relative power) for visualization purposes. C) Mean power percentage change (mind wandering – breath focus) (solid line) and standard deviation (shaded) in the 2–30 Hz frequency range across electrodes in meditators (black) and controls (orange). D-E) Matrix depicting the t-values resulting from comparing power at each frequency (x-axis; 2–30 Hz) and electrode (y-axis) between conditions (mind wandering vs breath focus) in the meditators (D) and control (E) group. The colours code for the direction of the differences between conditions (yellow = higher during mind wandering; blue = higher during breath focus). F) Matrix of t-values resulting from comparing power at each frequency (x-axis; 2–30 Hz) and electrode (y-axis) between groups during mind wandering (relative to breath focus). The colours code for the direction of the differences between groups (yellow = higher in meditators; blue = higher in controls). In all matrices, solid contours indicate significance at $p<0.025$ while dotted contours indicate statistical tendency ($p<0.1$). G-I) Topographical plots depicting differences in individual alpha power (IAP), individual alpha frequency (IAF) and the slope of the 1/f trend between conditions in each group (panel G for meditators and panel H for controls) and between groups (panel I). The colours code for the direction of the differences in each panel is the same as in the t-value matrices. Asterisks indicate statistical significance at $p<0.025$ whilst the symbol ‘x’ indicates non-significant differences (p-values between 0.025 and 0.1).

fects on arousal levels (Britton et al., 2014) and/or included subjects without meditation experience (Lee et al., 2018; Lomas et al., 2015). Another possibility is that the lack of consensus in the literature is related to the adopted analytical approach. Since previous studies estimated power in an *a priori* definition of the alpha band (i.e. ~8 – 13 Hz) without peak detection nor control for the 1/f trend of the spectrum, we cannot rule out the possibility that their results are a mix of changes in oscillatory power, frequency and/or the 1/f slope (Donoghue et al., 2020, 2020).

Experience sampling during meditation practice revealed that non-meditators showed a significant increase in alpha power during mind wandering in the context of meditation practice. Based on previous literature, we interpret the observed increase in alpha amplitude during mind wandering to be reflective of a temporary increase in inhibition of sensory areas (Klimesch et al., 2007) that would result in decoupling from external stimuli (Baird et al., 2014; Smallwood et al., 2008). Although our findings are in line with studies that associated mind wandering to a relative increase in alpha power in different cognitive tasks (Boudewyn and Carter, 2018; Compton et al., 2019; Gouraud et al., 2021; Groot et al., 2021; Jin et al., 2019, 2020), they directly contradict three previous studies that found the opposite pattern of results in the context of meditation practice (Braboszcz and Delorme, 2011; Rodriguez-Larios and Alaerts, 2020; van Son et al., 2019). There are several factors that could explain this inconsistency. On the one hand, two of the three previous studies that reported decreased alpha power during mind wandering relative to breath focus adopted a self-caught experience sampling paradigm (i.e. participants are instructed to press a button whenever they realize that they are mind wandering) (Braboszcz and Delorme, 2011; van Son et al., 2019) instead of a probe-caught experience sampling paradigm (i.e. participants are instructed to report whether they are mind wandering after they hear a bell sound). It is possible that self-caught and probe-caught mind wandering are associated with different EEG spectral modulations. In fact, periods of mind wandering identified in self-caught paradigms also include other components such a meta-awareness and motor preparation that have been previously associated with alpha suppression (Deiber et al., 2012; van Driel et al., 2012). Another factor that could be contributing to the inconsistency of previous results is drowsiness. In this line, our previous study suggests that lapses of attention that are accompanied by a relative decrease in alpha power could be reflecting drowsiness and/or hypnagogic states rather than mind wandering *per se* (Rodriguez-Larios and Alaerts, 2020). In support of this idea, the spectral profile identified for mind wandering in Rodriguez-Larios & Alaerts (2020) looks qualitatively similar to the one that we associated with drowsiness during meditation practice in the current study (see **Fig. 5E** this paper and Fig. 2 in Rodriguez-Larios & Alaerts (2020)).

