Measuring Mind Wandering during Online Lectures Assessed with EEG

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1 Abstract

Mind wandering can inhibit learning in multimedia classrooms, such as when watching online lectures. One explanation for this effect is that periods of mind wandering cause learners' attention to be redirected from the learning material towards task-unrelated thoughts. The present study explored the relationship between mind wandering and online education using electroencephalography (EEG). Participants were asked to attend to a 75 min educational video lecture, while task-irrelevant auditory tones played at random intervals. The tones were of two distinct pitches, with one occurring frequently (80%) and the other infrequently (20%). Participants were prompted at pseudo-random intervals during the lecture to report their degree of experienced mind wandering. EEG spectral power and event-related potentials (ERP) were compared between states of high and low degrees of self-reported mind wandering. Participants also performed pre/post quizzes based on the lecture material. Results revealed significantly higher delta, theta and alpha band activity during mind wandering, as well as a decreased P2 ERP amplitude. Further, learning scores (improvement on quizzes pre to post) were lower among participants who reported higher degrees of mind wandering throughout the video. The results are consistent with a view that mind wandering during e-learning is characterized by a shift in attention away from the external world and towards internal thoughts, which may be a cause of reduced learning.

2 Introduction

In 2020 higher learning institutions across the world quickly transitioned their teaching to an online format, in response to social distancing requirements enacted to limit the spread of COVID-19. Though in the early days of the outbreak many instructors adopted synchronous online lecture course formats, there were soon calls in the higher education community to adopt asynchronous activities, as awareness was raised about the limitations of synchronous online lectures (Flaherty, 2020). Many universities and colleges have since adopted pre-recorded asynchronous lectures, which are often viewed as a more accessible alternative (Flaherty, 2020). However, there is evidence to support that online lectures, particularly when they are pre-recorded, do not benefit students similarly to their in-person equivalent (Williams, Birch & Hancock, 2012) potentially because they do not facilitate student engagement (O'Callaghan et al., 2017).

One of the ways that pre-recorded online lectures may fail to replicate in-person experiences is that students' minds are more likely to wander (Szpunar, Moulton & Schacter, 2013). Mind wandering is a phenomenon characterized by a shift in attention away from a primary task, towards unrelated self-generated thoughts (Smallwood & Schooler, 2006; 2015). It has been found to impact performance on monotonous tasks, such as driving long distances (Y. Zhang & Kumada, 2017; Baldwin et al., 2017) or learning from long texts or long lectures (Wammes and Smilek, 2017; Forrin et al., 2020). It follows that students who experience mind wandering learn less, as their attention is directed away from the material they are supposed to learn. Some scholars have concluded that teaching practices should therefore be developed to prevent mind wandering (Smallwood & Schooler 2015). Online lectures might similarly benefit by incorporating design principles that limit mind wandering and/or provide corrective feedback when it occurs.

However, it is difficult to identify which pre-recorded or online lecture designs inhibit mind wandering because of the difficulty of measuring the mind wandering phenomenon in the first place. Although ex post questionnaires (i.e., administered after a learning video) can effectively measure the amount of subjective mind wandering across a period of time (Mrazek et al., 2013), they are unlikely to offer insights into when individual mind wandering episodes may occur during that period. Experience sampling is an alternative approach, in which people are prompted to respond to questions about their state of mind wandering at intervals throughout a task. However, this disrupts both mind wandering and the target task that the mind wandering occurs during (Schooler, 2004; Wammes & Smilek, 2017). It is desirable to identify an alternative approach which does not disrupt mind wandering or task performance, while also giving insights into the cognitive mechanisms behind the phenomenon. One potential approach is using electroencephalography (EEG), which monitors brain activity during an activity, in real time, without disrupting the activity as experience sampling does.

Although we are not aware of any EEG studies of mind wandering while watching recorded instructional lectures, this phenomenon can be incorporated into existing models of executive attention and control, and the neuroimaging techniques for measuring them (Smallwood & Schooler, 2006). Past research on the presence of mind wandering during meditation tasks have suggested that the regulation of attention is linked to heightened activity in the prefrontal cortex and anterior cingulate cortex (Hasenkamp et al., 2012; Xu et al., 2014). We can posit that there may be a similar link in the online lecture context and that it is measurable.

EEG studies have similarly found associations between mind wandering and attentional disengagement with stimulus processing. Braboszcz and Delorme (2011) identified two varieties of EEG measures which were associated with mind wandering. First, they investigated spectral frequency (oscillatory) effects in their EEG data, and noted increased frontal delta and theta, as well as decreased occipital alpha power during mind wandering. Second, they observed an increased-amplitude of the attention-related P2 event-related potential (ERP) component response to auditory stimuli during reported states of mind wandering in a meditation task. These findings have been corroborated by further work which found theta power to be a reliable measure of mind wandering generally (van Son et al., 2019) as well as increased P2 amplitude (Xu et al. 2018). Given this evidence, it may be possible to measure oscillatory and ERP correlates of mind wandering during an e-learning task, such as when learning from online lectures.

