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Inter-trial alpha power indicates mind wandering

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Abstract

Mind wandering during ongoing tasks can impede task performance and increase the risk of failure in the laboratory as well as in daily-life tasks and work environments. Neurocognitive measures like the electroencephalography (EEG) offer the opportunity to assess mind wandering non-invasively without interfering with the primary task. However, the literature on electrophysiological correlates of mind wandering is rather inconsistent. The present study aims toward clarifying this picture by breaking down the temporal dynamics of mind wandering encounters using a cluster-based permutation approach. Participants performed a switching task during which mind wandering was occasionally assessed via thought probes applied after trial completion at random time points. In line with previous studies, response accuracy was reduced during mind wandering. Moreover, alpha power during the inter-trial interval was a significantly increased on those trials on which participants reported that they had been mind-wandering. This spatially widely distributed effect is theoretically well in line with recent findings linking an increased alpha power to an internally oriented state of attention. Measurements of alpha power may, therefore, be used to detect mind wandering online during critical tasks in traffic and industry in order to prevent failures.

KEYWORDS

alpha, EEG, mind wandering, resource allocation, time-frequency analysis

1 | INTRODUCTION

Mind wandering, that is, the experience of one's attention drifting away from the external environment toward inner thoughts and feelings, is a frequent phenomenon. Mind wandering is an umbrella term for divergent states of inattention (Seli, Kane, et al., 2018) but is often conceptualized in a more specific manner, namely as a redirection of attention away from a currently ongoing task (Mrazek, Phillips, Franklin, Broadway, & Schooler, 2013). In this article, we use the term mind wandering in this more specific sense, as a reference to task-unrelated thoughts that occur while one is engaged in some ongoing task.

Indeed, it seems that during many mundane tasks—even when writing a manuscript on mind wandering—we often find ourselves preoccupied with thoughts totally unrelated to our tasks at hand. In one large-scale ambulatory assessment study deploying experience sampling during the daily lives, mind wandering was reported during 46.9% of all daily activities (Killingsworth & Gilbert, 2010). Although the prevalence of mind wandering was found to be lower in some more recent studies (i.e., around 30%; Kane et al., 2017), these findings render mind wandering a relevant factor to deal with when investigating cognitive performance. Decrements in performance due to mind wandering have been observed in sustained attention (Allan Cheyne, Solman, Carriere, & Smilek, 2009; Denkova, Brudner, Zayan, Dunn, & Jha, 2018), memory (Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012; Smallwood, Baracaia, Lowe, & Obonsawin, 2003), working memory capacity (Kane & McVay, 2012; Mrazek et al., 2012), reading (Franklin, Smallwood, & Schooler, 2011; Schad, Nuthmann, & Engbert, 2012), simulated driving (Lemercier et al., 2014; Zhang & Kumada, 2018), and random number generation (Teasdale et al., 1995). In studies aiming toward higher ecological validity, mind wandering was also found to impair real-world driving performance (e.g., Burdett, Charlton, & Starkey, 2019; Galéra et al., 2012; Qu et al., 2015) as well as daily life performance (McVay, Kane, & Kwapil, 2009).

One limiting factor for the investigation of mind wandering is its assessment. Most research on mind wandering relies on participants' self-reported mental states. That is, participants either need to catch themselves when they are off task by pressing a designated key (self-caught method) or they are randomly asked from time to time during an ongoing task whether they had just been on task or off task before the thought probe occurred (probe-caught method). Although both methods have been used very successfully for studying the wandering mind (Smallwood & Schooler, 2015), they also impose some methodological limitations (see Weinstein, 2018, for a review). To capture all mind wandering instances, the self-caught method would require participants to be fully aware of their own mental states all the time while performing a task, which is often not the case (Smallwood, McSpadden, & Schooler, 2007). The probe-caught method captures mind wandering with and without awareness but requires participants to temporarily interrupt their primary task to report on their thoughts. Although mind wandering probes do not interfere much with task performance, at least during simple cognitive tasks (Wiemers & Redick, 2018), they still interrupt the ongoing task and thus alternative indicators of mind wandering are needed (cf. Steindorf & Rummel, 2019). Different mind wandering indicators have been suggested, such as changes in response time variabilities (McVay & Kane, 2012), changes in pupil dilation (Unsworth & Robison, 2018), or changes in neural activity (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009). The last method is particularly promising, because identifying a neurocognitive signature of mind wandering would not only allow to assess mind wandering without thought probes but also to better understand the temporal dynamics of mind wandering episodes when using methods with high temporal resolutions such as EEG. The present study thus aims to investigate the neurocognitive signature of mind wandering by means of the EEG.

Some previous studies investigated the relationship between mind wandering and EEG activity. In most studies, Event-Related Potentials (ERP) responses were found to be decreased during mind wandering episodes. In a study comprising simulated driving as well as cognitive tasks, Baldwin and colleagues (2017) found reduced P3a amplitudes in mind wandering episodes at frontal and central recording sites. Barron and coworkers (2011) used a retrospective self-report measure to compare the electrophysiological data of a high versus a low mind wandering group in an oddball paradigm. They observed reduced ERP responses to targets (P3b) as well as to standard (P3a) in the high mind wandering group. Decreased P3 components during mind wandering were also observed by Kam and Handy (2013). The P3 amplitude has repeatedly been associated with the allocation of cognitive resources (Allison & Polich, 2008; Kok, 2001). Reduced ERP amplitudes during mind wandering have also been observed for early sensory components such as the visual P1 (Baird, Smallwood, Lutz, & Schooler, 2014; Kam & Handy, 2013) and the auditory P2 (Braboszcz & Delorme, 2011).

When considering EEG oscillatory activity, theta and alpha band dynamics might be of particular interest in the context of mind wandering. Theta, especially event-related frontal-midline theta activity has been associated with the exertion of cognitive control (Cavanagh & Frank, 2014; Cavanagh, Zambrano-Vazquez, & Allen, 2012). Cognitive control allocated to a task should be decreased in mind wandering situation, as attentional resources are drawn away from the primary task (Mrazek et al., 2013). Alpha activity, on the other hand, was found to be suppressed by sensory stimulation (Thut, Nietzel, Brandt, & Pascual-Leone, 2006) and increased in periods without stimulation (Carp & Compton, 2009; Compton, Arnstein, Freedman, Dainer-Best, & Liss, 2011). Alpha power seems to reflect an internally oriented attentional state (Hanslmayr, Gross, Klimesch, & Shapiro, 2011). Consequently, it was found to be increased during mental imagery (Cooper, Croft, Dominey, Burgess, & Gruzelier, 2003) and has been associated with default mode network activity (Knyazev, Slobodskoj-Plusnin, Bocharov, & Pylkova, 2011; Mo, Liu, Huang, & Ding, 2013). An internal focus of attention and mental imagery are relevant aspects in mind wandering situations, which renders alpha power a promising variable to reflect certain aspects of mind wandering in the EEG.

