Lost in thoughts: Neural markers of low alertness during mind wandering

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ABSTRACT

During concentration tasks, spontaneous attention shifts occurs towards self-centered matters. Little is known about the brain oscillatory activity underlying these mental phenomena. We recorded 128-channels electroencephalographic activity from 12 subjects performing a breath-counting task. Subjects were instructed to press a button whenever, based on their introspective experience, they realized their attention had drifted away from the task. Theta (4–7 Hz) and delta (2–3.5 Hz) EEG activity increased during mind wandering whereas alpha (9–11 Hz) and beta (15–30 Hz) decreased. A passive auditory oddball protocol was presented to the subjects to test brain-evoked responses to perceptual stimuli during mind wandering. Mismatch negativity evoked at 100 ms after oddball stimuli onset decreased during mind wandering whereas the brain-evoked responses at 200 ms after stimuli onset increased. Spectral analyses and evoked related potential results suggest decreased alertness and sensory processing during mind wandering. To our knowledge, our experiment is one of the first neuro-imaging studies that relies purely on subjects' introspective judgment, and shows that such judgment may be used to contrast different brain activity patterns.

Introduction

While reading books, most people have had the experience of finding their attention drifts towards self-centered matters. After some time (ranging from seconds to minutes), the readers realize they are mind wandering and bring their attention back to their reading. Mind wandering episodes thus correspond to the emergence of task-unrelated thoughts and affects that are attracting the attention away from the task at hand (Smallwood and Schooler, 2006; Mason et al., 2007). Not surprisingly, mind wandering episodes occur in our everyday life quite often—for instance, as soon as we perform a task and start realizing we are thinking about something else while doing it. One may think that avoiding these attention shifts is only a matter of concentration and willingness to carry out a mental task. Yet, after weeks, months, or years of training in tasks involving sustained concentration–such as focused meditation practice–subjects realize that these events seem to just happen, despite purposefully trying to avoid them—see Braboszcz et al. (2010) for a review of mind wandering during meditation practice.

The experience of mind wandering thus highlights the existence of moment to moment subjectively-attested changes of attentional focus from a task to non-task related thoughts and we believe that these changes would most likely be associated with different brain activity. Although it is a common phenomenon, and although its implication for consciousness research and the study of attentional processes is critical, the brain dynamics associated with mind wandering have not yet been studied directly.

Mind wandering has been associated with lower level of alertness and vigilance (Oken et al., 2006), a mental state with limited external information processing where attention is decoupled from the environment (Smallwood and Schooler, 2006). Supporting this hypothesis, human subjects exhibited decreased performance in rare-target oddball detection tasks during mind wandering (Giambra, 1995). In addition, the amplitude of the P300 event-related potential component was reduced during mind wandering, suggesting a decrease in attentional resources directed towards stimulus processing (Smallwood et al., 2008).

Although the brain dynamics associated with mind wandering have not been studied, a number of studies have investigated the brain dynamics associated with the resting state—an awake neutral state that is not associated with any specific cognitive task and that is prone to mind wandering (Gusnard and Raichle, 2001; Mazoyer et al., 2001). Studies coupling both EEG and fMRI found that the activity in different EEG frequency bands is spontaneously fluctuating at rest and can be correlated to spontaneous fluctuations of the BOLD signal (Laufs et al., 2006; Mantini et al., 2007). These fluctuations seem to underlie two distinct modes of cerebral activity: a mode dominated by

fast frequency waves (12–30 Hz, beta) that may index higher degrees of task-related attention (Ray and Cole, 1985; Laufs et al., 2006), and a mode dominated by slow 3–7 Hz theta waves oscillations that has been linked to decreased sustained task-related attention and diverse stages of transition from wake to sleep (Loomis et al., 1937; Makeig and Inlow, 1993; Klimesch, 1999; Smit et al., 2005). Based on these results, we hypothesized that task-unrelated attentional drifts–i.e. mind wandering–would be associated with decreased vigilance and increased delta and theta power.

It has also been shown that brain evoked responses to external stimuli change with the degree of vigilance or sleep stage. For example, the negative brain evoked response to the sensory detection of a sudden change in the flux of auditory perception called mismatch negativity (Naatanen et al., 2007) is reduced during the early sleep stages and drowsiness (Lang et al., 1995; Winter et al., 1995). Since the mind wandering state should be associated with decreased vigilance, we expected to observe a decrease in the mismatch negativity amplitude in the mind-wandering state compared to the breath focus state.

We designed an experiment allowing subjects to experience mind wandering in conditions we believe to be as close as possible to the way they are experiencing it in their daily life. We chose a simple concentration task–a silent breath counting task–that only requires weak cognitive involvement from the subject, a characteristic known to favor the induction of mind wandering (Giambra, 1995; Cheyne et al., 2006). Simultaneously we presented frequent and rare pure-frequency auditory stimuli that subjects were instructed to ignore, and we used these stimuli to assess the evoked electrophysiological activity during the mind wandering and breath concentration states.