In this study, we sought to identify EEG markers of mind wandering during an online lecture task which required sustained attention. We designed an experiment which administered frequent and infrequent auditory stimuli (and “oddball” paradigm) which participants were instructed to ignore (Squires et al., 1975; Braboszcz & Delorme, 2011). Participants also underwent experience sampling and were prompted to report their degree of mind wandering at pseudo-random intervals throughout the lecture (Wammes & Smilek, 2017). Following Braboszcz and Delorme (2011), we compared EEG responses to auditory tones in the 10 s period immediately preceding periods of heightened mind wandering, to those preceding on-task thought. Participants were also given quizzes on the lecture content both before and after the lecture, and an ex post self-report questionnaire. Based on the work of Sullivan et al. (2015) and the NASA Task Load Index (NASA TLX 1989), the questionnaire measures were administered to identify whether there was an effect of task load or whether the reported mind wandering was related to the information technology artifact.

As noted, Braboszcz and Delorme (2011) observed a heightened P2 response to both standard and oddball during periods of mind wandering, which was possibly the result of increased sensitivity to outside stimuli. They also observed heightened oscillatory activity at the delta and theta bands, as well as reduced activity at the alpha band in the occipital region during periods of mind wandering. We hypothesized that these markers would be similarly present in a sustained e-learning task. We also predicted that self-reported mind wandering would be negatively correlated with online lecture learning outcomes. Such results would provide evidence that mind wandering is related to changes in attention, that these changes have an impact on learning during online lectures. It would also suggest markers of mind wandering which could be used to evaluate online lecture design in the future.

3 Methods

3.1 Participants

Fifty-two students (36 women and 16 men, aged 17-28 years; M = 20.6, SD = 2.5) gave written consent to participate in the experiment. Five participants’ data from the EEG analyses are not reported here due to technical errors with the recording, leaving a sample size of 48 individuals. Participants were excluded from the study if they were not fluent in English, were taking medication that could lead to abnormal EEG, or identified as having neurological disorders. Participants were also excluded if they had taken a course in venture capital, the subject of the learning video. Participants provided written and informed consent and were financially compensated CAD $25 for their time. All procedures were reviewed by the Dalhousie University research ethics board, according to the Canadian Tri-Council Policy Statement and the Declaration of Helsinki.

3.2 Stimuli

The teaching video was a 75-minute English language video about venture capital (Fu, 2017). The subject matter and video were chosen because it was on a subject not commonly taught to our subject population (who comprised mainly psychology and neuroscience students, and who were screened to have no knowledge of the topic). The video consisted exclusively of two lecturers talking, and questions from the lecture hall audience. Pilot testing suggested that this video would trigger variations in mind wandering and attention for most participants.

The auditory stimuli were tones of 100 ms duration; standard (frequently presented) tones were 500 Hz and oddball (infrequent) tones were 1000 Hz.

The quiz consisted of 10 multiple-choice questions on content from the video. The quiz was administered before and after the video. The pre study and post study quiz was developed by the research team based on the video lecture content. The ex post questionnaire consisted 25 items including degree of task load (NASA TLX, 1988), the degree of experienced mind wandering related to technology (Sullivan et al., 2015), and sources of experienced mind wandering unrelated to technology (Sullivan et al., 2015). Additional items to measure interest in the course material and perception of attention throughout the video were also added.

3.3 Procedure

After providing informed consent, participants were fitted with the EEG cap and were brought to the testing room. Participants completed the pre-study quiz and then were instructed to pay attention to the video and ignore the audio tones. Once EEG recording commenced, the video was started, and tones were played such that they were distinguishable over the lecture audio track. Tones were presented at intervals chosen randomly from a uniform distribution (1.0–1.5 s; mean 1.25 s), the order of standard and oddball tones was randomized, constrained such that 80% of the tones were standards and 20% oddballs. Ten mind wandering prompts were presented at pre-determined intervals throughout the video with the intervals between prompts being selected from a uniform random distribution ranging from 1–16 min. At each prompt, participants were asked to report their degree of mind wandering or on-task experience from the time period immediately before the mind wandering prompt (Wammes & Smilek, 2017). The options were structured in a 5-point Likert-like scale ranging from “completely on task” to “completely mind wandering”. Stimulus presentation was controlled by a personal computer running the Windows 8 operating system. The video was played using Windows Media Player, while presentation of auditory tones, and collection of manual responses, was controlled by code written in the PsychoPy library (version 1.81; Pierce, 2007). Videos were presented on a ViewSonic VS 16265 video monitor located 32 cm from the participant’s face and audio was delivered through Mackie MR5 MKIII speakers connected through a Mackie ProFX8 mixing board. Following the study, the ex post questionnaire was administered, followed by the post-study quiz.