The findings of previous research with respect to the representation of mind wandering in time-frequency space are rather inconclusive. Atchley and colleagues (2017) used a Stroop task to assess mind wandering by defining segments preceding error-trials as mind wandering episodes. They found the spectral power in the theta and alpha band to be decreased compared to segments preceding correct trials. Baldwin et al. (2017), however, found an increase of alpha power during mind wandering at parietal electrodes using the probe-caught assessment method during simulated driving as well as during a vigilance task. Similar results were observed by Compton, Gearinger, and Wild (2019), who also found increased alpha power in episodes preceding reports of mind wandering during a Stroop task. Baird and colleagues (2014) also used the probe-caught method to investigate mind wandering during a vigilance task. They observed a larger event-related reduction of alpha power in the Event-Related Spectral Perturbation (ERSP) of the EEG during mind wandering episodes at frontal and parietal leads as compared to on-task trials. Braboszcz and Delorme (2011) combined breath counting as the primary task with the self-caught method to assess mind wandering. Braboszcz and Delorme (2011) compared EEG segments that preceded button presses indicating self-caught mind wandering with episodes after the button press. Using a cluster-based permutation approach (Maris & Oostenveld, 2007), Braboszcz and Delorme (2011) found significantly increased delta and theta power in the pre-button-press segment as compared to the post-button-press segment at all electrodes. The result pattern was opposite for the alpha and beta band. For the alpha band, however, the lower power in the pre- compared to the post-button-press segment was only significant at occipital electrodes. Other studies investigated spectral power ratios in order to identify reliable correlates of mind wandering in the EEG. Applying the self-caught method, van Son et al. (2019) found increased *theta*/*beta* ratio at frontal electrodes during mind wandering. Similar findings have been reported for the *beta*/*alpha* ratio and the *beta*/(*alpha*+*theta*) ratio (Cunningham, Scerbo, & Freeman, 2000).

The inconsistency in previous findings on the electrophysiological representation of mind wandering is somewhat unsatisfactory and most likely due to the large variety of methods used. Already the context or tasks in which mind wandering is assessed may play an important role in the observed inconsistencies in the neurocognitive signature. Mind wandering is more prevalent and interferes less with task performance in low as compared to high demand tasks (Robison & Unsworth, 2018; Rummel & Boywitt, 2014). Mind wandering is also more prevalent in practiced versus non-practiced tasks (Cunningham et al., 2000; Giambra, 1995) and in automated environments (Gouraud, Delorme, & Berberian, 2018), which are both situations in which less attentional control is needed. Moreover, individuals report higher rates of mind wandering when probed less frequently (Schubert, Frischkorn, & Rummel, 2019; Seli, Carriere, Levene, & Smilek, 2013).

The choice of signal processing methods like the electrodes of interest, whether absolute or relative power measures are used, and the kind of baseline correction normalization may affect the outcome substantially as well. Choosing a condition-specific over a condition-general baseline, for example, might even shift mind wandering-related variance in time. This would be the case if mind wandering occurred in the baseline period. Using a condition-specific baseline would then nullify mind wandering-related variance by subtracting the neural signature of mind wandering from the neural signature of mind wandering in the baseline episode. On the other hand, this approach could also create variance in non-baseline time windows by subtracting mind wandering (the baseline variance) from non-mind wandering.

Finally, the assessment of mind wandering appears to be crucial in particular as the findings of recent research with respect to the alpha band seem to be the opposite for the probe-caught compared to the self-caught method. It might be questionable, whether the pre-response period in the self-caught approach reflects mind-wandering, the cognitive process of getting aware of mind-wandering, response preparation, or a mixture of these processes.

The present study aims toward investigating mind wandering by means of the EEG. We tried to avoid some of the difficulties described above, by choosing assessment and signal processing parameters accordingly. The participants performed a switching task. The assessment of mind wandering was done by applying the probe-caught method in which the participants were intermittently asked whether they experience mind wandering at that respective moment or not. Trials in which mind wandering was reported as well as the two preceding trials were defined as mind wandering trials. Trials in which participants stated that they focused on the task were defined as on-task trials. In order not to focus on specific electrodes and also to address the problem of multiple comparisons, a cluster-based permutation approach was chosen to statistically test for differences between mind wandering and on-task episodes (Maris & Oostenveld, 2007). As we wanted to avoid a priori assumptions about the temporal structure of the effects of mind wandering in relation to the primary task, we analyzed segments covering task-related processing as well as the inter-trial interval. We chose a decibel normalization approach using the frequency-specific power averaged across all conditions, that is, mind wandering and on-task episodes, in a pre-stimulus interval as baseline. In doing so, the systematic mind-wandering-related variance during the baseline period would not be reflected to time-frequency points outside the baseline. The switching task used as the ongoing task in the present study has the additional advantage that it provides contexts in which task demands are higher (i.e., on switching trials) and contexts in which task demands are lower (i.e., on repeat trials). Beside the factor mind wandering versus on-task trials, we thus also tested for the effects of switch versus repeat trials, as well as for the interaction.

2 | METHOD

2.1 | Sample

For the experiment, 100 participants were recruited via a local newspaper advertisement, announcements on social media platforms, as well as via the distribution of flyers in Heidelberg. The inclusion criteria were an age between 18 and 60 years, normal or corrected to normal vision, and not having a history of mental illness. Two participants had to be excluded for not completing the experiment. For the present study, we only considered those participants that reported to have experienced mind wandering at least 30 occasions during the experimental task. The exclusion of participants with less than 30 occasions of mind wandering was necessary in order to obtain a sufficiently high signal to noise ratio when analyzing the EEG signal in an event-related manner. The excluded and the included subsamples did not differ significantly in terms of sex ($t(96) = -1.23$, $p = .22$) and age ($t(96) = -0.74$, $p = .48$). This reduced our sample size to $N = 33$ (20 females) with a mean age of 29.79 years ($SD = 11.73$). All participants signed an informed consent form before participating in the experiment. The study was approved by the ethics committee of the Heidelberg University and all methods used are in accordance with the declaration of Helsinki.

