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Frontal EEG theta/beta ratio during mind wandering episodes

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Highlights

- -The first study directly investigating the relation between mind wandering versus focused attention and task-related and resting state frontal EEG theta/beta ratio
- Frontal EEG theta/beta ratio was increased during mind wandering compared to focused attention
- -Providing further support of EEG theta/beta ratio as a marker of brain processes involved in executive control processes.

Abstract

Background: In resting-state EEG, the ratio between frontal power in the slow theta frequency band and the fast beta frequency band (the theta/beta ratio, TBR) has previously been negatively related to attentional control. Also, increased theta and reduced beta power were observed during mind wandering (MW) compared to episodes of focused attention. Thus, increased resting-state frontal TBR could be related to MW, suggesting that previously observed relationships between TBR and attentional control could reflect MW episodes increasing the average resting state TBR in people with low attentional control.

Goals: To replicate and extend the previous theta and beta MW effects for frontal TBR recordings and test if MW related changes in frontal TBR are related to attentional control.

Methods: Twenty-six healthy participants performed a 40-minute breath-counting task, after a baseline EEG recording, while EEG was measured and participants indicated MW episodes with button presses.

Results: Frontal TBR was significantly higher during MW episodes than during on-task periods. However, no relation between frontal TBR and attentional control was found.

Conclusions: This confirms that frontal TBR varies with MW, which is thought to reflect, among other things, a state of reduced top-down attentional control over thoughts.

194 words

Keywords: EEG theta/beta ratio, mind wandering, attentional control

The electroencephalographic (EEG) signal represents the combined electrical fluctuations in membrane potentials generated from the interactions of the primary inhibitory and excitatory neurons (Gordon, 2000; Nunez, 1995) and can be decomposed into power estimates of different frequency bands. Typically measured under resting conditions, the ratio between the slow wave theta (4-7 Hz) and fast wave beta (13-30 Hz) band power, in other words the theta/beta ratio (TBR), has been utilized as a source of critical information about brain activity that may be associated with increased cognitive demand (Barry, Clarke, & Johnstone, 2003). TBR has also been found to have a very high test-retest reliability (Angelidis, van der Does, Schakel, & Putman, 2016; Keune, Hansen, Weber, Zapf, Habich, Muenssinger, Wolf, et al., 2017).

Several lines of evidence suggest that TBR is of interest when investigating attentional control. A frequently replicated finding, for example, is that TBR is increased in patients diagnosed with attention-deficit/ hyperactivity disorder (ADHD; Barry et al., 2003), though also non-findings have been reported (Arns, Vollebregt, Palmer, Spooner, Gordon & Kohn et al., 2018; Loo, Cho, Hale, McGough, McCracken, & Smalley, 2013; Kitsune, Cheung, Brandeis, Banaschewski, Asherson, McLoughlin, & Kuntsi, 2015). Additionally, TBR was negatively correlated with self-reported trait attentional control (using the Attentional Control Scale, or ACS; Derryberry & Reed, 2002) in healthy participants (especially when controlling for an often-correlated measure of trait anxiety; Putman, van Peer, Maimari & van der Werff, 2010, replicated by Putman, Verkuil, Arias-Garcia, Pantazi & van Schie, 2014, Angelidis et al., 2016; van Son, Angelidis, Hagenaars, van der Does & Putman, 2018a). Also, TBR was negatively related to objectively measured attentional control in multiple sclerosis patients with mild cognitive impairment (Keune et al., 2017). Furthermore, TBR was found to be positively correlated with a stress-induced decline in state attentional control (Putman et al., 2014).

All in all, the relation between TBR and attentional control seems to span the spectrum from healthy student samples to clinically impaired groups (Keune et al., Barry et al., 2003; Arns, Conners & Kraemer, 2013). Frontal TBR has been suggested to reflect cortical-subcortical interactions associated with inhibitory functioning and cortical inhibition of subcortical processes (Knyazev, 2007; Schutter & Knyazev, 2012; Putman et al., 2014). This could reflect voluntary top-down processes like attentional control carried out by the dorsolateral prefrontal cortex (Bishop, 2008; Gregoriou, Rossi, Ungerleider, & Desimone, 2014) over automatic bottom-up processes mediated by limbic areas such as the anterior cingulate cortex and the amygdala, facilitating attention to salient information (Hermans, Henckens, Joëls & Fernández, 2014).

Recent studies from our lab showed that TBR moderated attentional bias to stimuli of different threat levels (Angelidis, Hagenaars, van Son, van der Does & Putman, 2018; van Son et al., 2018a) as predicted for attentional control in influential models of attentional bias (Mogg & Bradley, 1998, 2016). However, attentional bias does not solely include attentional processing of external stimuli. Anxious people, for example, also worry a lot, which represents biased internal activation of threatening cognitions in working memory, and shares mechanisms with biased attention (Hirsch & Mathews, 2012). Worry can be seen as self-generated off-task thought, and is sometimes referred to as a negative form of the umbrella term 'mind wandering' (Ottaviani, Shahabi, Tarvainen, Cook, Abrams & Shapiro, 2015).

Like worry, mind wandering (MW) episodes correspond to the emergence of task-unrelated affects and thoughts that draw attention away from the task at hand (Smallwood & Schooler, 2006). MW can occur while performing a task, and is manifested as thinking of something else while executing a task (Mason, Norton, Van Horn, Wegner, Grafton, & Macrae, 2007). MW has been shown to play a role in processes like prospection and future planning (Baumeister & Masicampo, 2010; Baumeister, Masicampo & Vohs, 2011), creativity (Baird, Smallwood, Mrazek, Kam, Franklin & Schooler, 2012) and mental breaks, remediating an unpleasant mood (Ruby, Smallwood, Engen, & Singer, 2013). Besides its relation with these more beneficial processes, others have repeatedly conceptualized MW as a state of reduced working memory and attentional control (McVay & Kane, 2009; Unsworth & McMillan, 2014), and as a predictor of performance errors (Smallwood &

Schooler, 2006). MW has furthermore directly been related to reduced attention and focus (Smallwood, Nind, & O'Connor, 2009; Stawarczyk, Majerus, Catale, & D'Argembeau, 2014; Unsworth & McMillan, 2014). Also, ADHD was found to relate to increased MW (Bozhilova, Michelini, Kuntsi, & Asherson, 2018). It is this latter aspect of MW that is addressed in our paper: MW as a state of reduced cognitive control and vigilance, as related to working memory performance and cognitive failure.