3.4 EEG Recording

Participants were fitted with 32 scalp electrodes (ActiCap, BrainProducts GmbH, Munich, Germany) positioned at standard locations in a soft cap according to the International 10-10 system and referenced during recording to the average of all electrodes. Bipolar recordings were made between the outer canthi of the two eyes and above and below one eye, to monitor for eye movements and blinks. Electrode impedances were kept below 30 kOhm throughout the experiment. Electroencephalography data were sampled at 512 Hz using Refa8 amplifier (Advanced NeuroTechnologies, Enschende, The Netherlands), bandpass filtered between 0.01 and 170 Hz, and saved digitally using the ASAlab software (Advanced NeuroTechnologies). The identity of each audio tone (standard/oddball) was communicated to the EEG amplifier via TTL codes sent from PsychoPy via the parallel port (Peirce, 2007). To precisely synchronize the onset timing of each auditory tone with the EEG system, a custom-built, Arduino-based device (Baker, 2013) was used which took its input from the audio output of the mixing board that also fed the speakers, and sent a TTL pulse to the EEG system every time a voltage deflection (sound onset) was detected.

3.5 Artifact Correction and Data Processing

The MNE-Python library (Gramfort et al., 2013; 2014) was used for all data preprocessing. The onset of each audio event was defined by the timing of the signals from the Arduino device, with the identity of the tone type (standard/oddball) defined by the event code sent immediately prior to sound onset. For ERP analysis, a 0.1 to 40 Hz bandpass filter was applied to the data, followed by manual identification and removal of electrodes and epochs with excessive noise. The data were then segmented into epochs spanning 200 ms prior to the onset of each auditory tone, to 1 s after. Independent components analysis was then used to identify and remove artifacts such as eye blinks and eye movements (Delorme et al., 2004) using the FastICA algorithm (Hyvarinen, 1999). Following ICA artifact correction, data were re-referenced to the average of the two mastoid electrodes (TP9 and TP10). EEG data were analyzed for stimuli occurring from 0–10 s before a mind wandering prompt, and labeled based on user responses to the prompts (i.e., a 5-point Likert scale). For ERPs, epochs were analyzed in the time domain by calculating the average amplitude during the component time windows (see below). Oscillatory analyses were performed by transforming the time-locked epoch data into the frequency domain using Morlet wavelets with 100 log-spaced frequencies ranging from 2 to 30 Hz with 1 cycle at the lowest frequency increasing linearly to a maximum of 15 cycles at the highest frequency. We also used Welch's (1967) method to compare mean power spectrum density (PSD) from the whole 1 s epoch from the delta (2-4 Hz), theta (4-7 Hz), alpha (8-12 Hz) and beta (13-30 Hz) frequency bands.

3.6 Statistical Analysis

Given that there were exactly 10 mind-wandering prompts for each participant, there was no variability in the number of responses, though there was variability in the degree of mind wandering reported. Data from 4 participants were excluded due to technical issues in their recording. This resulted in a total of 5525 epochs between the 10 conditions (2 tone types × 5 levels of mind wandering).

We predicted the effect of the P2 component and chose the time windows of 225–275 ms, based on a prior study with a similar paradigm (Conrad & Newman, 2019). After assessing the grand average waveforms from the present study, however, we realized that the timings from the prior study did not generalize. We thus selected new time intervals for statistical analysis, based on visual inspection of the present dataset. We also observed visual differences in the N1 component immediately preceding the P2, which might have reflected mind wandering. Dependent measures for ERP analysis were mean amplitudes over the 75–125 ms (for the N1) and 150–200 ms (for the P2) intervals, over a frontal region of interest (including electrodes Fz, F3, F4, FC3, FC4, Cz, C3, and C4).

For oscillatory analysis, the dependent measures were the power in each of the frequency bands of interest centered on two regions; a frontal region (including electrodes Fz, Fp1, Fp2, F3, F4) and an occipital region (including electrodes POz, Oz, O1 and O2).

All statistical analysis was performed using linear mixed effects (LME) using the R language (version 3.6.1) the mgcv library (Wood, 2020). The model's fixed effects included reported mental state (5-point scale) and stimulus type (standard, oddball); random effects included by-subject slopes for mental state and stimulus type, as well as random intercepts for each subject. Random effects of electrode location were included in the PSD comparisons. Analyses of self-report measures were conducted using linear regression. All results were interpreted for significance using the Bonferroni-Holm correction to account for multiple comparisons.