2.2 | Procedure

The experiment started immediately after participants completed an intelligence test (data reported in Schubert, Hagemann, Löffler, Rummel, & Arnau, 2019) and after the preparation of a 32 electrode EEG montage. At the start, instructions for the mind wandering assessment were given to the participants on the screen, reading: "*Sometimes, after having responded, you will be asked whether your thoughts were focused on the task during the presentation of the previous digit or on something else. Please answer this question honestly. You can take your time and consider your response thoroughly.*" Stimuli were presented using MATLAB 2017b (The MathWorks Inc., Natick, Massachusetts) against a black background on a 21.3 Inch monitor (EIZO FlexScan S2100) with a resolution of 1,600 × 1,200 pixels and a refresh rate of 60 Hz. The participants performed in a shifting task (Sudevan & Taylor, 1987) during which digits ranging from 1 to 4 and 6 to 9 were presented at the central position on the screen that subtended a visual angle of 0.6° at a viewing distance of approximately 74 cm. Depending on the color of the digit, participants had either to decide whether the presented number was odd or even, or if the number was less or more than 5. The colors indicating the task were red (#F00000) for the less/more task and green (#00F000) for the odd/even task. After 40 practice trials which included feedback, each participant completed 640 trials without feedback that were divided into ten blocks with 64 trials each. Both tasks as well as whether the task changed from one trial to the next (switch-trial) or stayed the same (repeat-trial) were equally likely for each trial. Responses had to be given by pressing the D and L buttons on a computer keyboard with

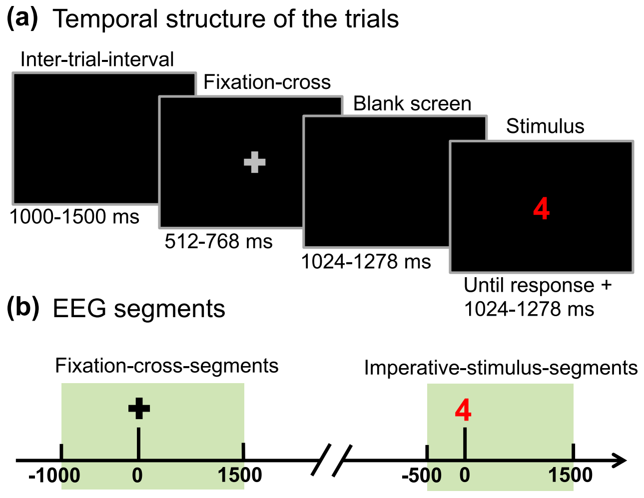

FIGURE 1 This figure depicts the temporal structure of the trials (a) as well as the position of the fixation-cross-locked and stimulus-locked segments used for the EEG analysis within the trials (b)

the left and right index fingers. In order to prevent the systematic variance due to anticipation, the temporal structure of the trials was jittered. Each trial started with the presentation of a fixation cross in grey (#787878, 0.6° visual angle) for 512 to 768 ms, followed by a blank screen for 1,024 to 1,278 ms. Subsequently, the imperative stimulus, that is, the colored digit, was presented until 1,024 to 1,278 ms after the participants' response. The following inter-trial interval was 1,000 to 1,500 ms long. The temporal structure of the trials is depicted in Figure 1. After a trial, there was a random chance that the participants were asked *"Where have your thoughts just been?"*. The participants were asked to respond with the left arrow button if they were focused on the task (the screen displayed "On the task." on the left side) and to answer with the right arrow button when they experienced mind wandering (the screen displayed "Not on the task." on the right side). The minimum lag between two thought probes was 5 trials and the maximum lag was 10 trials. As there were 640 trials in total and thoughts were probed every 7.5 trials on average, there were on average 85.33 mind wandering probes for each participant. Trials for which the participants reported mind wandering as well as the two preceding trials were defined as mind wandering trials, whereas other trials were defined as on-task trials.

2.3 | EEG recording

The EEG recording took place in a dimly lit and sound-attenuated cabin. A montage of 32 Ag/AgCl EEG electrodes was used, which were equidistantly distributed on the scalp (Equidistant Montage No. 7, Easycap GmbH, Herrsching, Germany). The ground electrode was placed at AFz and Cz was used as an online reference. The EEG data were sampled at 1,024 Hz using the BrainAmp amplifier (Brain Products, Munich, Germany). A 0.1 Hz hardware hi-pass filter was used and impedances were constantly kept below 5 kΩ.

2.4 | EEG preprocessing

Signal processing and analysis of EEG data was performed in Matlab 2018b (The MathWorks Inc., Natick, Massachusetts) using custom scripts incorporating functions of the EEGLab (Delorme & Makeig, 2004) and field trip (Oostenveld, Fries, Maris, & Schoffelen, 2011) toolboxes. The data were band-pass filtered at 1 to 30 Hz and corrupted channels were identified and removed based on kurtosis and probability criteria. On average 0.97 channels ($SD = 0.93$) were removed. Subsequently, data were re-referenced to common average reference, resampled at 200 Hz, and segmented into epochs ranging from −2,000 ms to 2,000 ms relative to the onset of a fixation cross or imperative stimuli. Fixation cross and imperative stimulus events were segmented separately due to the temporal jitter in the inter-stimulus interval as well as of the fixation cross-presentation time (see Figure 1a). After the automatic detection and removal of epochs containing artifacts, an independent component analysis was performed. Independent components (ICs) representing artifacts were identified and removed using ICLabel (Pion-Tonachini, Kreutz-Delgado, & Makeig, 2019) by retaining only ICs which were labeled in the *Brain* IC-category with a probability of at least 0.5. ICs were also visually inspected in order to check for remaining artifact ICs which were not detected by ICLabel. On average, 11.58 ICs ($SD = 3.54$) were excluded. Figure 2 depicts the distribution of the ranks of the rejected ICs in terms of the variance in the data the respective IC can be accounted for. Again, corrupt epochs were rejected automatically and all fixation cross and imperative stimulus segments without the respective counterpart were removed as well. On average, 235.88 ($SD = 17.70$) fixation-cross-locked and imperative-stimulus-locked segments entered the analysis of behavioral and electrophysiological data.

