Attenuation of deep semantic processing during mind wandering: an event-related potential study

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Although much research shows that early sensory and attentional processing is affected by mind wandering, the effect of mind wandering on deep (i.e. semantic) processing is relatively unexplored. To investigate this relation, we recorded event-related potentials as participants studied English–Spanish word pairs, one at a time, while being intermittently probed for whether they were 'on task' or 'mind wandering'. Both perceptual processing, indexed by the P2 component, and deep processing, indexed by a late, sustained slow wave maximal at parietal electrodes, was attenuated during periods preceding participants' mind wandering reports. The pattern when participants were on task, rather than mind wandering, is similar to the subsequent memory or difference in memory effect. These results support previous findings of sensory attenuation during mind wandering, and extend them to a long-duration slow wave by suggesting that the deeper and more sustained levels of processing are also disrupted. ***NeuroReport*** **29:380–384**

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Introduction

It is known that we spend up to half our waking moments mind wandering [1]. This propensity for one's thoughts to drift onto things unrelated to the task at hand, has been shown to affect performance across a wide variety of activities such as reading comprehension [2], learning and memory [3,4], and vigilance or target detection [5,6]. These consequences are thought to arise from one's mind decoupling from the external environment and task at hand onto unrelated internal thoughts [7].

Indeed, work with event-related potentials (ERPs) indicates that when an individual's mind wanders, she/he exhibits diminished sensory processing of the external world, as indexed by ERP components such as the P1 [2,9]. In similar fashion, researchers have found that mind wandering also attenuates later-onset, higher-order cognitive processing, as indexed by the P3 component [5,8,9]. Although no investigation has been conducted on the P2 component, which is thought to index perceptual processing [10], it is presumable that this would also be attenuated during mind wandering. More important, however, much of this work on cognitive processing has relied on relatively simple tasks, such as the oddball task [8], a variant of a go no-go task [5], and image categorization [9]. As such, they are unable to address the neurocognitive impact of mind wandering on mental activities requiring ongoing deep, semantic elaborative processing such as episodic encoding during learning.

To examine the impact of mind wandering on deep processing, we recorded ERPs while participants studied English–Spanish word pairs and were intermittently probed for whether they were 'on task' or 'mind wandering'. These ERPs were then compared depending on whether participants had reported being on task or mind wandering. If participants had failed to process the task-relevant information deeply when they were mind wandering, we predicted that the magnitude of a slow wave process similar to the subsequent memory or difference in memory (Dm) effect (which is thought to reflect semantic processes [11,12]) would be attenuated relative to when participants were on task.

Participants and methods

Participants

A total of 29 participants (15 males and 14 females; M = 24.03 years, SD = 4.46) were recruited from the Columbia University community and were compensated at a rate of $15/h. All participants were native English speakers with no self-reported history of any psychiatric disorder. All participants gave written, informed consent and were treated in accordance with the ethical principles of the Declaration of Helsinki. Study approval was given by the Internal Review Boards of Columbia University and New York State Psychiatric Institute.

One participant, whose data were included in the ERP tracings, did not complete the final test. All analyses were, however, also computed with this participant removed and there were no differences in the results.

Materials

The materials were 179 English–Spanish word pairs varying in difficulty taken from Xu and Metcalfe [4].

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A total of 35 pairs from this set were sorted into each of the easy, medium, and difficult conditions, as described below.

Design

Word pairs were presented for study using a 3 (Difficulty of word pairs: easy, medium, and difficult) $\times$ 4 (Block Duration: time during which pairs at the same level of difficulty were presented, 15, 30, 60, or 90 s) $\times$ 2 (Study Half) within-participants design. Successive pairs at a single level of difficulty were presented for study at a rate of 1.5 s per pair, until the designated amount of time (15, 30, 60, or 90 s) had passed, in what we will call a block. At the end of each block, a mind-wandering probe was presented. Twelve blocks in the 3 $\times$ 4 design, were presented in each Study Half. The order of presentation of the 12 blocks in each of the two halves, was randomized with the following constraints: (i) Difficulty was randomized and permuted a total of four times, (ii) all three difficulty levels were presented at each of the four time conditions, in a randomly assigned order, and (iii) the position in the sequence of blocks of each difficulty level was equated across participants.