4 Results

We collected 480 responses to experience sample probes from the 48 participants whose data is included in the study of which 112 corresponded to "completely on task" (Level 1 on a Likert scale), 149 to "somewhat on task" (Level 2 on a Likert scale), 110 to "neither mind wandering nor on task" (Level 3 on a Likert scale), 81 to "somewhat mind wandering" (Level 4 on a Likert scale), and 28 to "completely mind wandering" (Level 5 on a Likert scale). In line with Wammes and Smilek (2017), we observed increased degrees of mind wandering as the lecture progressed, noticing a pronounced difference between samples collected at the 15-minute and 30-minute marks and a significant linear relationship between degree of reported mind wandering and elapsed lecture time ($t = 7.541$; $p < 0.001$). Multivariate linear regression of the ex post scales and experience sampling questions revealed a significant positive correlation between ex post reported mind wandering and the experience sample average scores ($F\ (1, 46) = 10.59$; $p = 0.0021$; $R^2 = 0.169$). We also observed a significant effect of gender on ex post reported mind wandering ($F\ (1, 46) = 12.09$; $p = 0.001$; $R^2 = 0.191$).

Participants' scores on the quiz assessing their knowledge of the lecture content were significantly higher after watching the video ($M = 4.82$; $SE = 2.18$) than before ($M = 2.86$; $SE = 1.27$; $t = 5.13$, $p < 0.001$), which suggests that participants attended to, and learned from the video. However, in both the pre- and post-lecture quizzes, participants correctly answered fewer than 50% of the 10 questions asked. Linear regression analysis of the improvement of quiz scores revealed a significant negative relationship between the average of the ex post mind wandering measures and quiz score improvement ($F\ (1, 46) = 5.047$; $p = 0.0295$; $R^2 = 0.079$).

The grand average waveforms are illustrated in Figure 1, for a cluster of electrodes over the anterior-central midline. We observed ERP components corresponding to the P1-N1-P2 complex, which varied in amplitude between conditions. These included a positive component peaking around 50 ms, a negative component peaking around 100 ms, and then a positive component peaking around 175 ms.

Results of the LME comparisons of event-related potentials are provided in Figure 2. Analysis revealed a significantly lower amplitude generated by standard stimuli ($\beta = -0.953$; $\mathrm{t} = -2.88$; $p = 0.0041$) during states reported at level 4 on the scale compared to those at level 1 during the 150-200 ms window corresponding to the P2 component. We also observed significantly lower amplitude generated by oddball stimuli ($\beta = -1.135$; $\mathrm{t} = -2.71$; $p = 0.0067$) during states reported at level 3 compared to those reported at level 1. Significantly greater negative amplitude was also observed among oddball stimuli at the 75-125 ms window, corresponding to the N1 component.

Power spectral density is represented as topographic maps and value by frequency in Figure 3. Results from LME analysis on oscillatory activity are summarized in Figure 4. As can be seen in this figure, power in all three frequency bands analyzed increased steadily as self-reported level of mind wandering increased. Analysis of band power over the 1 s windows revealed increased delta power in the frontal region during states reported at level 5 relative to those reported at level 1 ($\beta = 0.938$ $\mathrm{t} = 3.24$; $p = 0.001$). We similarly observed significantly greater frontal theta band power during states reported at both level 4 ($\beta = 0.543$; $\mathrm{t} = 2.52$; $p = 0.011$) and level 5 ($\beta = 1.035$; $\mathrm{t} = 3.52$; $p < 0.001$) when compared to level 1. Significantly greater occipital alpha band power was observed during states reported at both level 4 ($\beta = 0.763$; $\mathrm{t} = 2.747$; $p = 0.002$) and level 5 ($\beta =1.051$; $\mathrm{t} = 2.77$; $p = 0.0055$). We did not find any significant trends in beta band power. All trends in oscillatory activity appeared to increase linearly with heightened degrees of mind wandering.

5 Discussion

We corroborated some of the past frequency domain findings, namely that of increased frontal theta and delta band power during mind wandering, which were also reported by Braboszcz and Delorme (2011) and other literature (van Son et al., 2019). However, we did not observe the same trend of decreased occipital alpha reported by Braboszcz and Delorme (2011) and instead observed increased occipital alpha during states of reported mind wandering. Furthermore, contrary to Braboszcz and Delorme (2011) and subsequent studies (Xu & et al., 2018), we observed decreased, rather than increased, P2 amplitudes during periods of heightened mind wandering during level 4 of the Likert scale, though not level 5. The lack of significance of the latter may be due to the imbalance of the number of trials in the level 1 (“completely on task”; 1472 standard / 278 oddball trials) and level 5 (“completely mind wandering”; 362 standard / 72 oddball trials) bins, however.