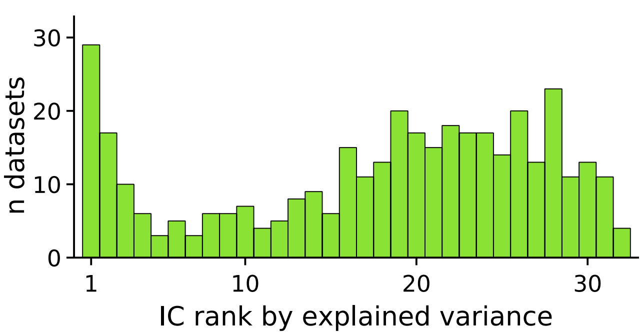

FIGURE 2 This figure depicts the distribution of the ranks of the rejected ICs across all data sets. The rank refers to the variance in the data the respective IC can be accounted for

2.5 | Time-frequency decomposition

A time-frequency decomposition of the data was performed by convolving the electrophysiological data with complex Morlet wavelets defined as complex sine waves tapered by a Gaussian. A set of 50 wavelets was used with frequencies ranging from 2 to 30 Hz in logarithmically spaced steps. The widths of the corresponding tapering Gaussians were defined in a way that the resulting wavelets had a temporal resolution ranging from 600 to 50 ms at full-width at half-maximum (FWHM; Cohen, 2018), which corresponds to a FWHM ranging from 1.25 to 17.25 Hz in the frequency domain. Power estimates were extracted squaring the absolute values of the complex convolution result. For the group-level analysis, data were subsequently decibel normalized in time-frequency space relative to a baseline ranging from −500 to −200 ms before the onset of a fixation-cross or an imperative stimulus. It is important to note that the baseline was calculated based on all trials. In contrast to applying a baseline normalization specifically for each condition, or even for each trial, variance related to the experimental condition thus remains present in the baseline period and may be observed there. When applying a baseline normalization of the data in a condition-specific manner, however, the systematic variance that may be present in the baseline period would be shifted to extra-baseline periods. An exemplary comparison of both baselining approaches is illustrated in Figure 6. In order to avoid temporal overlap (cf. Figure 1) and also to remove edge artifacts, fixation-cross segments were pruned to −1,000 to 1,500 ms and imperative stimulus segments were pruned to −500 to 1,500 ms to obtain the final ERSPs.

2.6 | Statistics

In order to test for the effect of trial type (repeat vs. switch) as well as of reported mind wandering (on-task vs. mind wandering), linear mixed models were fitted to the behavioral data on single-trial level. Response speed and response accuracy entered the respective model as dependent variables and the experimental factors trial type and reported mind wandering entered the model as fixed effects. A random intercept was modeled for each participant (dv ~ trial type * mind wandering + (1|subject)).

In order to test for significant effects in the electrophysiological measures in time × frequency × sensor space, cluster-based permutation tests were performed (Maris & Oostenveld, 2007). This approach has the advantage of controlling for Type I error rates, which is crucial for dealing with multiple comparisons in high-dimensional data. For each data point in time × frequency × sensor space, *t*-statistics were computed and a clustering algorithm identified clusters of neighboring data points associated with a

t value corresponding to $p < .01$. The test statistic for each identified cluster was computed as the summed t values of all data-points included. Type I error was controlled for by evaluating this test statistic under a H0 distribution of maximum cluster-level statistics determined in a randomization procedure with 1,000 iterations. In each of these iterations, the maximum cluster statistic was determined based on data with randomized factor level assignments. Subsequently, the actually observed test statistics were compared against this H0 distribution in a two-sided test. Clusters with $p < .05$ were regarded as significant. Overall, three cluster-based permutation tests were performed. In order to test for significant effects of the trial sequence, the assignment of the data to repeat and switch trials was permuted in the randomization procedure. For the test for the effects of mind wandering the randomization procedure utilized reported mind wandering. In order to test the interaction, the differences of repeat and switch trials were computed for each mind wandering level and the result entered the same procedure as the main effects. The tests for the effects of trial sequence and the interaction were only performed on segments locked to the imperative stimulus, since the fixation cross did not contain any information about the subsequent task. The test for the effects of mind wandering, however, was performed on fixation cross locked segments as well, as we assumed mind wandering to occur during the inter-trial-interval as well. All effect sizes were estimated as bias-corrected partial η^2 (Mordkoff, 2019; subsequently referred to as η^2) and classified as small, medium or large according to conventions of Cohen (1992).

3 | RESULTS

3.1 | Behavior

The behavioral data are depicted in Figure 3 and the corresponding test statistics are listed in Table 1. The statistical analysis revealed that the participants responded significantly faster in repeat trials as compared to switch trials (M = 839.55 ms, SD = 118.32 vs. M = 906.11 ms, SD = 127.45). No significant main effect was observed for the factor mind wandering (M = 878.59 ms, SD = 126.9 for trials without mind wandering and M = 866.01 ms, SD = 116.71 for trials with mind wandering) and also no interaction between the factors mind wandering and trial type. Response accuracy was not significantly affected by trial type (M = 96.6%, SD = 2.68 in repeat trials vs. M = 95.77%, SD = 3.05 in switch trials), but was significantly higher in trials in which participants did not report mind wandering than in trials in which participants reported mind wandering

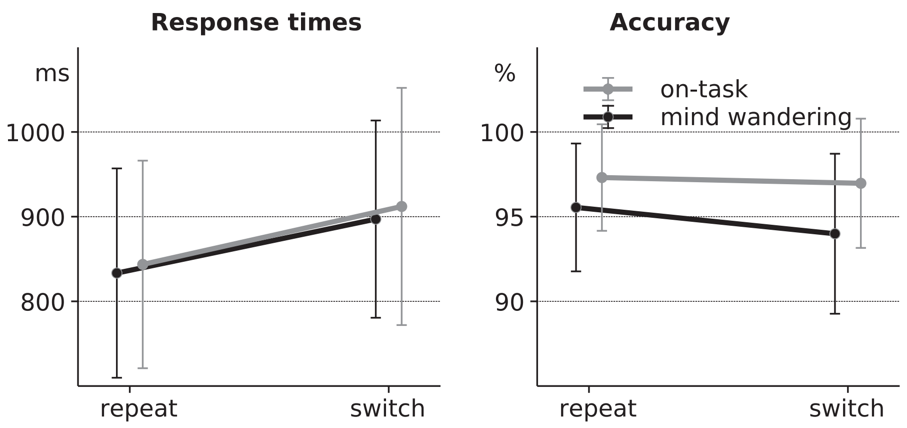

FIGURE 3 This figure depicts the behavioral measures response time (left panel) and accuracy (right panel). The error bars are representing the standard deviations

TABLE 1 For response time and accuracy, this table shows t-statistics (t) with the corresponding effect sizes (η^2), regression coefficients (β) and the 95% confidence interval (CI) for the fixed effects mind wandering (MW), trial sequence (SEQ, that is, switch vs. repeat trials), and their interaction

	Response time			Accuracy		
	$t(\eta^2)$	β	95% CI	$t(\eta^2)$	β	95% CI
MW	−1.69 (0.05)	−14.54	−31.4, 5.91	−2.75* (0.17)	−0.018	−0.03, −0.005
SEQ	−9.31** (0.72)	69.61	54.96, 84.27	−0.6 (−0.02)	−0.003	−0.014, 0.005
MW × SEQ	−0.48 (−0.02)	−5.72	−29.06, 17.61	−1.36 (0.02)	−0.009	−0.03, 0.005

Note: Test statistics corresponding to $p < .05$, or $p < .001$ are marked with one and two asterisks, respectively.