An important difference between studies assessing mind wandering during cognitive tasks and meditation practice is that eyes are normally closed in the latter case only. Crucially, it has been recently shown that eye closure affects alpha modulations during cognitive tasks

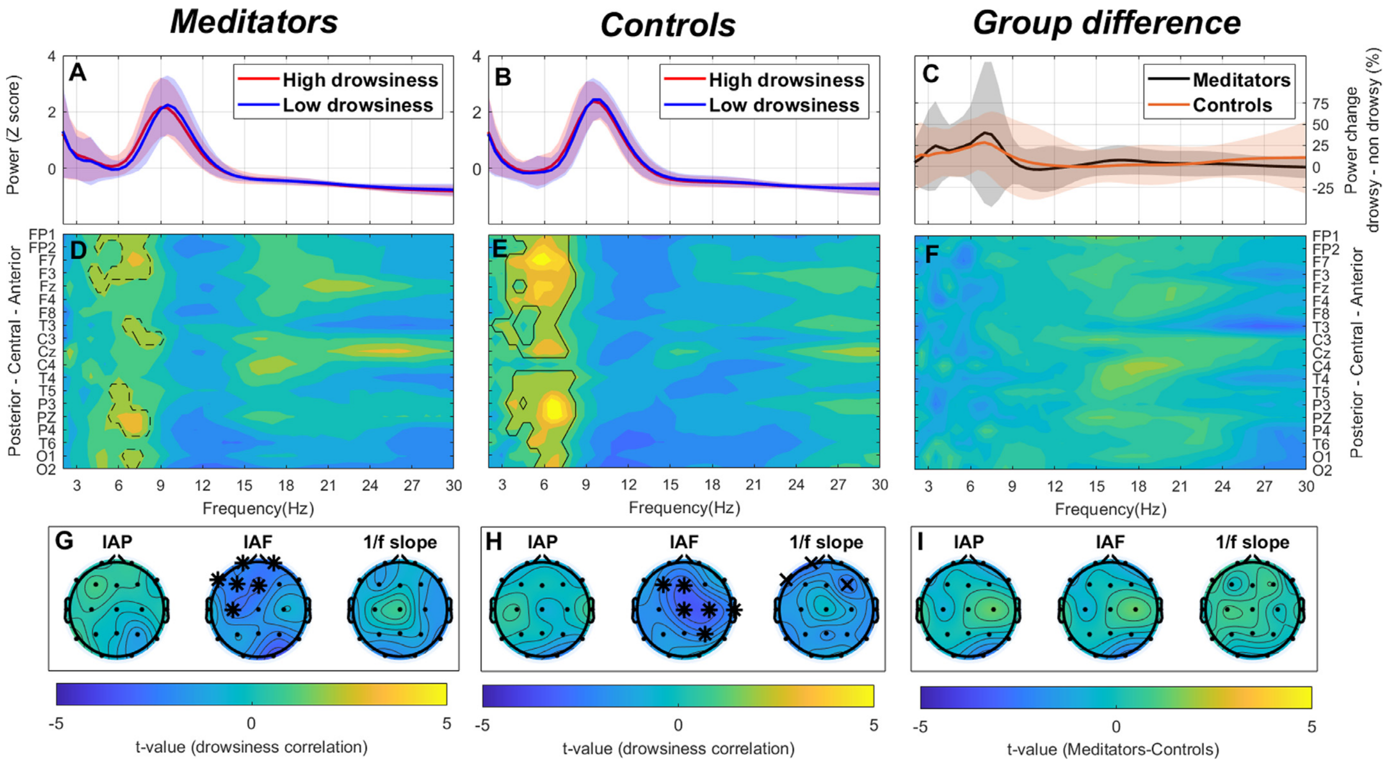

Fig. 5. EEG spectral modulations associated with drowsiness during meditation with experience sampling across groups. A-B) Average power spectrum (solid line) and standard deviation (shaded) in the 2–30 Hz range across electrodes during high drowsiness (red) and low drowsiness (blue) in meditators (A) and control (B) groups. The power spectrum was z-scored (relative power) and a median split was performed based on drowsiness for visualization purposes. C) Mean power percentage change (high – low drowsiness) (solid line) and standard deviation (shaded) in the 2–30 Hz frequency range across electrodes in meditators (black) and controls (orange). D-E) Matrix depicting the t-values resulting from the statistical assessment of the correlation between power at each frequency (x-axis; 2–30 Hz) and electrode (y-axis) and drowsiness in the meditators (D) and control (E) group. The colours code for the direction of the correlation with drowsiness (yellow = positive correlation; blue = negative correlation). F) Matrix of t-values resulting from comparing the correlation with drowsiness at each frequency (x-axis; 2–30 Hz) and electrode (y-axis) between groups. The colours code for the direction of the differences between groups (yellow = higher in meditators; blue = higher in controls). In all matrices, solid contours indicate significance at $p<0.025$ while dotted contours indicate statistical tendency ($p<0.1$). G-I) Topographical plots depicting the correlations between individual alpha power (IAP), individual alpha frequency (IAF) and the slope of the 1/f trend and drowsiness in each group (panel G for meditators and panel H for controls) and the differences between groups (panel I). The colours code for the direction of the correlations and group differences is the same as in the t-value matrices. Asterisks indicate statistical significance at $p<0.025$ whilst the symbol 'x' indicates non-significant differences (p-values between 0.025 and 0.1).

(ElShafei et al., 2021). Hence, it is possible that this is also the case for mind wandering. In the light of previous literature (Boudewyn and Carter, 2018; Compton et al., 2019; Gouraud et al., 2021; Groot et al., 2021; Jin et al., 2019, 2020), our findings support the idea that mind wandering is associated with alpha power increases with both eyes open and eyes closed. Nonetheless, it is possible that the spatial and/or frequency specificity of alpha power increases are different with eyes open and eyes closed. Therefore, future studies are warranted to test whether the EEG correlates of mind wandering and focused attention states (during meditation and other cognitive tasks) are modulated by eye closure.