It is possible that the differences observed in P2 amplitude are due to the differences in the tasks and experience sampling methods employed by study and the one conducted by Braboszcz and Delorme (2011). The first difference between the studies is that Braboszcz and Delorme (2011) employed a different experience sampling method involving a counting task, rather than a random prompt. The second difference is that the prior study investigated mind wandering in a meditation context, with no ongoing lecture video or related soundtrack. Seli et al. (2015; 2018) posit that mind wandering is better understood as a series of distinct phenomena united by family resemblances, rather than a uniform mechanism. It is possible that mind wandering experienced during an e-learning task is distinct from mind wandering observed during meditation.

An alternative explanation for these results is that the reduction in P2 amplitude is the result of sensory gain control which is lost when not attenuated to the task of learning. In a series of experiments described by Kam et al. (2011, 2014), ERP responses to images of painful situations were consistently found to be attenuated during states of mind wandering. It is thus possible that the pattern observed in our study similarly reflects a sort of “tuning out” of the outside world as attention drifts away from the task and towards unrelated thoughts. Furthermore, the questionnaire results in our experiment revealed a clear relationship between mind wandering and lecture length. A possible explanation for these results is that many participants occasionally deliberately engaged in mind wandering throughout the video due to boredom.

Another interesting difference between our results and those reported by Braboszcz and Delorme (2011) is that though we observed consistent patterns at the delta and theta bands, we did not replicate their findings of decreased beta power during states of mind wandering. It is possible that we did not observe differences in beta because users were engaged in a cognitive task (that of the online lecture) despite being in a state of mind wandering. Heightened beta activity is known to reflect active cognitive processing (Ray & Cole, 1985), and it is possible that differences in beta activity observed by Braboszcz and Delorme (2011) reflect differences in cognitive processing when participants lost count during states of mind wandering, but not during online lectures.

We also observed increased occipital alpha power during states of reported mind wandering. This finding conflicts with results reported by Dhindsa et al. (2019) who found that mind wandering was associated with decreased occipital alpha among 15 participants who similarly attended a lecture. However, other studies reported a correlation between EEG alpha activity and reported mind wandering (Baldwin et al., 2017; Compton et al., 2019) when engaged in monotonous activities. We similarly interpret our results to support the notion that increased alpha is associated with mind wandering during monotonous activities.

A limitation to our findings was that task load was not significantly associated with either mind wandering or learning. We would expect task load to have either a positive or u-shaped impact on learning in this case. The cognitive theory of multimedia learning (Mayer & Moreno, 2003) posits that task load generated by extraneous factors inhibits learning but that a moderate degree of cognitive load facilitates learning. Future research could explore the relationship between mind wandering and cognitive load to potentially discover how these factors interact using different measures than the NASA TLX. Such future work could include an active or mentally demanding task, which was not observed by this study.

Finally, though we sought to distinguish between varieties of technology-related and technology-unrelated mind wandering using the ex post scales, we did not distinguish the possible varieties of mind wandering. There is growing awareness about differences varieties of mind wandering experiences, particularly among spontaneous and deliberate mind wandering (Seli et al., 2015). Future work may explore different dimensions of the mind wandering constructs, the relationship with the findings described in this study, and their effect on learning outcomes.

Regardless of these limitations, the findings overall suggest that attention is redirected away from videos and towards external stimuli during periods of mind wandering during online lecture use, and that this may explain the negative impact of mind wandering in learning environments. E-learning technology users may benefit from techniques which limit mind wandering. Developers of such technologies may wish to consider factors which limit mind wandering in multimedia and curriculum design, such as through the use of active learning techniques, or by employing a blend of both synchronous and asynchronous content.

6 Data Availability

The datasets generated by this study are available on request to the corresponding author.

7 Ethics Statement

This study was carried out in accordance with the recommendations of the Dalhousie University Research Ethics Board in Canada with informed written consent from all subjects, in accordance with the Canadian Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans and the Declaration of Helsinki.

8 Author Contributions

CC designed the study under the supervision of AN. CC collected the data. CC analyzed the data under the supervision of AN. CC and AN wrote the final manuscript.