(M = 97.14%, SD = 3.36 vs. M = 94.74%, SD = 3.17). The interaction was not significant.

3.2 | Time-frequency-decomposition of EEG data

The cluster-based permutation test in time × frequency × sensor space for significant differences in trials with mind wandering versus trials without mind wandering revealed 4 significant clusters, illustrated in Figure 4 All of these 4 clusters had negative sums on t values, indicating a significantly greater spectral power relative to the baseline in mind wandering trials as compared to on-task trials. Cluster 1 is located in the alpha and theta band. It comprises the inter-trial-interval and lasts until approximately 700 ms after the fixation cross onset. The effect size is largest in the alpha band during the inter-trial-interval (see Figure 4c). In sensor space, Cluster 1 is significant at all recording sites and exhibits the largest effect sizes at lateralized central and parietal electrodes. Cluster 2 and Cluster 3 are located in the alpha and theta band as well. These clusters comprise the time from approximately 1,000 ms after the onset of the fixation cross (Cluster 2 in the segments locked to the fixation cross) until the onset of the imperative stimulus (Cluster 3 in the segments locked to the imperative stimulus). Cluster 2 and Cluster 3 show the largest effect sizes in the theta band and at posterior leads, although the effect is significant at a large number of electrodes (see Figure 4d). Cluster 4 is located in the alpha, theta, and delta band. It starts approximately 500 ms after the onset of the imperative stimulus and ranges into the inter-trial-interval. Like Cluster 1, it is significant at all recording sites and shows the largest effect sizes in the alpha band (see Figure 4c) and at central and parietal electrodes (see Figure 4d).

The cluster-based permutation test for the effects of trial type revealed one significant cluster illustrated in Figure 5. This cluster, Cluster 5, is positive, thus indicating a greater spectral power relative to the baseline in repeat trials compared to switch trials. Cluster 5 is situated in the alpha and lower beta range and significant at a large number of electrodes (see Figure 5d). The largest effect sizes of Cluster 5 are in the alpha range (see Figure 5c) at the frontal and posterior recording sites (see Figure 5d). The cluster-based permutation test for the interaction of the factors trial sequence and mind wandering revealed no significant results.

4 | DISCUSSION

In the present study, we investigated electrophysiological correlates of mind wandering during a switching task. To this end, we compared mind wandering episodes to on-task episodes in time × frequency × sensor space of the EEG. Details of the experimental design, signal processing parameters, and statistical methods were chosen with respect to avoiding as much a priori assumptions as possible. The behavioral data clearly indicate the validity of the task-switching paradigm and the probe-caught method to assess mind-wandering. Participants responded significantly slower to the imperative stimulus in switch as compared to repeat trials, which was a very large effect (η^2 = 0.73). In contrast, no differences between the two trial types could be observed in terms of accuracy. The opposite pattern emerged from the comparison of mind wandering to on-task episodes. Accuracy was significantly reduced in mind wandering trials, which was a medium to large effect (η^2 = 0.19), but no effect was visible in response times. Not finding an effect of mind wandering on response times might appear counter-intuitive at first glance. Recent research found mixed results as some studies found mind wandering to negatively affect response times (e.g., Leszczynski et al., 2017) whereas others did not (e.g., Thomson, Seli, Besner, & Smilek, 2014). Specific task properties might determine whether mind wandering results in increased response times or not. In the present study, cues were presented to indicate upcoming stimuli. These cues might have led to preparatory processes offsetting potentially detrimental effects of mind wandering on task performance.

The largest effect of mind wandering in the EEG data, with respect to its extension in time × frequency × sensor space as well as with respect to the associated statistical effect sizes, was an increased alpha power in the inter trial interval in mind wandering episodes (Cluster 1 and 4, depicted in Figure 4. This effect was significant at all electrodes and largest over the central and parietal cortex, where it gains large effect sizes (up to η^2 = 0.21). This finding is consistent with previous research on electrophysiological correlates of mind wandering that used the probe-caught method to assess mind wandering. A significantly increased alpha power prior to probe-caught reports of mind wandering was observed by Baldwin and colleagues (2017) during simulated driving and a vigilance task. Baird et al. (2014) found a spatially distributed effect of mind wandering in terms of a larger decrease of alpha power in response to a stimulus in mind wandering episodes during a vigilance task. Since they applied a condition-specific baseline in order to calculate the ERSPs, it might be the case that this effect actually reflects a larger alpha power in the baseline period, that is, the inter-trial interval. A condition-specific baseline forces the baseline spectral power to a mean of zero and power differences in the baseline between the conditions would then be reflected by larger relative values in non-baseline episodes. Figure 6 illustrates the effect of applying a condition-specific versus a condition-general baseline, exemplarily for a single electrode. It becomes evident that a condition-general baseline