Word pairs were presented in blocks at the three levels of difficulty, because past research indicated that experts tend to mind wander on easy materials whereas novices tend to mind wander on more difficult materials [4]. Blocking ensured that participants would get streams of items together at roughly the same level of difficulty. By presenting particular levels of difficulty in blocks we hoped to ensure that all participants – whether experts or novices – would mind wander on at least some of the materials. The number of seconds for which materials at a particular difficulty level were presented was also varied to prevent participants from anticipating the appearance of the mind-wandering probe. Finally, we added a short break in the middle of the study phase – segmenting the study stream into two halves – to enable us to check, and correct when necessary, the impedance of the electrodes.

There were 25 pairs in each of the three difficulty level conditions. Each pair was presented repeatedly over the course of study, within its own difficulty level block, and repeated randomly across Block Durations. Each word pair was presented an average of 10.17 times (SD = 3.03) during study.

The dependent variables were: (i) cued recall, which was assessed at the end of the experiment, (ii) mind wandering, which was assessed at the end of each block, and (iii) ERP voltage, which was assessed throughout the study phase, time-locked to word-pair presentation.

Procedure

The experiment consisted of three sections: pretest, study, and final test. ERPs were recorded during the study phase. During the pretest, participants viewed the English words and had up to 10 s to provide the correct Spanish translation. In the event that they did not know the answer, participants were instructed to try and provide an educated guess of what they thought the translation might be. After each response, participants were asked for a judgment of learning (JOL) on a slider scale for word pairs they had answered incorrectly. Word pairs were then sorted into three difficulty levels: 'easy' items were correctly recalled; 'medium' items were inaccurate but accompanied by high JOLs; 'difficult' items were inaccurate and accompanied by low JOLs. Thirty-five items were sorted into each condition: 25 of which were presented for study, and 10 of which were reserved to be unstudied control items which were given on the final memory test. (One participant provided only 25 correct responses. For this participant, all of the 25 'easy' word pairs were presented for study, and the participant did not have any unstudied easy control items).

After completing the pretest, participants were presented with the English–Spanish word pairs and asked to study them for an upcoming test. They were also intermittently asked to report whether they were 'on task' or 'mind wandering'. All participants received and were asked to repeat the definitions of 'on task' or 'mind wandering' before the study phase to ensure they understood what the terms meant. Word pairs were presented one at a time on screen for 1000 ms followed by a blank screen for 500 ms until the end of the block. The English word was 100 pixels above the midpoint of the screen and the Spanish word was 100 pixels below the midpoint. A mind-wandering probe was presented at the end of each block, as indicated above, for a total of 24 attentional reports.

Participants were given a cued-recall test at the end. Each English word was presented on screen and participants were asked to type in the correct Spanish translation. All word pairs presented for study were tested, as were the additional unstudied 10 word-pair controls. Presentation order was randomized and no feedback was provided. Participants' responses were leniently scored offline by a research assistant for accuracy.

Event-related potential recording

Brain electrical activity was recorded during the study phase from 62 scalp sites (sintered Ag/AgCl) mounted in an Electrocap (Neuromedical Supplies; Compumedics USA Inc., Charlotte, North Carolina, USA) and digitized at 500 Hz (DC; high-frequency cutoff of 100 Hz; right-forehead ground). Electrodes were placed on the outer canthus of each eye to record horizontal eye movements, and directly above and below the left eye for vertical movements. Activity was originally referenced to the nose and rereferenced offline to the average of the left and right mastoids. Impedances were maintained below 10 kΩ throughout the experiment.