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10 Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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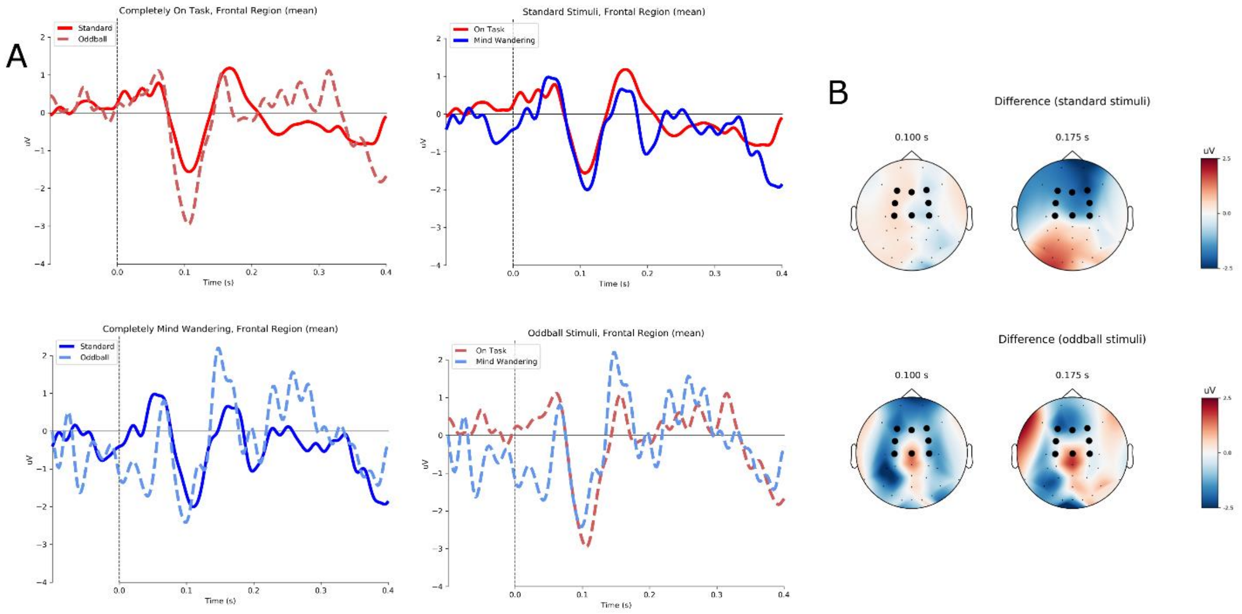

Figure 1: Effect of the extremes of the mind wandering states (“completely on task”, “completely mind wandering”) on event-related potentials elicited by standard and oddball stimuli. (A) Grand average waveform at channels Fz, F3, F4, FC3, FC4, Cz, C3, and C4 for the two states. (B) Topographic maps depicting the average ERP difference between “completely on-task” and “completely mind wandering” during the 75-125 ms and 150-200 ms windows.