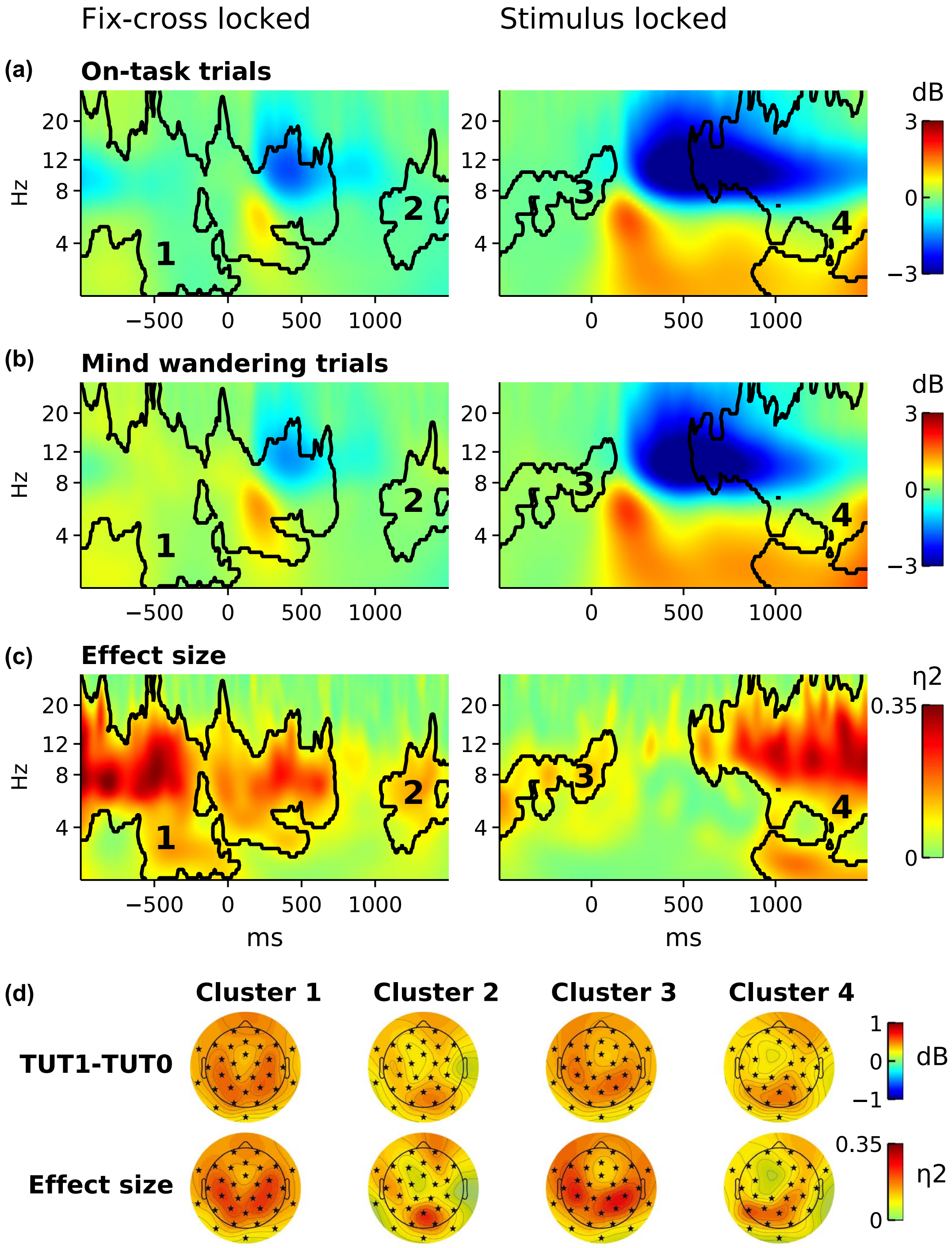

FIGURE 4 The figure illustrates the four significant clusters for the effects of mind wandering. The ERSPs averaged across all channels for on-task trials are depicted at (a) and for mind wandering trials at (b). Panel (c) illustrates the corresponding effect sizes. The left column of (a), (b), and (c) represent EEG segments locked to the fixation cross, the right side the segments locked to the imperative stimulus. The black contour lines indicate significant clusters and the black numbers represent the cluster number. Panel (d) depicts the topographies for the clusters with the power difference between mind wandering and on-task trials illustrated in the upper row and the corresponding effect sizes illustrated in the lower row. The black asterisks indicate channels with significant effects of the respective cluster

is superior in maintaining the temporal structure of spectral power modulations of the raw data, as compared to the condition-specific baseline.

An increased alpha power in non-stimulus locked segments of the EEG is a well-known phenomenon in the research on mental fatigue (Arnau, Möckel, Rinkenauer, &

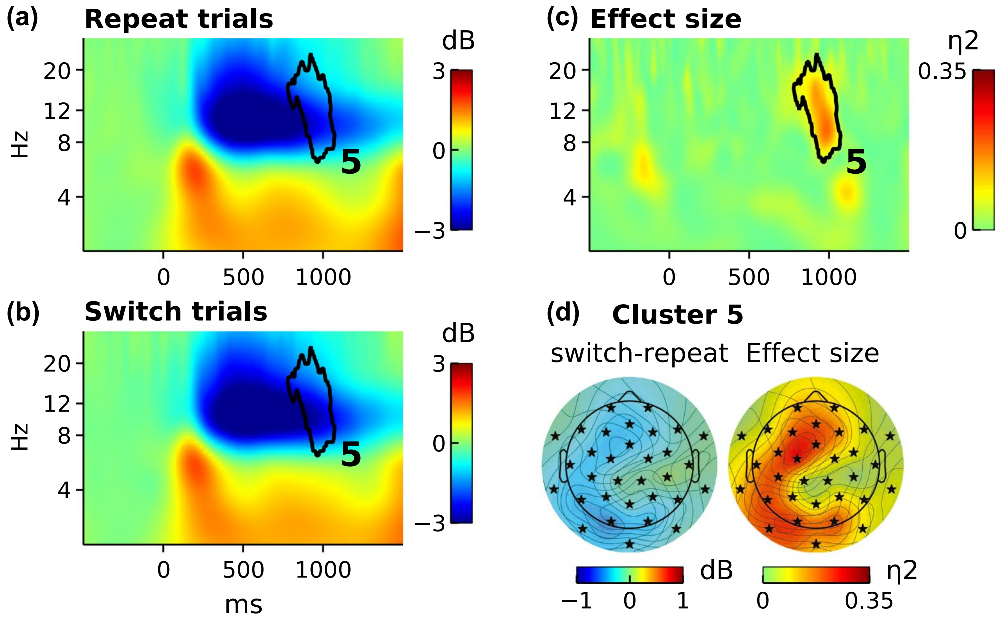

FIGURE 5 This figure illustrates the significant cluster for the effects of trial sequence. The ERSPs averaged across all channels for repeat trials are depicted at (a) and for switch trials at (b). (c) illustrates the effect sizes. The black contour lines indicate significant clusters and the black number 5 represents the cluster number. Panel d depicts the topographies for Cluster 5, the power difference between repeat and switch trials is illustrated at the left side and the corresponding effect sizes are illustrated at the right side. The black asterisks indicate channels with significant effects of Cluster 5