In a proof of principle study, Braboszcz and Delorme (2011) reported that higher EEG theta band power and lower EEG beta band power were related to a state of MW. Participants were asked to focus on counting their breaths and to press a button as soon as they became aware that their mind had wandered off task. EEG spectral analysis showed higher theta and lower beta (likely higher TBR) before the button press, but lower theta and higher beta (likely lower TBR) after the button press, when they again focused on breath counting. These results were observed for windows of a -8 to -2 second period before the button press and a 2 to 8 second period after the button press, omitting the four seconds surrounding the button press. These time-windows correspond with theoretical and empirical observations concerning short periods of low, but growing awareness and a shift in attentional orientation just before and after the button press respectively (Hasenkamp, Wilson-Mendenhall, Duncan & Barsalou, 2012). The two seconds immediately before the button press were considered as 'participants becoming aware that their mind wandered off', and the two seconds immediately after the button press as 'getting back into breath-counting'.

As outlined above, MW itself is described as a deficit in working memory and attentional control (McVay & Kane, 2009; Unsworth & McMillan, 2014) and is a predictor for performance errors (Smallwood & Schooler, 2006); TBR's relation to attentional control might therefore be associated with a higher tendency to mind wander during resting state, increasing the average TBR in people with low attentional control. Studying this hypothesis would greatly benefit our understanding of TBR's relation to attentional control in healthy people (Putman et al., 2010; 2014; Angelidis et al., 2016; van Son et al., 2018a) and clinical samples (Keune et al., 2017; Arns et al., 2013; Barry et al., 2003). If the TBR–attentional control relationship reflects mainly changes in TBR when people engage in mind wandering episodes, it might also be interesting to consider possible interactions

between the number of mind wandering episodes and the assumed TBR–attentional control

correlation. Therefore, if the TBR-ACS relation is observed in our present sample (despite null-

findings reported in Morillas-Romero, Tortella-Feliu, Bornas, & Putman, 2015; Angelidis et al.,

2018), this hypothesis regarding the mediating underlying processes causing the relation between

TBR and attentional control can be tested.

The aim of the current study was to replicate and extend the design and results of Braboszcz

and Delorme (2011) as pertaining to the MW related changes in EEG, in order to gain further insight

into the role of TBR during MW episodes. Our primary hypotheses will be tested using frontal TBR,

since previous studies examining TBR in relation to executive processes using healthy participants

focused almost exclusively on frontal TBR (Putman et al., 2010, 2014; Angelidis et al., 2016, 2018;

van Son et al., 2018a; Schutter & van Honk, 2004; Schutter & van Honk, 2005; Sari, Koster, Pourtois,

& Derakshan, 2016; Tortella-Feliu, Morillas-Romero, Balle, Llabrés, Bornas, & Putman, 2014;

Morillas-Romero et al., 2015). We hypothesized that:

I) Frontal TBR is higher during MW episodes than during on-task periods.

II) Baseline spontaneous frontal TBR is expected to negatively correlate with attentional control as

measured by the ACS when controlling for trait anxiety.

III) The MW related changes in frontal TBR (assessed in hypothesis I) are related to baseline TBR

during resting state and ACS.

IV) The MW related changes in frontal TBR (assessed in hypothesis I) mediate the correlation

between baseline spontaneous TBR and ACS (hypothesis II).

These hypotheses were tested in a female sample (unlike Braboszcz and Delorme [2011] who

included both males and females) since the majority of previous studies on TBR in healthy samples

were (mostly) female and because of the gender imbalance in our available participants. Also, it is yet

to be verified if TBR at frontal regions is the optimal predictor of attentional control and MW, thus

the present study additionally explores the topographical occurrence of MW-related TBR.

Furthermore, after testing the hypotheses for the MW versus focused attention epochs corresponding

to Braboszcz and Delorme's (2011) analysis, we further explore effects of time within these 6 second

epochs (pre- and post-button press) as visual inspection of their data suggests that TBR increased

following the button press. Finally, we correlated EEG data with the number of button presses that the participants made, as the occurrence of MW awareness might be related to the qualitative nature of mind wandering episodes; that is, less profound mind wandering might occur in participants who often become aware of their mind wandering.

Methods

Participants

Fifty-three female participants (between 18 and 30 years old) recruited at Leiden University took part in this study. Only females were included because of the low prevalence of men signing up to participate in the study and for better comparison with previous studies of relations between TBR and attentional control functions in healthy participants. Exclusion criteria were factors which would likely adversely affect participation, EEG, or attention; these included severe physical or psychological dysfunction, and/or the use of psychotropic medication. As described in detail below, 27 participants were excluded because they retained too few (<11) acceptable mind wandering epochs of acceptable EEG data quality. Informed consent was obtained prior to testing, and participants received a monetary reimbursement for their participation. The study was approved by the Leiden University local ethics review board.

Materials

Questionnaires

Participants completed the trait version of the State-Trait Anxiety Inventory (STAI-t; Spielberger, 1983) and the Attentional Control Scale (ACS; Derryberry & Reed, 2002). The STAI-t assesses trait anxiety (20 items, range 20-80; Cronbach's alpha in the current study = 0.88), by indicating agreement with items like 'I feel nervous and restless' and 'I have disturbing thoughts' on a four-point Likert scale. The ACS assesses self-reported attentional control in terms of attentional focus, attentional switching and the capacity to quickly generate new thoughts (20 items, range 20-80; Cronbach's alpha in present study = 0.80), by indicating agreement with items like 'I can quickly

switch from one task to another' and 'I have a hard time concentrating when I'm excited about something'.