Materials and methods

Participants

Sixteen volunteers from the laboratory staff and local universities (8 females and 8 males; age 19–36 years old, mean: 27 and standard deviation 5) gave written consent to participate to the experiment. Participants stated that they were not taking any substances or medications that could potentially affect their concentration nor having histories of major psychological disorders or any auditory deficiencies. Before starting the experiment, all participants read the instructions and had the possibility to ask questions about the experiment before giving written consent to participate in the experiment. As detailed below, 4 of the 16 participants had to be excluded because they did not report enough mind wandering episodes.

Procedure

Participants sat in a dark room. We asked them to keep their eyes closed during the recording session. Participants were instructed to count each of their breath cycles (inhale/exhale) from 1 to 10. As subjects often lack immediate awareness of their mind wandering episodes (MWE), we could not ask them to signal MWE occurrence at the moment their attention was drifting away from the task. Instead, we asked them to indicate whenever they realized their attention had drifted, that is whenever they gained meta-consciousness (Schooler, 2002) of their mind wandering episodes. We asked subjects to hold a button in their right hand and press it whenever they became aware of having lost track of their breath count. The following instructions were given to subjects to define what was meant by losing track of the count: "you stopped counting," "you counted over 10 breaths" or "you had to reflect intensively to figure out what was the next count." Once they pressed the button, participants were instructed to bring their focus back to their breath and start counting again from one. We read task directions to participants and made sure they understood them. The experiment lasted about 1 h and 10 min, split into three blocks of 20 min separated by 5 min of rest. At the end of each block, we asked

subjects to evaluate their alertness level during the past session ("Did you feel like falling asleep?"), their eye movement activity ("Did you open your eyes —if yes can you estimate how many times"), and their subjective experience when reporting mind-wandering episodes ("Did you press the button? If yes, what was your subjective experience?"). None of the participants reported systematically opening their eyes and none of the participants reported falling asleep. However, 6 of the 12 selected participants reported some level of drowsiness at one time or another during the 1-h experiment (see Discussion).

Auditory stimuli

While performing the breath counting task, subjects were also presented with a passive auditory oddball protocol that they were instructed to ignore. The auditory oddball protocol was composed of pure sounds of 500 Hz for the standard stimuli (80% of the stimuli) and 1000 Hz for the oddball (20% of the stimuli). Each sound lasted 100 ms with 10 ms linear amplitude rising and falling times. Inter-stimulus intervals randomly varied between 750 and 1250 ms. Oddball stimuli presentation was pseudo-random to ensure there were never two oddball stimuli presented successively. Auditory stimuli were calibrated at 72 dB and played through a loudspeaker located at 1.20 m in front and 45 degrees on the right of the subject.

Recording

We recorded data using a 128-channel Waveguard™ cap (Advanced Neuro Technology Company—ANT) out of which we used 124-channels—electrodes AFZ, PO6, TP7, and PO5 were damaged and left out. We plugged the Waveguard™ cap into two synchronized 64-channel EEG amplifiers also from the ANT Company. We kept most electrode impedances below 5 KOhm although about 10% of the electrodes still had higher impedance at the end of preparation–all impedances were kept below 20 Kohm as recommended in ANT ASA 4.0 software user's guide–ANT recommendation is higher than the standard 5 Kohm because of the high impedance of its amplifier. We used M1 mastoid electrode as reference and sampled the data at 1024 Hz. We also recorded EKG by placing two bipolar electrodes on each side of the subject's torso.

Artifacts correction

We first removed bad electrodes—from 2 to 17 bad electrodes per subject. We then manually pruned the continuous data from non-stereotyped, unique artifacts such as paroxysmal muscles activity–high frequency activities with large amplitude over all electrodes–as well as electrical artifacts resulting from poor electrode contacts–short-lasting aberrant oscillatory activity localized at a few electrode sites. We then used Infomax Independent Component Analysis (Infomax ICA) on the pruned data to reject artifacts. For each subject, we visually identified and rejected one to five well-characterized ICA components for eye blink, lateral eye movements, and temporal muscle noise (Delorme et al., 2007a). We used visual inspection of component scalp maps, power spectrum and raw activity to select and reject these artifactual ICA components.