Data analyses

ERPs were time-locked to word-pair presentation and computed with a 200 ms baseline in EEGLAB [13] and

ERPLAB [14]. Following methodology used in previous research [5,6,9], only the seven items presented during the 12 s immediately preceding each attentional probe were used in the ERP mind wandering or on-task averages. ERPs were categorized on the basis of participants' reported attentional state for each block (i.e. on task or mind wandering) and averaged across Difficulty, Block Duration, and Study Half.

Before analyses, all recordings were filtered using a 0.1–10-Hz IIR-Butterworth bandpass filter to remove DC drift and muscle movements. Offline artifact rejection and independent component analysis [15,16] were used to remove eye blinks, eye movements, and other muscle activity. For two participants, one electrode had to be interpolated due to an abnormal electroencephalography pattern (P1 and CZ, respectively).

Results

The criterion for significance was set at P value less than 0.05 for all analyses. Partial eta squared (η_p^2) was used as the measure of effect size for analysis of variance (ANOVA). F-tests with Greenhouse–Geisser adjusted degrees of freedom were used when the assumption of homogeneity of variance was violated. When applicable, post-hoc Tukey's tests were computed for follow-up comparisons and are directly reported. For brevity, only the statistics for significant effects are reported.

Behavioral data

Final test performance

Test performance was computed on the basis of the proportion of leniently-scored items participants answered correctly. Average performance on the final cued-recall test was 0.58 (SD = 0.09). There was an expected effect of Difficulty on performance [$F(1.45, 39.08) = 368.40$, $P < 0.0001$, $\eta_p^2 = 0.93$], such that participants performed best on easy ($M = 0.95$, SD = 0.05), next best on the medium ($M = 0.68$, SD = 0.18), and worst on difficult pairs ($M = 0.12$, SD = 0.11). Performance on easy pairs was significantly better than on medium or difficult pairs [$t(54) = 8.56$, $P < 0.0001$ and $t(54) = 26.58$, $P < 0.0001$, respectively]. Performance on medium pairs was higher than on difficult pairs [$t(54) = 18.03$, $P < 0.0001$].

Mind wandering

Participants mind wandered an average of .36 (SD = 0.20) of the time. We first collapsed over Block Duration. A 3 (Difficulty) × 2 (Study Half) ANOVA revealed that the rates of mind wandering were fairly consistent across easy ($M = 0.40$, SD = 0.26), medium ($M = 0.34$, SD = 0.23), and difficult pairs ($M = 0.33$, SD = 0.29) [$F(1.96, 54.87) = 0.88$, $P = 0.418$, $\eta_p^2 = 0.03$]. There was an expected effect of Study Half, such that participants mind wandered more in the second half ($M = 0.41$, SD = 0.25) than in the first half ($M = 0.30$, SD = 0.20) [$F(1, 28) = 8.18$, $P = 0.008$, $\eta_p^2 = 0.23$]. There was no interaction between Difficulty and Study Half.

We then collapsed across Difficulty condition and computed a 4 (Block Duration) × 2 (Study Half) ANOVA. As anticipated, the same effect of Study Half, showed up in this analysis as in the previous one. There was also an effect of Block Duration such that participants mind wandered more on longer relative to shorter blocks [$F(2.75, 76.88) = 4.18$, $P = 0.010$, $\eta_p^2 = 0.13$]. There was more mind wandering reported for the 90 s as compared with the 15 s block [$t(84) = 3.09$, $P = 0.014$]. None of the other pairwise comparisons across Block Duration were significant. There was no interaction between Block Duration and Study Half.

Mind wandering and performance

The between-participant correlation between mind wandering and final test performance was not reliable [$r = -0.30$, $t(26) = 1.60$, $P = 0.121$].