Breath counting task

The breath counting task was reproduced from Braboszcz and Delorme (2011). Participants were asked to keep their eyes closed and count their breath cycles (one inhalation and one exhalation) from 1 to 10 and then start from 1 again during two blocks of 20 minutes. They were instructed to press a button when they realized they had stopped counting, continued counting further than 10, or when they had to reflect intensively on what the next count would be. Participants were instructed to refocus on breath-counting again after any button presses. In order to maintain procedural consistency with Braboszcz and Delorme (2011), a passive auditory oddball task was presented concurrently with the breath counting task and participants were instructed to ignore the auditory stimuli. We were not interested in studying oddball-related EEG, but since it is possible that this particular detail of the procedure could influence mind wandering, we included it for the sake of close methodological replication. For the same reason, we also presented some debriefing questions at the end of each block (as done by Braboszcz and Delorme, 2011) that were not analyzed here.

EEG recording and software

EEG recordings were obtained continuously from 31 electrodes at 10/20 positions using Ag/AgCl electrodes of the ActiveTwo BioSemi system (BioSemi, The Netherlands). Electrodes placed on the left and right mastoids were used for offline re-referencing. Data were collected with a sampling rate of 1024 Hz with a gain of 16x at a bandwidth between DC-400 Hz. For processing purposes, data were down-sampled to 256 Hz.

Procedure

General Procedure

After informed consent had been obtained, participants completed the ACS and the STAI-t. This was followed by the measurement of resting-state EEG for ten minutes with eyes closed, and then the breath counting task was conducted while recording EEG.

Data Reduction

Button presses

For each subject, the EEG data were segmented into 16 second data epochs around their button presses. We considered that participants were mind wandering during the -8 to -2 second period preceding the button press, and that participants were concentrating on their breath during the 2 to 8 second period that followed the button press (as in Braboszcz & Delorme, 2011). One participant pressed the button 111 times (more than 3 standard deviations above the mean number of button presses) and was therefore removed from further analysis. Twenty-seven subjects did not have enough clean (i.e., artefact free) data epochs to be considered for further analysis; specifically, these participants had below 11 button presses with EEG data of sufficient quality and were excluded.

EEG pre-processing and FFT during resting-state

EEG baseline data were re-referenced offline to the linked mastoids and automatically corrected for ocular artifacts (Gratton, Coles, & Donchin, 1983) in segments of 4 seconds using Brain Vision Analyzer V2.04 (Brain Products GmbH, Germany). Baseline resting state EEG was then subjected to a Fast Fourier transformation (Hanning window length 10%) to calculate power for the beta (13-30 Hz) and theta (4-7 Hz) band. Theta/beta ratio was calculated by dividing the theta by the beta power. All EEG baseline variables were non-normally distributed and therefore log-normalized with a log10 transformation.

EEG pre-processing and Fourier analysis during the breath-counting task

For the EEG data during the breath counting task, offline re-referencing and ocular correction procedures were done as for the resting-state EEG. Neuroscan 4.5 Edit software was then used to interpolate bad channels and extract single trial epochs for 8.25 second pre- to 8.25 second post-

button press. The remaining data quantification was completed within MATLAB (The Mathworks, Version 8.0.0.783, R2012b) using EEGLAB (Version 13.4; Delorme and Makeig, 2004) and custom scripts. For each electrode and for each participant, 1 second intervals of sequential and non-overlapping data from 8 to 2 second before, and 2 to 8 second after each button press were individually selected, DC corrected, and then a 10% Hanning window was applied. Discrete Fourier Transformation (DFT) was used to derive the frequency spectra at 1 Hz resolution, and a correction was applied for the use of the Hanning window. Wide band power data were then computed for the delta (1-3 Hz), theta (4-7 Hz), alpha (8-12 Hz) and beta (13-30 Hz) bands. Theta/beta ratio was calculated by dividing the theta power by the beta power.

Event-related spectral perturbations (ERSP) for EEG during the breath-counting task.

To inspect differences in EEG pre-versus post-button press in more detail within the time-frequency domain, we computed Event Related Spectral Perturbations (ERSPs). For these analyses, we decomposed the EEG signal in brief overlapping segments using DFT. DFT separates oscillations in short epochs thus we considered this method to be better suited for studying effects over time within the 6s window after the button press, as opposed to wavelet decomposition as was utilized by Braboszcz and Delorme (2011); e.g., see Figure 2, Barry, Fogarty, De Blasio, and Karamacoska (2018). Following Braboszcz and Delorme (2011), baseline corrections were not applied to either the full-length epochs or their ERSP data. Each ERSP used 257 sliding DFT windows with a size of 128 data points (500 ms). Data in each window were DC corrected, and a 10% Hanning window was applied. Data were zero padded to 256 data points (1 second duration) and subjected to DFT. This gave us EEG power data at 1 Hz frequency resolution, with a 62.5 ms time resolution. We assessed DC to 30 Hz.

Each ERSP resulted in a three-dimensional matrix of EEG power at each frequency step and at each time point, containing all the information in the EEG throughout the trial. These ERSPs were obtained from 8 seconds before to 8 seconds after the button press for each trial and then averaged to obtain a mean ERSP for each subject. Contrary to Braboszcz and Delorme (2011), we did not assess the auditory oddball task as we were mainly interested in the spectral composition during mind

wandering and breath focus.

For the explorative topographical analyses, the following division in electrodes per region were made: Frontal; Fp1, Fp2, F3, Fz, F4, F7, F8, AFz, FCz, FC3, FC4, FT7, FT8; Central; C3, Cz, C4, CP3, CPz, CP4, T7, T8, TP7, TP8; Posterior; P3, Pz, P4, P7, P8, O1, Oz, O2; Left; Fp1, F7, F3, FT7, FC3, T7, C3, TP7, CP3, P7, P3, O1; Midline; AFz, Fz, FCz, Cz, CPz, Pz, Oz; Right; Fp2, F4, F8 FC4, FT8, C4, T8, CP4, TP8, P4, P8, O2.