Data processing

Data processing was performed under Matlab 7.0 (The Mathworks, Inc.) using the EEGLAB 7 toolbox (Delorme and Makeig, 2004). We first downsampled the EEG data from 1024 Hz to 256 Hz and performed high-pass filtering at 1 Hz using a non-linear elliptic filter. In addition, we applied an elliptic non-linear notch filter between 45 and 55 Hz. For each subject, we then segmented the EEG data into 20-s data epochs centered on subjects' button presses. We considered that participants were mind wandering during the 10-s period that

preceded the button press and we considered that participants were concentrating on their breath during the 10-s period that followed the button press (Christoff et al., 2009). Four subjects did not have enough clean data epochs to be considered for further analysis—the four subjects had six, five, five and one clean epochs respectively. All the selected subjects had between 13 and 52 of such 20-s clean EEG data epochs (mean of 30 per subject; standard deviation of 14). This ensured that, for each subject, there would be at least 20–30 auditory stimuli in each condition to compute ERPs (Kappenman and Luck, 2010)—see ERP analysis below. The total number of analyzed mind wandering events across all subjects was 358.

For each of the two conditions, mind wandering and breath focus, we also extracted data epochs from 1 s before to 2 s after the presentation of auditory stimuli. So that auditory stimuli do not occur too close to a button press, we removed all 3-s data epochs containing a button press—thus button presses were at least 1 s prior to the stimulus or at least 2 s after the stimulus. This procedure ensured that the brain activity related to the button press does not contaminate our analysis. In addition, we processed brain activity from electrodes (Oz, Fz) that were not over pre-motor and motor regions limiting potential contamination of button press brain-related activity. We thus obtained four groups of data epochs—oddball and standard stimuli defined over two conditions, mind wandering and breath focus. We computed mean event related potential (ERP) using a –300 to 0 ms baseline and we performed ERP visualization after applying a 30 Hz linear low pass filter—note that we used the non-filtered data for computing statistics. We counted a total of 4326 standard stimuli (mean of 180 per subject; standard deviation of 101) and 1040 oddball stimuli (mean of 43 per subject; standard deviation of 23).

EEG time-frequency analysis

We applied Morlet wavelet decomposition (Goupillaud et al., 1984) to both the 20-s long data epochs time-locked to button presses and the short 3-s data epoch time-locked to auditory stimuli. We used 200 linearly-spaced time points and a series of 100 log-spaced frequencies ranging from 1 Hz to 100 Hz, with 1.5 cycle at the lowest frequency increasing linearly and capping at eight cycles at 30 Hz. For long 20-s epochs, we visualized absolute log power $- 10 \times \log 10$ (X), X being absolute power at a given time-frequency point. For short 3-s epochs time-locked to auditory stimuli presentation, we also removed baseline spectral activity by subtracting the pre-stimulus average baseline log-power at each frequency in order to visualize power changes in dB unit (Delorme and Makeig, 2004).

Statistics

Statistical tests were performed on ERPs, time-frequency maps and topographic maps using two-tailed paired parametric student t-test ($df = 11$). Since most representation involves hundreds of tests, correction for multiple comparisons was performed using the cluster method as developed by Maris and Oostenveld (2007). This method first measures the extent of 1-D (length) or 2-D (surface) of significance regions (uncorrected) and then tests if the extent of these regions is significant using a Monte-Carlo approach. For channel topographies, we set the number of channel neighbors to 4.5 before running Maris and Oostenveld (2007) Matlab function. We also used FDR (False Discovery Rate) (Benjamini and Yekutieli, 2001) to correct for multiple comparisons and obtained similar results compared to the cluster method.

Results

EEG activity time-locked to meta-consciousness events

The time frequency analysis of EEG data time-locked to meta-consciousness event–button press shows a significant influence of the subject's attentional state at all frequency bands from 2 to 25 Hz
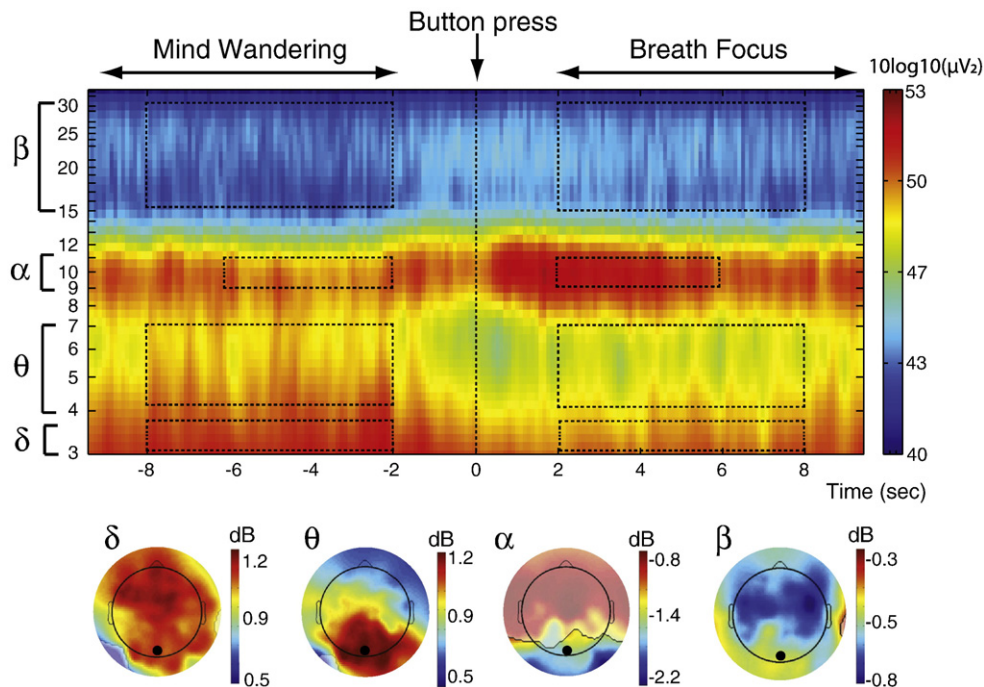