We were unable to assess the relation between mind wandering and learning within-participants because the word pairs repeated many times over the course of the study phase. As such, there might have been instances in which a participant might have mind wandered, or were on task, and also cases in which their attentional state was unknown (e.g. items presented at the beginning of a block) during the presentation of each pair. This feature of the design prevented us from being able to cleanly segment items into those that had been presented while the participant was mind wandering and those that had been presented when she/he was on task.

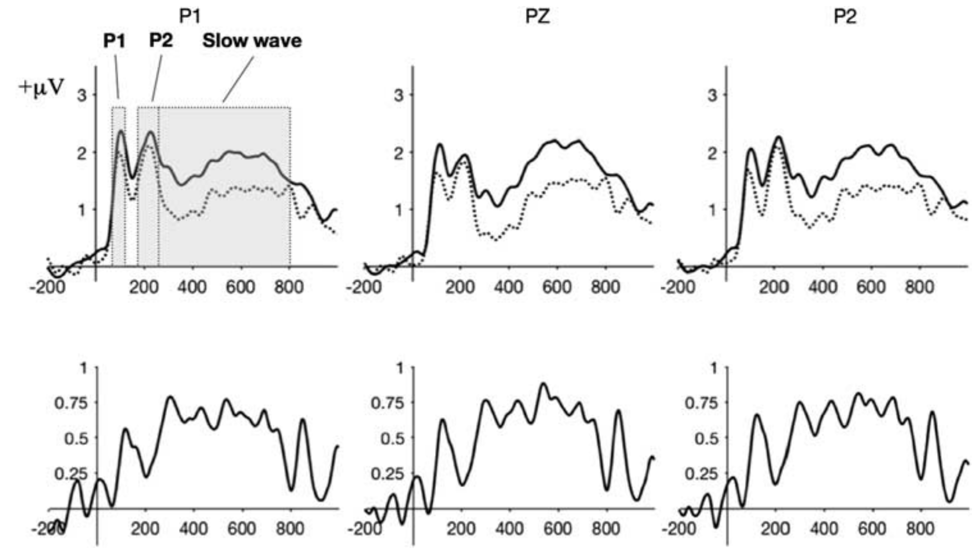
Event-related potential data

Omnibus ANOVAs were computed using Electrode (see below) and Attentional State (on task vs. mind wandering). Average amplitude was computed over the measurement time windows of interest as described below.

ERP waveforms, presented in Fig. 1, were time locked to the presentation of a word pair during study and categorized according to self-reported attentional state (mind wandering/on task). Only ERPs to word pairs presented 12 s, or seven word pairs, before each probe were included. Across participants, 106 trials were on task (SD = 32.99) and 60 were mind wandering (SD = 31.17).

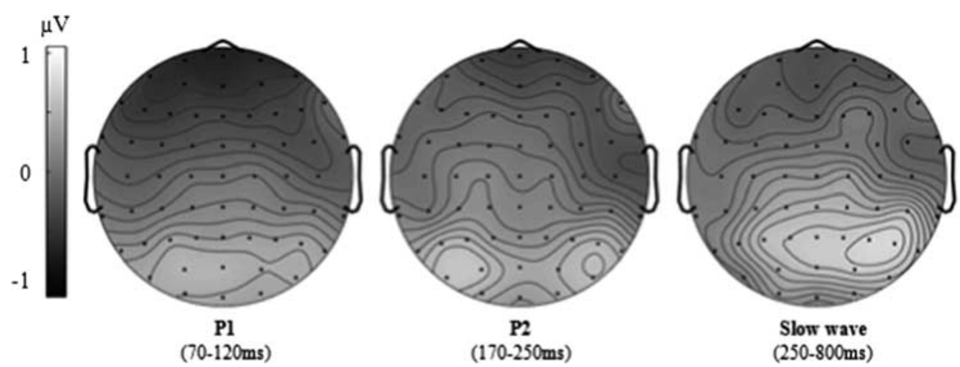
Although we were primarily interested in deep processing, three ERP components were investigated. First, we analyzed the early P1 component from 70–120 ms. This component has been investigated in previous mind-wandering experiments [6] and is thought to reflect basic visual-sensory processing. Second, we analyzed a P2 component from 170 to 250 ms. This component has not been investigated before in the context of mind wandering, and in the context of our experiment could index attention-modulated perceptual processing [10] or early/short-term encoding [17]. Third, and most importantly,