Our results show that the amplitude of alpha oscillations decrease during meditation relative to rest in experienced meditators (but not in novices) and during breath focus relative to mind wandering in novices (but not in experienced meditators). On the one hand, we hypothesize the alpha suppression during meditation relative to rest is less pronounced in non-meditators because the frequency of mind wandering for these participants is more similar in meditation and rest conditions. In line with this interpretation, self-reports showed that mind wandering during meditation is less frequent in experienced practitioners than in novices. On the other hand, we speculate that alpha power increases during mind wandering (relative to breath focus) is only present in novices because in experienced practitioners mind wandering was not sustained or intense enough to cause an alpha power increase (i.e. they quickly disengaged from mind wandering episodes when they occurred). Self-reports also support this hypothesis as they showed that the level of mind wandering engagement was generally lower for experienced practitioners than for novices. In this regard, it is important to note that although we did not find significant group differences in sociodemographic factors such as age, gender or level of education, we cannot completely rule out the possibility that groups differed in other factors that we did not consider (e.g. intelligence, personality traits, stress levels) and could have affected group differences in brain activity.

In addition to the analysis of alpha oscillations, we assessed meditation-related changes in the 1/f slope of the EEG spectrum and found significant differences between meditators and novices. In fact, the group difference in the 1/f slope was more robust (higher effect size and lower p-value) than the one found in individual alpha power and individual alpha frequency. Interestingly, while experienced meditators showed a more negative (steeper) slope during meditation relative to rest, controls presented the opposite pattern (flatter slope during meditation relative to rest). Previous literature suggests that a steeper 1/f slope reflects greater synaptic inhibition (lower E:I ratio), and that this is common in low cognitive load and/or low arousal states (Colombo et al., 2019; Kosciessa et al., 2021; Lendner et al., 2020; Voytek et al., 2015b; Waschke et al., 2021). In the light of previous literature, we hypothesize that given their lack of experience with meditation practices, novices found the meditation condition more cognitively demanding than rest (which would result in a flatter slope and a higher E:I ratio) whilst the opposite was the case for experienced practitioners (which would result in a steeper 1/f slope and lower E:I ratio). In this regard, it is important to underline that a recent study also found reduced long range temporal correlations (a measure of complexity that is also associated with reduced E:I ratio in the brain) during meditation relative to rest in experienced meditators (Irrmischer et al., 2018). Interestingly, this study also found the opposite pattern of results in non-experienced practitioners (i.e. increased long range temporal correlations during meditation relative to rest). Hence, we speculate that the here reported changes in the 1/f slope and the previously reported modulations in long range temporal correlations in relation to meditation (Irrmischer et al., 2018) could be reflecting the same phenomena (i.e. modulations in cortical E:I ratio).