Wascher, 2017; Fan, Zhou, Liu, & Xie, 2015; Getzmann, Arnau, Karthaus, Reiser, & Wascher, 2018). In the context of prolonged cognitive performance, alpha power was found to increase not just as a function of time on task (Arnau et al., 2017; Fan et al., 2015; Getzmann et al., 2018), but also as a function of task load (Getzmann et al., 2018; Wascher, Arnau, Gutberlet, Karthaus, & Getzmann, 2018). These findings mirror recent research on mind wandering frequency, which was also found to be increased when a task is well learned and little demanding (Baird et al., 2012; Cunningham et al., 2000; Giambra, 1995; Smallwood, Nind, & O'Connor, 2009). It has been discussed that mind wandering might play a crucial role in the time-on-task-related decline in performance in experiments on mental fatigue (Pattyn, Neyt, Henderickx, & Soetens, 2008). Additionally, a higher alpha power in posterior brain areas has been linked to an internally oriented cognitive state (Hanslmayr et al., 2011). Taken together, the increased alpha power in the inter-trial interval observed in the present study can be interpreted as a correlate of a redirection of attentional resources away from sensory input toward internal processing, that is, experienced as mind wandering. As a side note, this notion would also support the idea of mind wandering being at least partially causal to the performance decrement observed in mentally fatigued individuals. In the present study, the likelihood for mind wandering increased with time on task (see Figure 7). During the final stage of the task, however, mind wandering likelihood decreased again, probably due to anticipating the end of the experiment.

The observation of an increased alpha power in mind wandering episodes in the inter-trial interval is not in line with findings of studies on mind wandering using the self-caught assessment method, which found lower alpha power in episodes prior to the button press indicating self-detected mind wandering (e.g., Braboszcz & Delorme, 2011; van Son et al., 2019). It might be the case that these episodes identified via the self-caught assessment of mind wandering rather reflect metacognitive awareness (Smallwood & Schooler, 2006). As a consequence, the spectral properties of these episodes might differ from those of mind-wandering episodes as well. It is also worth mentioning that we did not differentiate between intentional and unintentional mind wandering in our thought assessment. However, previous studies have shown that most mind wandering occurs unintentionally as long as the ongoing task is not particularly easy (Seli, Konishi, Risko, & Smilek, 2018). Given that the ongoing task we used in this study can be considered a fairly demanding task, we would expect that the present pattern of results is most indicative of unintentional mind wandering. Future research should investigate whether intentional mind wandering and unintentional mind wandering differ in their neurocognitive underpinnings.

A further effect of mind wandering in time × frequency × sensor space of the EEG observed in the data is an increase of power in the lower alpha and theta range during the inter-stimulus-interval between the offset of the fixation cross and the onset of the imperative stimulus (Cluster 2 and 3). An increased theta power in response to an informative stimulus has been linked to the allocation of attentional

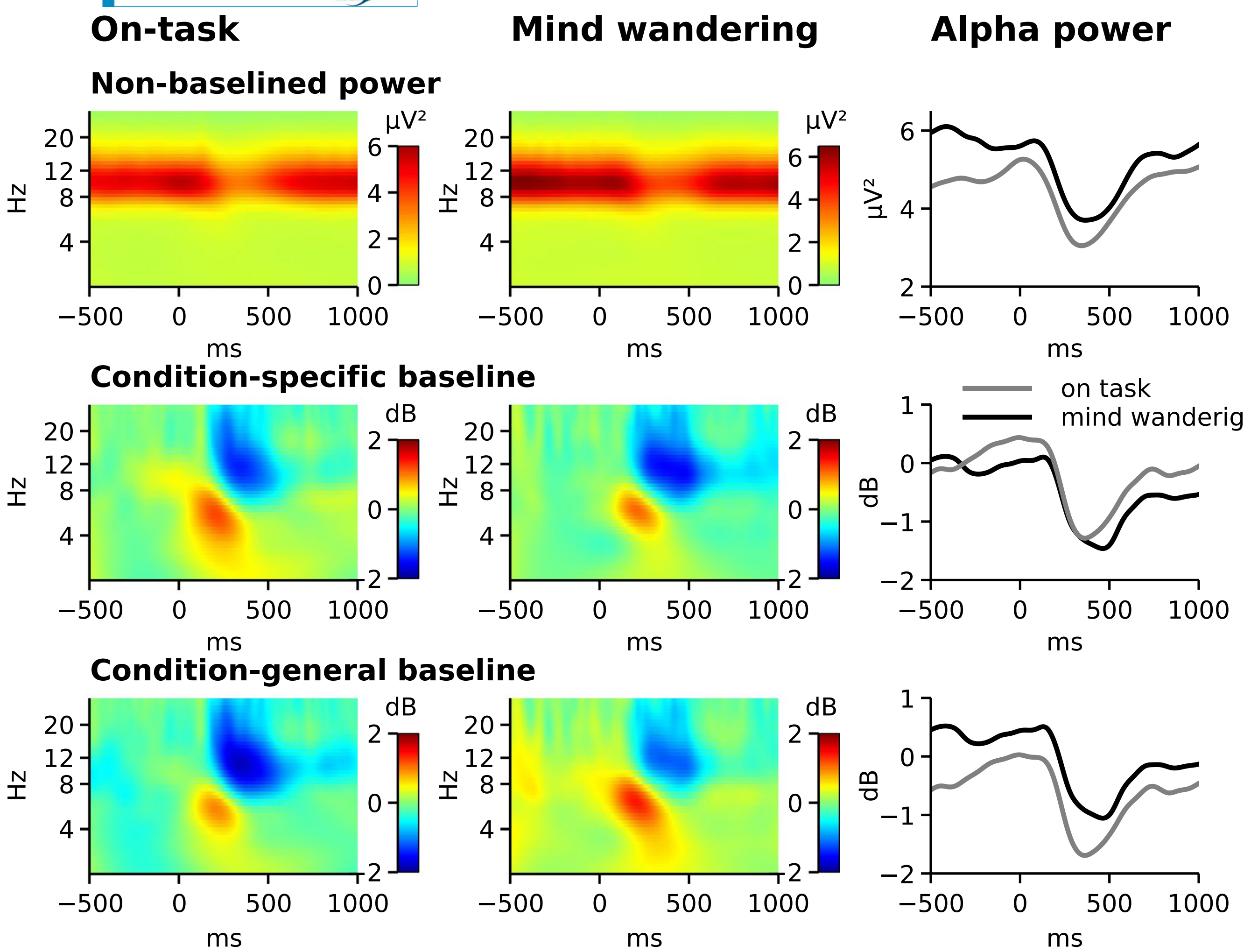

FIGURE 6 This figure illustrates a comparison of baselining approaches. The data used for this comparison is the fixation-cross locked data from this study of the right parietal channel 10. Effect sizes were largest for this recording site for cluster 1. The left column depicts the ERSP of on-task trials, the center column the ERSP of mind wandering trials, and the right column the alpha power over time for both trial types. The upper row shows the data without a baseline being applied, the middle row shows the data using a condition-specific baseline, and the lower row using a condition general baseline