Fig. 1



Event-related potentials to word pairs presented during study for electrodes – PZ, P1, and P2. Top: on-task trials are represented by the solid black line and mind-wandering trials are dotted. Components and time windows analyzed are shaded and labeled in the left-most panel for the P1 electrode. Bottom: difference waveforms with the mind-wandering event-related potentials subtracted from the on-task event-related potentials. Note that the P1 component was analyzed at electrodes PO3, PO4, and OZ (not shown).

Fig. 2



Scalp topography of the difference waveforms (mind-wandering event-related potentials subtracted from the on-task event-related potentials) for the P1, P2, and slow wave components.

we analyzed a late, sustained positive slow wave beginning at 250 ms and lasting until 800 ms. This component has not previously been investigated in the mind wandering situation, and may be associated with ongoing semantic processes during encoding [11,12]. Differences in scalp topography across these three time windows are presented in Fig. 2.

Analyses of the P1 component focused on the PO3, PO4, and Oz electrodes, as these electrodes overlie occipital cortex [6]. To choose the electrodes for measurement of the P2 and positive slow wave, we first collapsed across attentional state and computed a grand average scalp topography (not shown), from which we then selected the subset of electrodes maximally active during 170–250 and 250–800 ms. On this basis, a subset of parietal electrodes – PZ, P1, P2, P3, P4, P5, and P6 – were chosen for these analyses.

The difference between on-task and mind-wandering conditions on the P1 component was marginally significant [$F(1, 27) = 3.20$, $P = 0.085$, $\eta_p^2 = 0.11$]. Although this effect was not significant in a two-tailed test, the direction was consistent with past research which has shown effects of mind wandering on sensory processing [2,6].

There was also a significant difference between on task and mind wandering at 170–250 ms. The P2 component was attenuated when participants were mind wandering relative to when they were on task [$F(1, 27) = 4.19$, $P = 0.050$, $\eta_p^2 = 0.13$].

Finally and critically, there was an effect of mind wandering from 250–800 ms [$F(1, 27) = 5.48$, $P = 0.027$, $\eta_p^2 = 0.17$], such that mind wandering significantly attenuated processing relative to the on-task state. To the best of our knowledge, this pattern of late attenuation during mind wandering has not been observed before, and suggests that higher-order, deep processing of to-be-learned materials was dampened [11,12].

Discussion

This experiment examined the question of whether mind wandering attenuates deep semantic processing as reflected in a late, sustained positive-going process. We predicted that this processing would be reduced when participants were mind wandering relative to when they were on task. Indeed, there was a significantly attenuated brain response during mind wandering. The data presented here indicate that processing of materials is attenuated by mind wandering at a perceptual level (P2), and crucially, at a deep semantic processing level.

This attenuation in late positivity is qualitatively similar to the Dm effect indicating that ERPs during study of items that are later remembered are larger and more positive – particularly after about 400 ms – than those items that are subsequently forgotten [11,12]. To the extent that the Dm effect and our late mind-wandering effect reflect similar mechanisms, these results suggest that the late processing we observed may be qualitatively similar to the subsequent memory effect, and may be disrupted during mind wandering. Future experiments should assess whether this is, indeed, the case.

Conclusion

The findings of this experiment indicate that when a person is mind wandering, deep processing, which is associated with higher-order cognitive functions such as semantic encoding, is impaired.

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Conflicts of interest

The authors declare no conflicts of interest and are wholly responsible for the data and the interpretation of the data reported here.

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