Statistical analyses

All four formal hypotheses are tested using Fourier transformations for extraction of power estimates in baseline TBR and the pre- and post-button press windows for close comparison with previous studies. Results from ERSP analyses are also provided for a more comprehensive and in-depth approach to the additional explorative questions, as mentioned in the Introduction (e.g., visual inspection of other frequency bands and the time-course of TBR during the post-button-press-window). To test whether TBR was different pre- versus post-button press (hypothesis I), a 2-level (time) repeated measures analysis of variance (rm-ANOVA) was carried out. Next, four 2-level (time) rm-ANOVA's were conducted to exploratively test pre- versus post-button press differences in theta, beta, delta and alpha. We used Pearson's correlations to check whether there was a correlation between TBR change (pre- versus post-) and baseline TBR; baseline TBR and ACS; TBR pre-button press and ACS; TBR post-button press and ACS, and TBR change pre- vs post- and ACS (hypotheses II and III). These correlations were repeated by using partial correlations controlling for STAI-t score. To inspect the changes in the frequency bands of interest (theta, beta and TBR) pre-versus post-button press in more detail within the time-frequency domains, ERSP outcomes were examined. To test time differences using the ERSP data, mean narrow-band frontal ERSP data (across F3, Fz and F4) were summed to form the theta (4-7 Hz) and beta (13-30 Hz) frequency bands. These data were then averaged in 1 second non-overlapping sections to provide 6 averages from -8 to -2 seconds pre-button press, and 6 averages from 2 to 8 seconds post-button press. The same averages were calculated for theta/beta ratio by dividing the theta data by the corresponding data in beta. Then, a 6 level (time-points) multivariate analysis of variance [MANOVA] for time-points pre-button press and a 6 level

(time-points) MANOVA for time-points post-button press, were conducted for Frontal TBR to explore the linear trend over the time points. Furthermore, we exploratively evaluated topographical differences by conducting a 2 (pre-post) x 3 (sagittal; frontal [F], central [C], posterior [P]) x 3 (lateral; left [L], midline [M], right [R]) MANOVA for TBR. Finally, we exploratively checked whether differences pre- versus post- button press for theta, beta and TBR were correlated to the number of button presses by using Pearson's correlations. All baseline EEG variables and ERSP-derived EEG power values were non-normally distributed and therefore normalized with a log10 transformation. Bonferroni corrections for multiple testing were applied and reported where appropriate.

Results

Participants

The 26 remaining participants had a mean age of 22.8 years ($SD = 2.6$, range: 19-28). Mean ACS score was 53.88 ($SD = 5.44$, range 41-63), mean STAI-t score was 38.54 ($SD = 6.32$, range 29-50). The mean frontal TBR of the participants measured during the resting state (baseline) was 1.22 ($SD = 0.49$, range 0.52-2.47 [non log-normalized]). All subjects had between 11 and 60 button presses ($M = 23.76$, $SD = 12.54$).

EEG activity pre- and post-button press average differences

TBR was found to be significantly higher pre- compared to post-button press; $F(1,25) = 28.05$, $p < 0.001$, $\eta_p^2 = 0.53$. This confirms hypothesis I.

We exploratively tested pre- and post-differences for theta, beta, delta and alpha. Theta was significantly higher pre- versus post-button press; $F(1,25) = 13.60$, $p = 0.004$, $\eta_p^2 = 0.35$ (p-value is Bonferroni corrected by factor 4 as 4 bands were tested). Beta, on the other hand, was lower pre-compared to post-button press; $F(1,25) = 18.58$, $p = 0.001$, $\eta_p^2 = 0.43$ (Bonferroni corrected). Delta was significantly higher pre- versus post-button press; $F(1,25) = 9.07$, $p = 0.024$, $\eta_p^2 = 0.27$ (Bonferroni corrected). Alpha was significantly lower pre- versus post-button press; $F(1,25) = 17.64$,

$p = 0.001$, $\eta_p^2 = 0.41$ (Bonferroni corrected).

EEG baseline TBR related to ACS and TBR change pre- versus post- and ACS.

When controlling for STAI-t, no significant correlation was found between ACS and baseline frontal TBR (partial $r = 0.14$, $p = 0.518$). This correlation was also absent without controlling for STAI-t; $r = 0.16$, $p = 0.423$, this rejects hypothesis II. Also, no significant correlation was found between TBR change pre- versus post- and baseline TBR, $r = 0.06$; $p = 0.758$. Also, ACS did not correlate significantly with the difference score of frontal pre-minus-post TBR; $r = 0.17$, $p = 0.540$. This was also the case when controlling for STAI-t; ACS did not correlate with frontal TBR pre-button press (partial $r = 0.25$, $p = 0.220$), post-button press (partial $r = 0.16$, $p = 0.435$), or difference score of frontal pre-minus-post TBR; partial $r = 0.15$, $p = 0.483$. Thus, hypothesis III was rejected. Because of these non-significant results for relations between baseline TBR, TBR change and ACS, hypothesis IV (mediation) was not tested.

Event Related Spectral Perturbations (ERSPs).

First, we visually inspected the output of the ERSP analyses (**Figure 1**). The ERSP included averages for all epochs of -8 to 8 seconds around the button press for all participants and all electrodes. As our hypotheses were based on previous findings with frontal TBR, we visualized ERSP data of frontal electrode positions (average of F3, Fz and F4) averaged over all participants. This figure suggests that the power decreases post compared to pre-button press occurred not only in theta, but also in delta, while power increases were apparent not only in beta, but also alpha post-button press. **Figure 1** also suggests that prior to the end of the post-button press epoch, theta power starts to increase again, and beta power starts to decrease.

FIGURE 1 ABOUT HERE

ERSP pre- and post-button press slopes and topography

The values of the 6 pre- and 6 post-button press averages for frontal TBR are visualized in **Figure 2.** Testing ERSP time effects, a significant difference was found for TBR from pre- to post-, $F(1,25) = 26.69$, $p < 0.001$, $\eta_p^2 = 0.52$. Frontal TBR did not have a significant linear slope trend over time pre-button press, $F(1,25) = 0.44$, $p = 0.516$, $\eta_p^2 = 0.02$), but (as can be seen in Figure 2) there was a significant linear slope trend over time post-button press, $F(1,25) = 34.84$, $p < 0.001$, $\eta_p^2 = 0.58$ (Bonferroni corrected by a factor of 2), showing that TBR increased over time 2 to 8 seconds after the button press.