Fig. 1. Time frequency decomposition of transition from mind wandering to breath focus at electrode site Oz. Mind wandering was defined as the period preceding the meta-conscious event (button press) and breath focus was defined as the period following the meta-conscious event. Topographic maps of power difference are shown for the 2–3.5 Hz (δ), 4–7 Hz (θ), 15–30 Hz (β) frequency bands from −8 to −2 s before and from 2 to 8 s after the button press. Topographic map of differential power is shown for the 9–11 Hz (α) frequency band from −6 to −2 s before and 2 to 6 s after the button press (unlike other frequencies bands, the difference of power in the alpha band between mind wandering and breath focus was not significant for a larger time interval). Areas of statistical significance ($p<0.05$) are highlighted on the topographic maps (shaded areas represent non-significant regions for the alpha band topographic map; all electrodes are significant for other frequency bands). The black dot represents the position of electrode Oz.

(Fig. 1). The most pronounced state-associated change on the EEG spectral activity occurs in the theta band (4–7 Hz) where absolute spectral power is significantly higher in the mind wandering state compared to the breath focus state. This effect is observed at all electrode sites and is larger over occipital and parieto-central regions. Absolute power in the delta band (2–3.5 Hz) showed the same trend although the largest power difference was now observed over the fronto-central region. By contrast occipital alpha (9–11 Hz) and fronto-lateral beta (15–30 Hz) power was significantly lower in the mind wandering state compared to the breath focus state.

During the transition associated with the meta-consciousness (MC) event, the alpha frequency band in Fig. 1 is not only affected in terms of amplitude but also in terms of peak frequency. The peak frequency appears to increase by about 1 Hz after the meta-conscious event for a period of about 2 s. To test if this observation was significant across subjects, we defined three time windows, W1 from −6 to −4 s before the MC event; W2 from 0 to 2 s after the MC event; W3 from 6 to 8 s after the MC event. For each subject and for each time window, we then manually assessed the alpha peak frequency by taking the frequency of maximum power between 8 and 12 Hz on the power spectrum—the power spectrum was computed by averaging log-power values of Fig. 1 over the windows of interest W1, W2 and W3. Note that the alpha peak frequency could not be found for one of the 12 subjects so we computed statistics using 11 subjects only. Bootstrap statistics revealed significant difference between the central W2 window and the flanking W1 and W3 windows (W1 versus W2, $p<0.0005$, $df=10$; W3 versus W2, $p<0.002$, $df=10$) but not between W1 and W3. Supplementary Fig. 1 is a movie showing the dynamical change in the power spectrum where the alpha amplitude changes and peak frequency shifts are made clearly visible.

Stimulus evoked activity during mind wandering and breath focus

We first tested if the attentional state affected grand average ERPs of the auditory stimuli in the passive oddball paradigm. We observed that the ERP positive component at about 200 ms after stimulus presentation (P2) is significantly higher over fronto-central sites from 180 to 280 ms during mind wandering than during breath focus for both standard and oddball stimuli (Fig. 2). We did not observe any

significant interaction between mental state and type of stimuli in this latency range. However, as shown below, we did observe such an interaction at earlier latencies.

We found a significant effect of the type of stimulus–oddball or standard–on the amplitude of the early ERP negative component between 90 and 120 ms after stimulus onset (Fig. 3). After presentation of an oddball stimulus the ERP is significantly more negative over frontal and temporal regions than after presentation of a standard stimulus both in the breath focus and mind wandering conditions (Fig. 3C and D). This increased negativity for oddball is usually termed mismatch negativity (Naatanen et al., 2007). The mismatch negativity (MMN) was larger during breath focus compared to mind wandering over the right frontal region (Fig. 3E). Supplementary Fig. 2 shows single subject average ERP values and standard error for both the 180 to 200 ms and 90 to 120 ms ERP range.