Unlike meditation and mind wandering, the EEG spectral modulations associated with drowsiness did not differ significantly between meditators and non-meditators. In line with previous studies (Broughton and Hasan, 1995; Cantero et al., 2002), drowsiness was associated with a decrease in individual alpha frequency (IAF) (see **Fig. 5**). Note that the spectral modulations associated with drowsiness were qualitatively different from those associated with mind wandering (i.e. increased alpha power in controls only). Therefore, our results show that mind wandering and drowsiness during meditation practice are two separate phenomena that can be disentangled through their EEG spectral correlates.

To our knowledge, there are two main limitations of the study that need to be addressed. The first limitation is related to the relatively low number of EEG electrodes employed in this study (i.e. 19), which only allowed us to draw conclusions about EEG spectral changes at a sensor level. In this way, high-density EEG and source localization analysis (Michel and Brunet, 2019; Samogin et al., 2019) is warranted in the future to reveal the sources of the here reported EEG changes. Furthermore, source localization analysis might also allow to identify robust oscillatory activity in other bands in addition to alpha (i.e. spectral peaks in the theta and beta bands) (Dasari et al., 2017; Grandchamp et al., 2012). The second limitation is related to the use of experience sampling paradigms to study mind wandering and meditative states. Experience sampling paradigms entail a trade-off between the length of the inter-probe time interval and sufficient number of probes. Longer inter-probe time intervals would allow to detect mind wandering and breath focus states in a more naturalistic manner. In fact, it is possible that the frequent interruption during meditation practice (every 30- 90 s) in our study did not allow participants to fully immerse in breath focus or mind wandering states. However, increasing the time interval between probes (every few minutes) would have resulted in an even smaller number of mind wandering epochs (already only ~23% were classified as mind wandering in this study), rendering condition comparisons difficult. In order to overcome this limitation, future studies could perform multiple (mobile) EEG recording sessions in the same subjects (Reiser et al., 2020) thereby allowing the identification of more naturalistic mind wandering and breath focus states.

In summary, this study compared self-reports during meditation and meditation-related EEG spectral modulations between a group of experienced meditators and a control group without previous meditation experience. Self-reports revealed that meditators showed a greater level of focus and reduced mind wandering frequency and engagement than controls during meditation practice. In line with these reports, the EEG spectral modulations associated with meditation (relative to rest) and mind wandering (during meditation) also differed significantly between meditators and controls. While meditators (but not controls) showed a decrease in alpha/beta band power, reduced individual alpha frequency/amplitude and a steeper 1/f slope during meditation relative to rest, controls (but not meditators) showed a relative increase in alpha/beta band power and individual alpha power during mind wandering relative to breath focus. Based on these results, we conclude that the subjective experience of meditation and mind-wandering differs between experienced meditators and novices and that this is reflected in oscillatory and non-oscillatory components of brain activity.

CRediT statement

Julio Rodriguez-Larios: Conceptualization, Methodology, Software, Formal analysis, Data Curation, Writing – Original Draft, Visualization, Supervision, Project Administration, Funding Acquisition. **Eduardo Bracho Montes de Oca:** Investigation, Resources, Data Curation, Project Administration. **Kaat Alaerts:** Conceptualization, Writing – Review & Editing, Supervision, Funding Acquisition.

Declaration of Competing Interest

The authors declare no competing interests.

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Data and code availability statement

Raw EEG data and MATLAB code will be publicly available in the Open Science Framework webpage (see https://osf.io/3uszv/?view_only=d41ddd2200e642cf9992a016cb739b90).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2021.118669.

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