As for topographical differences, TBR was dominant in the midline compared to the lateral regions (M > L/R: $F = 66.96$, $p < 0.001$, $\eta_p^2 = 0.73$), and in the frontal compared to the posterior regions (F > P: $F = 36.53$, $p < 0.001$, $\eta_p^2 = 0.59$). TBR also showed two-way interactions, with the midline dominance significantly larger in the frontal than posterior regions (M > L/R x F > P: $F = 7.65$, $p = 0.011$, $\eta_p^2 = 0.23$). The midline TBR dominance was also significantly larger in central compared to frontal/posterior regional mean (M > L/R x C > F/P: $F = 15.61$, $p = 0.001$, $\eta_p^2 = 0.38$). Pre- vs post-button press interactions showed greater midline than lateral reductions (M > L/R x pre > post: $F = 4.50$, $p = 0.044$, $\eta_p^2 = 0.15$), particularly in posterior compared to frontal regions (M > L/R x P > F x pre > post: $F = 6.04$, $p = 0.021$, $\eta_p^2 = 0.19$). Thus, the effect of MW on TBR was maximal in the posterior midline region. The two-way interaction with TBR on midline over frontal and posterior regions and the pre- vs post-button press midline and posterior dominance effect would however become non-significant after Bonferroni correction.

ERSP data pre- and post-differences related to number of button presses.

As differences were found pre-versus post-button press, we explored whether these differences were related to the number of button presses that participants made. To analyse this, we first computed the average of the ERSP pre- (-8 to -2 seconds) and post-button press (2 to 8 seconds) and calculated the difference scores between these for frontal (average F3, Fz and F4) theta and beta band and the TBR. Correlational analysis showed no significant correlation between the number of button presses and the difference scores in theta ($r = 0.07$, $p = 0.741$), beta ($r = -0.24$, $p = 0.234$), or TBR ($r = 0.10$, $p = 0.618$). Thus, MW-related TBR change was independent of the number of button

presses.

Discussion

This study aimed to replicate and extend the design and results of Braboszcz and Delorme (2011) as pertaining to the MW related changes in EEG, to gain further insight into the role of frontal TBR during MW episodes. In our all-female sample, we found that frontal TBR was significantly higher during MW episodes compared to on-task time periods; this TBR – MW effect was strongest in the midline, particularly in posterior regions. When considering the EEG bands separately, theta power was higher and beta power was lower during MW episodes as opposed to on-task periods. Frontal baseline TBR did not correlate with ACS or the TBR-MW effect, resulting in an inability to test our hypothesis that previously observed relations between ACS and TBR might be mediated by EEG changes during MW.

Our first hypothesis that frontal TBR would be higher during MW episodes was confirmed. TBR's change between MW and focused episodes was stronger along the midline regions compared to the lateral regions and this effect was stronger in posterior compared to central and frontal regions, although these effects were relatively small and did not remain significant after correction for multiple testing. This finding seems comparable to the results of Braboszcz & Delorme, (2011) who found the MW effect on separate theta and beta bands to be strongest in parieto-occipital regions. Previous crucial findings for TBR however, repeatedly assessed TBR as measured frontally which was associated with prefrontally-mediated cognitive and emotional processes (Putman et al., 2010, 2014; Angelidis et al., 2016; 2018; van Son et al., 2018a; Tortella-Feliu et al., 2014). For example, it predicted acute stress-induced changes in self-reported state attentional control in addition to its reported correlation with self-reported trait and state attentional control (Putman et al, 2014; Angelidis et al., 2016). Moreover, working memory training was found to decrease frontal TBR (Sari et al., 2015). Also, a theta-based brain stimulation procedure that has been shown to enhance working

memory, decreased frontal and central TBR and increased flexible implicit rule learning in motivated

decision making (Wischnewski, Zerr & Schutter, 2016). Additionally, Schutter and van Honk (2005),

used a reward-punishment reversal learning task to measure higher order cognitive integration of

emotional information, and good performance on this same task correlated negatively with baseline

frontal TBR; a similar result was also found in another more recent study (Schutte, Kenemans,

Schutter, 2017). Additionally, several studies from our lab have provided evidence that resting-state

frontal TBR predicted spatial attentional bias for threatening pictures, also interacting with individual

differences in trait anxiety (Angelidis et al., 2018; van Son et al., 2018a). Relations between frontal

TBR and attentional interference from high threat pictures were also altered by administration of

caffeine, a catecholamine agonist that affects executive functioning in the PFC (van Son, Schalbroeck,

Angelidis, van der Wee, van der Does & Putman, 2018b). Currently, as in Braboszcz and Delorme

(2011), MW-related changes in TBR were not stronger over other than frontal areas. Therefore, if

future studies would verify our hypothesis concerning relations between baseline TBR, executive

functions like attentional control and MW, this would imply that research into relations between

baseline TBR and executive function should also consider non-frontal areas more extensively (see

also Putman et al., 2014a; Putman, Verkuil, Arias-Garcia, Pantazi, & Van Schie, 2014b). Combination

of EEG and other neuro-imaging techniques, like functional magnetic resonance imaging (fMRI), can

possibly further investigate more precise localization of TBR and MW-correlates in the brain. For

instance, since MW has been associated with connectivity of the default mode network (DMN;

Karapanagiotidis, Bernhardt, Jefferies, & Smallwood, 2017; Smallwood, Beach, Schooler & Handy,

2008; Christoff, Ream, Geddes, & Gabrieli, 2003), MW-related EEG changes might be related to

increased activation of this network and reduced activation of an executive control network. Although

(dorsolateral) prefrontal cortical areas are importantly involved in the latter (Seeley, Menon,

Schatzberg, Keller, Glover, Kenna et al., 2007), the DMN consists of other cortical and subcortical

areas and EEG activity related to activation of this network need not be restricted to frontal areas.