We then investigated event-related activity using time-frequency decompositions. The event-related spectral perturbation plot reveals increased theta band power (4–7 Hz) and decreased high alpha (10–14 Hz) and high beta (20–25 Hz) band power after stimulus presentation (Fig. 4). In general, statistical inference testing between the mind wandering and the breath focus state returned a lower *p*-value for standard stimuli compared to oddball stimuli—it might be a matter of number of observations since there was, on average, five times more trials for standard than for oddball stimuli. From 100 to 300 ms after standard auditory stimuli presentation, theta (4–7 Hz) power was significantly higher on frontal sites when subjects were mind wandering compared to when they were focusing on their breath. Delta (2–3.5 Hz) power 200 to 350 ms after standard auditory stimulation follows the same trend and we also observed a significant power increase for oddball stimuli at occipital and frontal sites. High beta (20–25 Hz) power from 100 to 300 ms after standard stimuli presentation is significantly higher on parieto-occipital sites during mind wandering compared to breath focus. Interestingly, despite large high alpha (10–14 Hz) evoked power to both standard and oddball stimuli, we did not observe any significant effect of the attentional state on the ERSP in this frequency band.

We also tested for difference of ERSP between standard and oddball stimuli during both the mind wandering and the breath focus states. Only beta band power from 100 ms to 300 ms after stimulus presentation differed significantly, being lower for oddball stimuli (not shown). This effect was not significantly different between the mind wandering and the breath focus states.
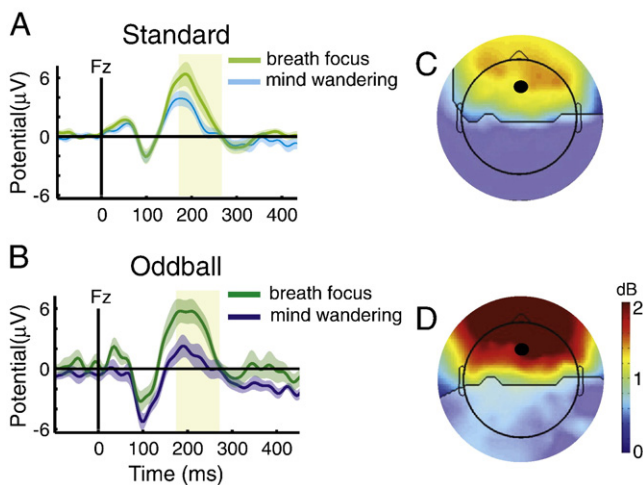
Discussion

Our study aimed at characterizing the neural correlates of spontaneous and task-unrelated mental activity (i.e. mind wandering) and its effect on sensory processing. Compared to a breath-focus mental state, we have shown that mind wandering is characterized by a power amplitude increase in the theta frequency band and a power amplitude decrease in the alpha and beta frequency bands. We also showed that, during mind wandering, standard auditory stimuli induce a higher power in the theta and delta frequency band over parieto-occipital regions and higher power in the high beta frequency band over frontal regions. The study of mean evoked related potentials revealed that the amplitude of the P2 positive ERP component is larger during mind wandering than during breath focus and that the MMN is of smaller amplitude during mind wandering than during breath focus. Taken together these results establish a strong link between the subjects' internal experience–mind wandering or breath focus–and distinct neural correlates.

Control task and novelty of the experimental design

The control task being used to study mind wandering was critical. We chose a breath focus task, which is a relatively neutral non-