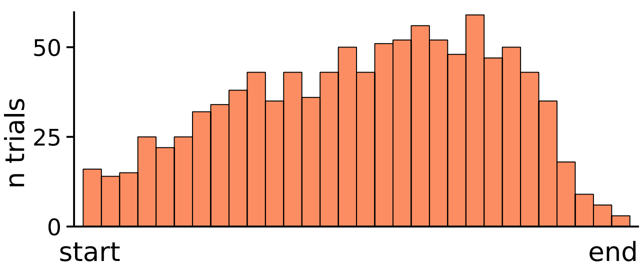

FIGURE 7 This figure depicts the distribution of reported mind wandering cumulated across all participants of the study over the course of the experiment

resources (Cavanagh & Frank, 2014; Cavanagh et al., 2012). The fixation cross can certainly be interpreted as an informative stimulus that even bears the potential of disrupting mind wandering. The observed effect thus might be interpreted as a compensatory recruitment of additional resources when getting aware of mind wandering. However, theta responses as a correlate of cognitive control are usually located over the frontal cortex (e.g., Onton, Delorme, & Makeig, 2005). Since the spatial distribution of the present finding is rather indistinct, the interpretation of an increased theta as a counteractive measure to compensate mind wandering remains speculative.

Mind wandering did not seem to affect task processing per se, as no significant difference between mind wandering and on-task episodes in oscillatory dynamics in response to the imperative stimulus could be observed. Other studies (e.g., Barron, Riby, Greer, & Smallwood, 2011; Kam & Handy, 2013) found that mind wandering affected task processing as reflected by changes in the ERP. Barron et al. (2011), however, did not use a fixation cross, which may explain why they observed the effects of mind wandering in the post imperative stimulus period that we observed in the pre-imperative stimulus period. Furthermore, there were no significant interaction effects between the factors mind wandering and trial type, that is, switch versus repeat trials. This is in so far in line with previous research, as Barron and coworkers (2011) observed not only reduced P3b amplitudes to target stimuli, but also reduced P3a amplitudes in response to standard stimuli when mind wandering. They concluded that mind wandering goes along with a general suppression of external stimuli rather than being a state of suppressed central executive functioning or a state of distraction.

The choice of methods in this study to assess the representation of mind wandering in the EEG has also some inherent disadvantages. This becomes obvious when considering that no effects in the theta range at frontal areas were significant for the comparison of switch versus repeat trials, although this is a common finding for this kind of task (e.g., Cunillera et al., 2012). This comparison has not been discussed here, but it shows that it might be hard to detect smaller, in the sense of spatially less distributed, effects with a cluster-based approach that comprises all channels. It thus might be the case that a more hypothesis-driven approach focusing on frontal electrodes would have been more appropriate for the purpose of detecting mind-wandering-related differences in executive functioning. Another possible limitation of this study is that we included only those participants that reported mind wandering on at least 30 occasions, which may have led to a selection bias reducing the external validity of the study. Both, the excluded and included subsamples, however, did not differ significantly from each other in terms of the demographic variables sex and age.

Overall, the findings of the present study clearly show that an increase of spectral power in the alpha band constitutes an electrophysiological correlate of mind wandering. In combination with recent findings of a non-stimulus-locked increase of alpha power in the context of mental fatigue, this might be interpreted as further evidence for the association of a spatially distributed increase in alpha power and a bias of attentional resources toward internal processing (cf. Hanslmayr et al., 2011). The alpha effect was located primarily in the inter-trial-interval. On the one hand, this has methodological implications as future research on mind wandering should account for this by choosing appropriate parameters for analysis. A baseline normalization procedure, for example, should allow for observing mind-wandering-related variance in the baseline period.

There are also theoretical implications of the alpha effect being present specifically in the inter-trial-interval. The fact that mind wandering does not occur randomly, but instead when it is unlikely to be detrimental to performance, might indicate that it is adaptive behavior (cf. Mooneyham & Schooler, 2013). Recent studies identified planning (Baumeister & Masicampo, 2010; D'Argembeau, Renaud, & Linden, 2011; Smallwood et al., 2009) and the fulfillment of intentions (Rummel, Smeekens, & Kane, 2017; Seli, Smilek, Ralph, & Schacter, 2018; Steindorf & Rummel, 2017) as potentially adaptive functionalities of mind wandering. According to a recent framework of Kurzban, Duckworth, Kable, and Myers (2013), the human cognitive resource management system will reallocate cognitive resources that are not absolutely necessary for adequate performance in a given task to another task in order to maximize the combined utility. Many tasks, however, simply cannot be engaged in simultaneously. In this context, mind wandering might be conceptualized as a collective term for all the tasks an individual is able to engage in while performing another task, which could explain its high prevalence (Kane et al., 2017; Killingsworth & Gilbert, 2010). The downside of such an optimization strategy is that unexpected and critical situations may lead to primary task failure (e.g., Galéra et al., 2012; Qu et al., 2015).

Finally, the identification of alpha power as a correlate of mind wandering may also have practical implications. It should be evaluated whether the online detection of alpha-power-increases in working environments prone to mind wandering is feasible in order to detect mind wandering and prevent performance failures.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The EEG data analyzed in the present study, the scripts used for analysis, a marker coding table, a table containing basic demographic data of the participants, as well as an illustration of the electrode setup is published as the OSF repository:

Arnau, S., Löffler, C., Rummel, J., Hagemann, D., Wascher, E., & Schubert, A.-L. (2020, February 12). Inter-Trial Alpha Power Indicates Mind Wandering. https://doi.org/10.17605/OSF.IO/SRDPU

The Matlab code used for the analysis can also be found at the GitHub repository:

https://github.com/fischmechanik/mind-wandering-EEG

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