Our data confirm and extend the findings by Braboszcz and Delorme (2011), and show that

phasic changes in TBR are related to variation of mental state between uncontrolled MW and focused

attention, or perhaps meta-cognitive vigilance. One view of MW is that it represents a state of reduced

cognitive control (McVay & Kane, 2009; Unsworth & McMillan, 2014), reduced vigilant processing of external stimuli, and increased bottom-up, memory-driven self-referential thought (Mason et al., 2007). Changes in brain function that are associated with MW and these underlying cognitive processes include increased activation of the posterior cingulate cortex, medial PFC and para-hippocampal regions – and decreased activation in (pre-frontal) cortical areas such as the dorso-lateral PFC and lateral inferior parietal regions (Hasenkamp et al., 2012; Karapanagiotidis et al., 2017; Hopfinger, Buonocore, & Mangun, 2000; Corbetta & Schulman, 2002; Delaveaux, Arruda Sanchez, Steffen, Deschet, Jabourian, Perlbarg, & Fossati, 2017). Also, it has been found that ADHD was related to altered deactivation of the DMN (Uddin, Kelly, Biswal, Margulies, Shehzad, Shaw, & Milham, 2008), which again strengthens the assumption of MW to represent a state of reduced cognitive control. The current data then likely again support the conjecture that baseline TBR represents relative activation of top-down (prefrontal) cortical versus more bottom-up and subcortical processes, as first suggested by Schutter and van Honk (2005) and Knyazev (2007), and supported by our own work (Putman et al., 2010; 2014a; Angelidis et al., 2018; van Son et al., 2018a), and that from several other labs (Schutter & van Honk, 2004; Schutter & van Honk, 2005; Sari et al., 2016; Tortella-Feliu et al., 2014; Morillas-Romero et al., 2015; Keune et al., 2017; Clarke, Barry, McCarthy, & Selikowitz, 2001). Additionally, the current confirmation that TBR may be used as a marker of MW-related changes in brain activity can likely be very useful for the study of MW (Smallwood & Schooler, 2006) and inattention (Jap, Lal, Fischer, & Bekiaris, 2009; Lorist, Bezdan, ten Caat, Span, Roerdink, & Maurits, 2009).

The breath-counting MW method as used in this study and in Braboszcz and Delorme's (2011) research (see also Hasenkamp et al., 2012, for a closely related method), has the potential limitation that it relies on introspection. Since the MW episodes that are examined are self-reported, their underlying brain activity might be different from other MW episodes that might have remained undetected, or from earlier phases of the reported MW episodes. Also, it is reasonable to assume that participants who were better able to realize that their mind wandered off the breath-counting, pressed the button more often, resulting in the results being driven by these participants. In other words, one could speculate that using the time periods before a button press might not capture episodes

representative of all MW, but possibly predominantly MW episodes that are associated with more meta-attentional control or awareness. If this were so, one would expect that participants who are more aware of their MW episodes (and press the button more often than participants who are less aware of this) would show different EEG results. We tested if there was a correlation between the number of button presses and the TBR change, and this was not the case. The absence of this correlation is reassuring and likely indicates that the results are not confounded by meta-attentional introspective awareness. Also, if our results and the results from Braboszcz and Delorme (2011) partially reflect biased influence of MW episodes that are subsequently introspectively detected, one would expect that this should lead to a smaller pre- to post- button press effect. One could thus speculate that the results found using this method might, if anything, underestimate the effect of spontaneous, inattention related, mind wandering on TBR. Moreover, given that the currently-used method specifically instructed the participants to focus (on counting breaths), the most straight-forward assumption is that the periods before and after the button press represent unfocussed and focussed periods, rather than, for example, task related interference or deliberate mind wandering (e.g. Ruby et al., 2013), although these options cannot be fully excluded. However, future studies might opt to include MW measurements that are not self-generated, but instead rely on more qualitative experimenter controlled thought-probing.

We used ERSP-derived one-second averages to further investigate slope changes over time in frontal TBR. The plotted slopes revealed that frontal TBR after a drop that started just before the button press, increased again quite rapidly post-button press. This pattern of pre- versus post-button press raises an interesting speculation: is it really *high* TBR that we see during MW episodes, or perhaps rather *low* TBR shortly and briefly after the button press? Looking at the relatively fast rebound of frontal TBR, one explanation might be that individuals start to lapse back into a new MW episode again relatively quickly after the button press. We are however unsure how likely it is that they would often start to mind wander again within eight seconds of becoming aware of their mind wandering. Another potentially interesting speculation concerning this seemingly quick rebound of frontal TBR is that the on-task focused periods might represent a short hypervigilant meta-awareness or meta-attentional control (realising that one lost count and was mind wandering, and subsequently

increasing the use of executive resources for goal-directed monitoring of breath counting), which possibly contributed to the frontal TBR change post- versus pre-button press. This would be in line with literature on increased hypervigilance after error realization (e.g. Hollins, Harper, Gallagher, Owings, Lim, Miller et al., 2009; Weymar, Keil & Hamm, 2013). This hypervigilance can be described as meta-cognition of one's attentional control and could possibly disappear relatively quickly without having to engage back into a MW episode per se. It should be noted however, that such error realization is associated with short-lived *increased* theta activity (Hollins et al., 2009; Weymar et al., 2013), which seems at odds with our finding of *decreased* TBR (and theta) around the time of mind wandering realization. As mentioned before, future studies could take this speculation into account and compare MW periods with non-MW periods by using a design that does not rely on error related realizations.