Fig. 2. Effect of the attentional state on the grand-average ERP for oddball and standard stimuli. (A, B) ERP at electrode site Fz for the mind wandering and the breath focus state for standard (A) and oddball (B) stimuli. The shaded area surrounding each curve represents the standard error of the mean. (C, D) Topographical maps of the average ERP difference between mind wandering and breath focus for standard (C) and oddball (D) stimuli from 180 to 280 ms after stimuli presentation (corresponding to the yellow highlighted region on the ERP plots). Non-significant areas are grayed out in topographic maps and the black dot indicates the position of electrode Fz.
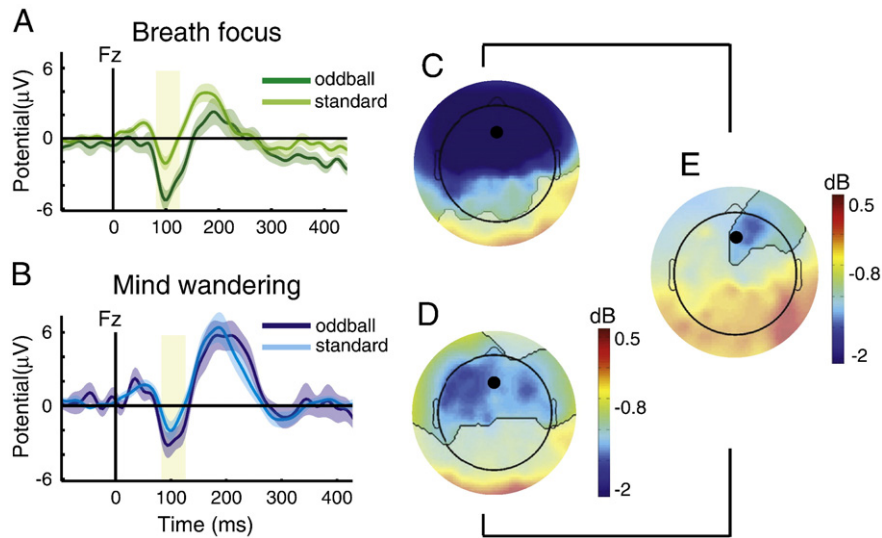
Fig. 3. Mismatch negativity during the mind wandering and breath focus states. (A, B) Grand-averaged ERP to standard and oddball stimuli for the breath focus and mind wandering state. As in Fig. 2, the shaded area surrounding each curve represents the standard error of the mean. (C, D) Topographical difference maps between the mean ERPs to oddball and standard stimuli (Mismatch negativity MMN) for the breath focus and the mind wandering state. (E) Topographical difference map between MMN maps in breath focus and mind wandering condition (map C–map D). Non-significant areas are grayed out on the topographic maps and the black dot indicates the position of electrode Fz.
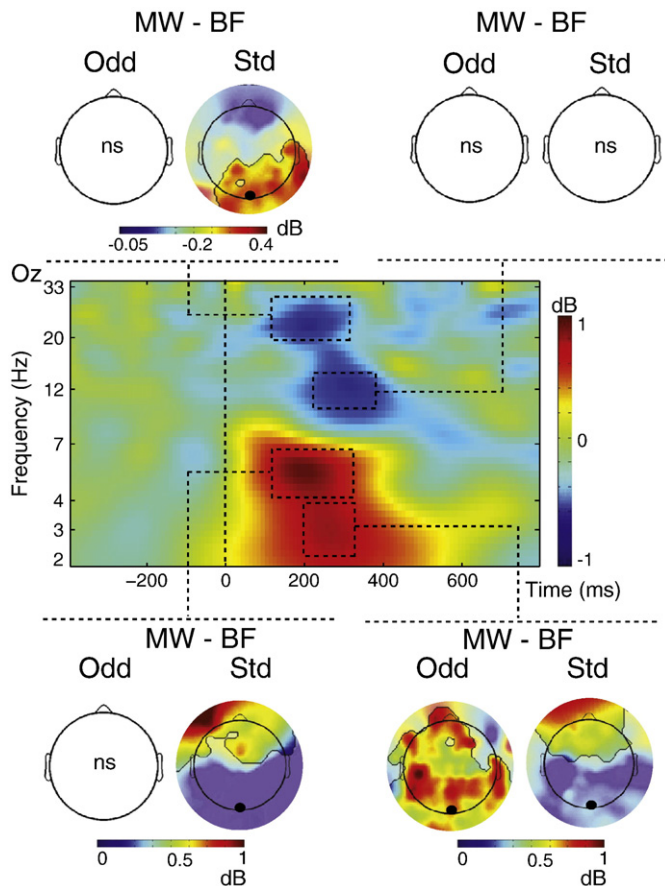

Fig. 4. Effect of attentional state and type of stimulus on event related spectral perturbation. The central panel indicates the grand-average ERSP at electrode site Oz averaged over both oddball (Odd) and standard (Std) stimuli for both the mind wandering (MW) and the breath focus (BF) state. Topographical maps of power difference between the mind wandering and the breath focus conditions are shown for oddball and standard stimuli at given time-frequency regions of interest (dotted rectangles). Shaded areas on the topographical maps represent non-significant regions. Topographical maps for which there were no significant electrodes are indicated using a blank map with the sign "ns" (non-significant). The black dot represents the position of electrode Oz.

cognitive task. Ideally, one would study mind wandering during several control attention engaging tasks. Here, we want to emphasize the difficulty and novelty of the experimental design and why it was impractical for us to use multiple control tasks. Other studies of mind wandering often use tasks where subjects have to respond continuously to stream of stimuli (e.g. Smallwood et al., 2008). By contrast, in our task, we asked subjects to press a button based on pure introspection. We wanted to collect as many behavioral responses as possible, but despite 1 h of recording for each subject, we only obtained 13–52 clean data epochs per subject. In addition, despite the instruction to stay still, subjects tended to exhibit muscle artifacts in their EEG after pressing the button, forcing us to reject about 25% of the data. Finally, subjects varied widely in their propensity to report mind-wandering events, and four subjects had to be excluded because they provided too few responses. This experiment was the first of its kind and is a proof of concept that, despite the difficulty encountered, this type of study is possible.