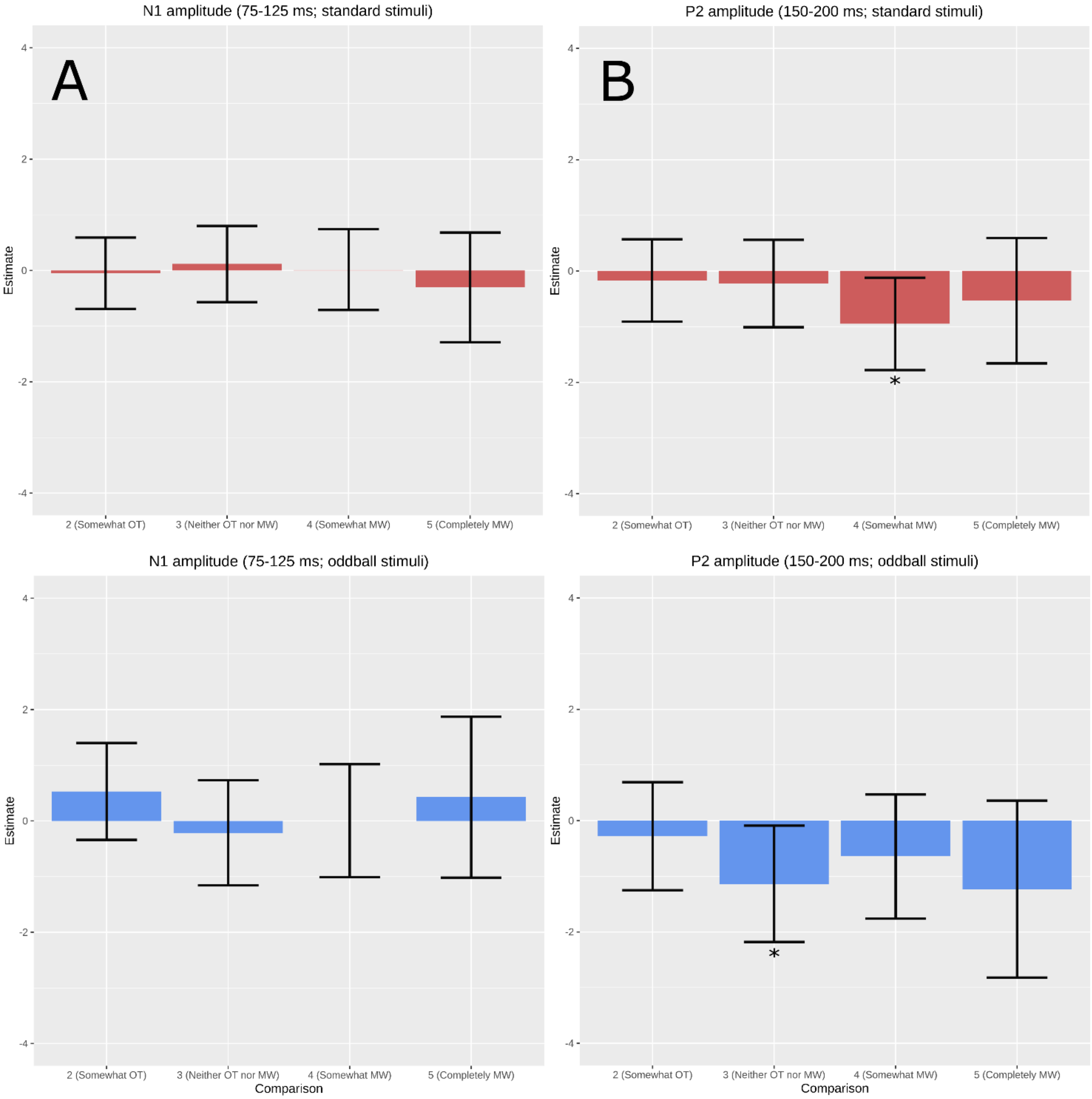

Figure 2: Comparisons of event-related potential estimates from linear mixed effects analysis using the "completely on task" state as the reference variable. (A) Responses to standard stimuli at the 75-125 ms window were not significantly different during the various reported mind wandering states, though responses to oddball stimuli were significantly lower. (B) Responses to standard stimuli at the 150-200 ms windows were consistently lower, though only significantly so during the "somewhat mind wandering" state.

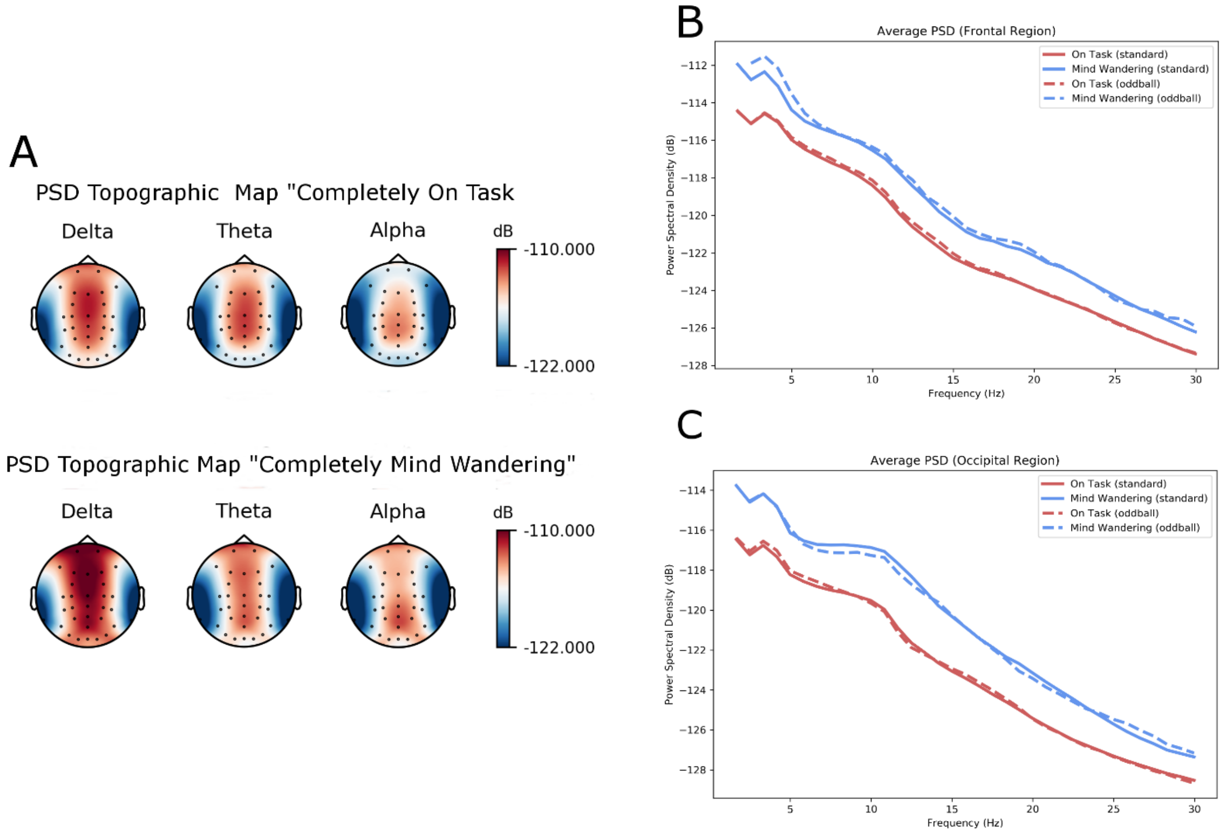

Figure 3: Effect of the extremes of the mind wandering states ("completely on task", "completely mind wandering") on power spectral density (PSD). (A) Topographic illustrations of PSD for the two states illustrate differences in delta and theta power in the frontal region, as well as increased alpha in the occipital region. (B) Average PSD in response to various stimuli are illustrated for channels Fz, Fp1, Fp2, F3 and F4 are represented. (C) Average PSD in response to various stimuli are again represented but for channels Poz, Oz, O1 and O2.