All in all, the current results suggest frontal TBR to be related to changes in focused attention and possibly meta-attentional control or awareness. Beta is found to be involved in top- down executive functions like behavioural inhibition, inhibitory motoric processes, sequential encoding of processed items in working memory, retrieval from long-term memory and visual attention (Brown, 2007; Baker, 2007; Jenkinson & Brown, 2011; Engel & Fries, 2010; Marrufo, Vaquero, Cardoso, & Gomez, 2001; Wróbel, 2000). Considering that beta activity has a strong coherence between frontal and parietal regions during top-down compared to bottom-up visual attention (Buschman & Miller, 2007; 2009; Engel & Fries, 2010) it was speculated that beta activity is to some extent related to the establishment of reciprocal control of bottom-up and top-down processes (Engel & Fries, 2010). Theta activity on the other hand has been associated with subjective sleepiness (Strijkstra, Beersma, Drayer, Halbesma, & Daan, 2003), decreased vigilance (e.g. Daniel, 1967; Belyavin, & Wright, 1987), and was suggested to be generated in limbic structures involved in a brain network subserving more bottom-up automatic attention as opposed to more cortically mediated executive control (Hermans et al., 2014; Seidenbecher, Laxmi, Stork, & Pape, 2003). These lines of research fit with functional correlates of TBR and its role in mind wandering conceived as a state of reduced executive attentional control and automatic self-generated thought (Mason et al., 2007; McVay & Kane, 2009; Unsworth & McMillan, 2014; Smallwood, 2013; Christoff et al., 2003).

Exploratively, we additionally tested differences in the delta and alpha bands, and found that delta was significantly higher during MW episodes compared to on-task focus periods, while alpha was significantly higher during on-task focus periods compared to MW episodes. Changes in delta were similar to changes in theta, possibly because these bandwidths are adjacent and their functions possibly have some overlap. Some studies have indeed described overlays in functionality for delta and theta in for example hippocampal – prefrontal coherent activity (Aleksanov, Vainstein & Preobrashenskaya, 1986) and homeostatic and motivational processes (Knyazev, 2012). Putman et al. (2010) found similar correlations for theta/beta ratio and delta/beta ratio with fearful modulation of response inhibition in an emotional go/no-go task. As for alpha, a post-button press increase in power similar to beta was found. Alpha activity has been positively related to inhibitory processes (Uusberg, Uibo, Kreegipuu, & Allik, 2013; Haegens, Luther, & Jensen, 2012; see also Pfurtscheller, Stancak, & Neuper, 1996; Klimesch, Sauseng, & Hanslmayr, 2007, for reviews). Like beta, alpha is found to be involved in top-down processes, and more specifically, control over stored motoric information via inhibition of the retrieval of interfering information (e.g. Hummel, Andres, Altenmüller, Dichgans, & Gerloff, 2002; Klimesch, 2012), and attentional control over sensory information (Wolfe & Bell, 2004). Moreover, alpha activity was related to timing of neural activity to facilitate different behavioural states (Nicolelis & Fanselow, 2002; Klimesch et al., 2007). As described above, beta is also related to top-down executive processes, which might explain why also alpha similarly varied as a function of mind wandering. The functions in which these bands are involved might have some overlap, explaining their similar increase during focused attention periods in the current results.   The expected correlations between baseline TBR, changes in TBR pre- versus post-button press and ACS were not found in the current study. A relation between baseline TBR and this difference in TBR during MW episodes and on-task periods would possibly affirm that higher TBR over the longer period of spontaneous TBR as measured during a typical resting state measurement is influenced by episodes of mind wandering, which could theoretically explain previously observed relations between such spontaneous TBR and attentional control and other cognitive executive processes (e.g. Putman et al., 2010; 2014a; Angelidis et al., 2016). As the current sample showed no correlation between spontaneous TBR and ACS, our study confirms that MW is related to changes in frontal TBR but did

not confirm the larger hypothesis that relations between executive control and baseline TBR are related to MW-related changes in brain activity. The absence of a significant correlation between baseline frontal TBR and attentional control is unexpected and contrary to several reports of this relation (Putman et al., 2010; 2014a; Angelidis et al., 2016; van Son et al., 2018a; Keune et al., 2017; but see Morillas-Romero et al., 2015; Angelidis et al., 2018), which include negative correlations between TBR and subjectively as well as objectively measured attentional control. It is also unexpected in light of many observations of high TBR in AD(H)D (Barry et al., 2003; Arns et al., 2013). The current EEG measurements, both during baseline and the breath counting task, were recorded with only eyes closed to keep the procedure methodologically consistent with Braboszcz and Delorme (2011); this diverged from the alternating eyes-open-closed method that is typically used in previous studies of spontaneous TBR. Unpublished data from our lab, however, suggested no systematic differences between eyes-open or eyes-closed measurements in terms of frontal TBR in relation to other variables. It is therefore not clear if this difference in resting-state method contributed to the absence of a frontal TBR-ACS relation in the current data. Note also that previous reports of TBR-ACS relations were based on larger samples than the current one. Future studies might seek to investigate the relation between TBR and attentional control using both task-based and self-report measures of attentional control (see Angelidis et al., 2018, van Son et al., 2018a, Morillas-Romero et al., 2015; van Son et al., 2018b). All in all, it is not clear why the current data show no relation between baseline TBR, attentional control and MW-related TBR changes. This study confirms that MW, here conceived as a state of reduced attentional control, is related to higher TBR, but the larger hypothesis related to trait attentional control should be revisited in future studies.

Potential limitations of this study include that the implemented method causes a high between-subjects variance in the number of button presses. A substantial number of participants had to be excluded from analyses as they had too few analysable button presses or clean data epochs around the button press to reliably conduct analysis on (as in Braboszcz & Delorme, 2011). However, we retained 26 participants, which is more than twice the number of participants ($N = 12$) as assessed in Braboszcz and Delorme's (2011) study, providing a robust replication of their proof of principle study. Also, the present study assessed only female participants which should be taken into account

for the generalizability of our findings. No clear gender differences in TBR have been found to our knowledge, however, some studies suggest resting-state beta activity to be higher in females compared to males (Putman, Arias-Garcia, Pantazi, & van Schie, 2012; Jaušovec, & Jaušovec, 2010; Wada, Takizawa, Zheng-Yan, & Yamaguchi, 1994). Such gender differences have not yet been investigated in MW-effects on EEG however, and future studies should therefore aim to include male subjects as well. Finally, although the results show a strong relation between scalp based EEG and mind wandering, and there is much evidence suggesting that TBR might reflect interactions between cortical and subcortical brain processes which could account for this finding, this interpretation remains based in indirect evidence. Future studies might attempt to revisit relations between TBR and mind wandering using for instance fMRI imaging to directly bridge this empirical gap.