Brain states fluctuation at rest and spontaneous reports of mind wandering

The difference in EEG activity between mind wandering and breath focus is consistent with the Laufs et al. (2006) EEG-fMRI study showing that spontaneous EEG alternates between two states at rest. Our study refines Laufs' results by showing that the low frequencies (theta-delta) and high frequencies (alpha-beta) changes he observed may be associated to a transition between a state of concentration on processing external stimuli and involuntary mind wandering. Our EEG study further confirms that when subjects are engaged in a task, the brain can spontaneously shift into another alertness mode, which is most likely mind wandering.

fMRI bold signal during the resting state shows spontaneous fluctuations between a "task positive" network comprising brain areas activated during attention-demanding tasks and a "task negative" (or "default") network being activated during rest and deactivated during these tasks (Fox et al., 2005). Preceding reports of mind wandering, Christoff et al. (2009) found increased BOLD activity both in the default network (precuneus, ventral anterior cingulate cortex and temporoparietal junction) and in the frontal executive network. This result is consistent with an fMRI study showing increased amount of mind wandering linked to increased amount of activity in the task

negative network (Mason et al., 2007). Continuous increase of BOLD activity in the occipital, frontal and temporal parts of the defaults network is also found during the transition from eyes-closed wakefulness to sleep (Olbrich et al., 2009). The higher occipito-parietal theta and fronto-central delta during mind wandering could thus be related to increased BOLD activity in these areas. Additional combined EEG-fMRI studies would be needed to establish a clearer link between EEG and BOLD signature of the mind wandering state and its relation to the default mode network, in particular regarding localization of the neuronal sources of the EEG rhythm correlated with the BOLD signal.

We also observed a delta power increase during mind wandering, an increase that we believe could be linked to decreased alertness. Spontaneous delta power increase has been linked to decreased performance during cognitive processing (Harmony et al., 1996). Spontaneous delta power increase has also been associated with decreased level of alertness in various experimental setups (Makeig and Inlow, 1993; De Gennaro et al., 2001; Caldwell et al., 2003). Moreover, as reviewed by Laufs et al. (2006) and shown in this report, delta power increase is associated with alpha power decrease, which has been associated with low stages of vigilance (Loomis et al., 1937; Roth, 1961). Note that 6 of the 12 subjects reported some level of drowsiness during the experiment. To be sure that our results did not pertain to drowsiness, Supplementary Fig. 3 shows the same time-frequency decomposition as Fig. 1 although it only includes subjects that did not report drowsiness. The time-frequency patterns of Supplementary Fig. 3 are almost identical to the ones visible in Fig. 1.

The meta-consciousness event allowing the transition from the mind wandering to breath focus state is finally marked by a transient increase of about 1 Hz of the alpha peak frequency and also by a more long lasting increase in alpha power. Re-directing the attention to the task requires increase working memory activity that has been shown to be correlated with alpha power increase (Jensen et al., 2002), a power increase that may index re-activation of thalamo-cortical pathways (Schreckenberger et al., 2004). The alpha-peak frequency increase may also be a marker of the attentional switch between mind wandering and the focused task since Angelakis et al. (2004) suggests that increase of peak alpha frequency might represent a state of "cognitive preparedness".

MMN, attention, alertness, and mind wandering

The study of evoked related potential shows an increased negativity at frontal electrode sites for the ERP of oddball compared to the ERP of standard stimuli from 90 to 120 ms after stimulus presentation. This result corresponds to the mismatch negativity (MMN) usually described as negative brain response to the sensory detection of a sudden change in the flux of auditory perception (Naatanen et al., 2007). The MMN typically occurs approximately 100 to 150 ms after stimulus presentation and is centered on fronto-central electrodes sites (Naatanen et al., 2007). The amplitude of the MMN is modulated by the direction of the subject's attention (Sabri et al., 2006), and is larger when the attention of the subject is directed toward the auditory stimuli (Alain and Woods, 1997). Our results show the MMN amplitude is lower during mind wandering compared to breath focus, which suggest a disengagement of the attention from stimuli processing during mind wandering.

The reduction of the MMN is also characteristic of drowsiness and the early sleep stages (Sallinen and Lyytinen, 1997; Nittono et al., 2001), which supports the idea that the mind wandering state is associated with decreased vigilance. This also suggests that mind wandering may share common traits with the decreased alertness characterizing the transition from wake to sleep (Sabri et al., 2003). Note that we did not observe in our data the late negativity at about 300 ms after stimulus presentation that accompanies advanced states of drowsiness leading to sleep or sleep itself (Winter et al., 1995;

Campbell and Colrain, 2002). This suggests that our subjects were not deeply drowsy. Mind wandering could thus correspond to an early state of drowsiness of decreased alertness and vigilance.