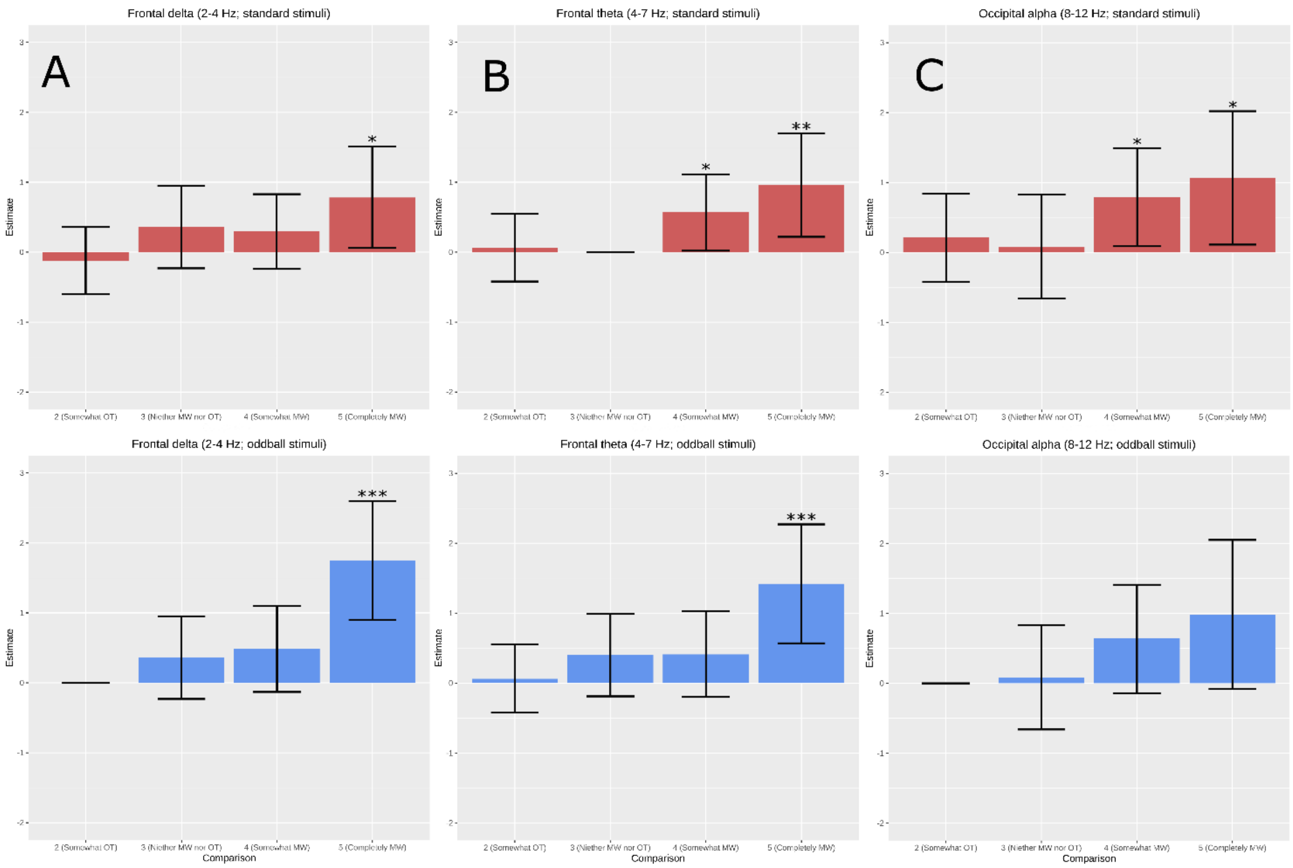

Figure 4: Comparisons of frequency band power (dB) estimates from linear mixed effects analysis using the “completely on task” state (1 on the Likert scale) as the reference variable. (A) Delta frequency band power in the frontal region is significantly higher during the “completely mind wandering” state and in response to oddball stimuli. (B) Frontal theta power is significantly higher during both “somewhat” and “completely” mind wandering states. (C) Alpha power in the occipital region is significantly higher during “somewhat” and “completely” mind wandering states though was only found to be significant in response to standard auditory stimuli. No significant results were found at the beta frequency band.