In conclusion, this study confirms that increased frontal TBR is related to mind wandering, which is thought to reflect, among other things, a state of reduced top-down attentional control over thoughts, but unexpectedly found no relations between EEG and self-reported attentional control. This should be revisited in future studies, possibly combining EEG and fMRI.

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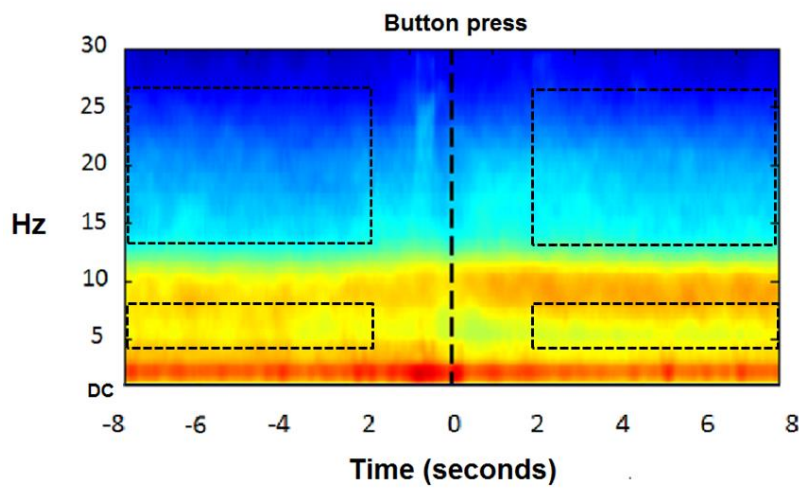
Figure 1, ERSP plot of the frontal average (across F3 Fz F4 sites) at 1 Hz frequency resolution, and 62.5 ms time resolution. Mind wandering was considered to have occurred in the -8 to -2 second period preceding the button press, and breath focus was considered to have occurred in the+2 to +8 second period following the button press. Rectangular frames highlight these data of interest.
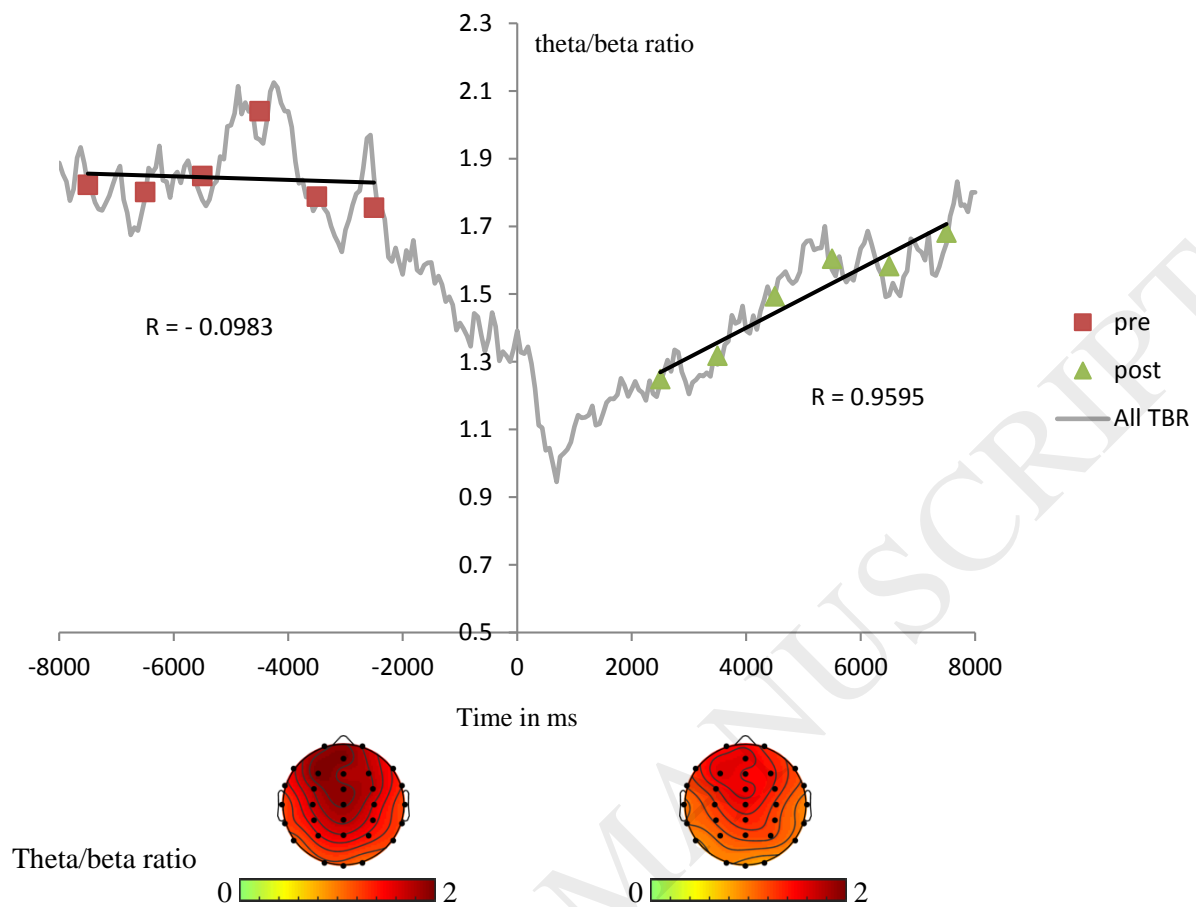
Figure 2. Plot of the ERSP-derived theta/beta ratio (TBR; non-logtransformed) data for Frontal electrode mean (F3, Fz and F4) showing slope trends plotted over six- 1 second averages pre- and post-button press. Topographic map of power pre (left) and post (right) button press is shown for TBR averaged from −8 to −2 second before and 2 to 8 second after the button press.