Late stimulus evoked activity and disengagement of attention from stimuli processing during mind wandering

ERP analysis also reveals that the amplitude of the positive component at about 200 ms (P2) is larger during mind wandering than during breath focus. This effect is also present, although to a lesser extent, in Cahn (2007) who found a P2 component larger for distracting stimuli when subjects were actively reactivating autobio-graphical memories–which may be considered similar to mind wandering–compared to when they were practicing meditation. Increase of the P2 component to auditory stimulus has also been associated with the disengagement of subjects' attention toward stimuli (Naatanen and Picton, 1987) and is also characteristic of the sleep onset period (Campbell and Colrain, 2002). Again, this result is consistent with attentional disengagement toward stimuli processing during mind wandering.

We did not observe a P300 ERP component associated with the presentation of the rare stimuli in our passive auditory oddball task. P300 is best observed in active experimental design where the subjects have to respond to rare targets and is usually hardly visible in passive oddball paradigms (Cahn and Polich, 2009). However, using an active task, Smallwood et al. (2008) showed a reduction of the P300 ERP during mind wandering. Consistent with our MMN and P2 results, Smallwood et al. (2008) results suggest a disengagement of attention towards external stimuli processing.

The study of ERSP is harder to interpret since it is rarely presented in literature. Increased evoked theta frequency over frontal regions may be related to increased autobiographical memory engagement during mind wandering (Jensen and Tesche, 2002; Onton et al., 2005). Note that the ERP differential scalp maps from 180 to 280 ms were similar to the theta frequency maps with strong changes over occipital regions. The ERP is a complex combination of stimulus-locked phase synchronization and spectral amplitude increase (Makeig et al., 2002; Delorme, Westerfield et al., 2007). We tested if ERP and ERSP activities were linked by computing the correlation between the ERSP activity and the ERP at electrode site Fz for the evoked delta, theta, alpha and beta frequency band activity shown in Fig. 2. We did not find any correlation between the early ERP negative component between 90 and 120 ms after stimulus onset and any of the ERSP components. However, when pooling data for both types of stimulus and both attentional states, we did find a positive correlation ($p < 0.001$; $df = 47$; paired t-test) between the evoked delta (2.5 to 3.5 Hz) and high alpha (10–14 Hz) activity 100 to 300 ms after stimulus onset and the late ERP positive component at 180 to 280 ms. This indicates that both the late ERP complex and delta ERSP activity may index similar processes in our passive auditory oddball task.

Function of mind wandering

The functional role of mind wandering remains debated in philosophy and experimental psychology. The concept of mind wandering plays an important role in Buddhist psychology (Trungpa, 2004) since it is a major obstacle to concentrative meditation practice. Buddhist psychology argues that mind wandering is a non-productive ego-centered state, a state of "sleep" where our unconscious constantly rehash the same thoughts and beliefs creating confusion and strengthening our sense of self. By contrast, some researchers have suggested that mind wandering may be useful to provide creative insight (Christoff, Gordon et al., 2009) in a way similar to sleep-induced insight (Wagner, Gais et al., 2004). Our result of finding mind wandering to be a state of low alertness supports both views. It can be considered a state of low concentration or relative "sleep"

as argued in Buddhist psychology but it could also be seen as a hypnagogic state that may lead to creative insights (Boynton, 2001). We believe that by studying the common brain structures and dynamics involved in mind wandering, meditation, self, and creativity, brain-imaging techniques could help bring new light to this debate.

Based on our results and previous studies, we conclude that mind wandering is a low-alertness state of rest. If mind wandering corresponds to a state of rest, one hypothesis is that subjects who are sleep deprived might spend more time mind wandering during the day. The time that a subject spends mind wandering may be estimated using probe-caught mind wandering techniques. Smallwood and Schooler (2006) place a distinction between self-caught and probe-caught mind wandering episodes. Self-caught mind wandering is the type of mind wandering studied in this report. By contrast, to assess the amount of time subjects spend mind wandering while being unaware of it, they may be probed at regular intervals about their state of mind wandering. We would thus anticipate that probe-caught mind wandering frequency would increase with the amount of sleep deprivation. Finally, if the activity in the default network is linked to mind wandering as previously claimed (Mason, Norton et al., 2007; Sonuga-Barke and Castellanos, 2007), we would expect that the activity in the default network during the day would also increase with sleep deprivation. Further studies should be able to verify or disprove these hypotheses.

In conclusion, we have shown the neurophysiologic markers of mind wandering. Based only on subjective reports about mind wandering, we have established that two different attentional states correspond to two distinct brain states underlying different modes of sensory processing. Our results suggest that mind wandering correspond to a state of rest, a state of low vigilance where stimulus evoked responses are reduced. This study is one of the first event-related neuroimaging study to rely only on behavioral responses based on pure–not stimulus induced–introspective subjective reports. It further demonstrates that neuro-phenomenological approaches to the study of subjective experience are possible in neuroscience (Lutz and Thompson, 2003) yet argues for the need of a more fine-grained taxonomy of private mental states.

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