



Early event-related brain potentials and hemispheric asymmetries reveal mind-wandering while reading and predict comprehension



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ABSTRACT

The electroencephalogram (EEG) of mind-wandering (MW) was examined in event-related potentials (ERPs) and pre-stimulus alpha (8–12 Hz), over lateral-posterior sites of left and right brain hemispheres, while individuals read text passages. After controlling for individual differences in general intelligence (g), P1-asymmetry was greater (right-minus-left) and N1 amplitudes were more negative, when individuals were not MW (i.e., they were reading attentively). Approximately 82% of variance in reading comprehension was accounted for by the predictors: g , pre-stimulus alpha, left- and right-hemisphere P1, and left-hemisphere N1 (when individuals were not MW). Together, individual differences in MW-sensitive ERPs uniquely accounted for approximately 38% of the variance in reading comprehension, over and above prediction by g and pre-stimulus alpha. The within-person effect of MW on P1-asymmetry was estimated to account for an additional 4.6% of criterion variance. Implications for EEG/ERP research into attention, language processing, hemispheric asymmetries, and individual differences are discussed.

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1. Introduction

Mind-wandering (MW) is a common human experience characterized by states of disengagement from goal-oriented transactions with the external environment, wherein attention is directed inwardly to self-generated, stimulus-independent, and task-unrelated thoughts (Schooler et al., 2011, 2013; Smallwood, 2013; Smallwood & Schooler, 2015). MW is commonly understood to mean “thinking about something else” besides a particular task-at-hand. When individuals are MW, cognition becomes focused on various task-unrelated thoughts and emotions, often connected to a person’s ongoing “current concerns” (Klinger, 1999). Mind-wandering is a kind of attentional fluctuation, but it is thought to occur spontaneously and have an endogenous source, unlike inattention due to distraction by external stimuli (Dixon, Fox, & Christoff, 2014).

MW is often accompanied by a process called “perceptual decoupling”—the brain’s responses to stimuli in the environment are blunted because attention is directed “inwardly” (Schooler et al., 2011; Smallwood, 2013). MW is often accompanied by a loss of “meta-awareness” (Schooler et al., 2011), the re-representation

of the contents of consciousness. Meta-awareness normally functions to keep attention focused on higher-level personal goals and tasks in the service of those goals, similar to the concept of executive function (Smallwood & Schooler, 2006). Thus, MW is thought to reflect either a failure (McVay & Kane, 2010) or co-opting (Smallwood, 2010) of central executive resources that are normally devoted to task-oriented cognition. MW has been prominently associated with increased activation of the “default-mode” network (DMN; Andrews-Hanna, 2012; Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason, Norton, Van Horn, Wegner, Grafton, & Macrae, 2007), which is generally thought to be in a competitive relationship with task-positive networks for sensory, motor, and executive control processes (e.g., Sonuga-Barke & Castellanos, 2007). However, it has also been noted that MW is frequently associated with co-activation of DMN with executive areas, especially lateral frontal cortex (Christoff et al., 2009; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Smallwood, Brown, Baird, & Schooler, 2012), suggesting that executive processes are indeed actively involved in MW.

Due to perceptual decoupling, people often fail to efficiently process critical task-relevant information in the environment; concurrently, owing to the loss of meta-awareness, people often do not recognize that they are disengaged from the current task until much time has elapsed. Thus, it is proposed that MW entails two kinds of attentional fluctuations, at perceptual and meta-cognitive levels, respectively (Schooler et al., 2011). Unsurprisingly, MW has harmful effects on performance of a wide range of cognitive

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tasks (for reviews, see [Mooneyham & Schooler, 2013](#); [Randall, Oswald, & Beier, 2014](#); [Schooler et al., 2013](#); [Smallwood & Schooler, 2015](#)). In particular, MW while reading is harmful to comprehension ([McVay & Kane, 2010, 2012](#); [Schooler, Reichle, & Halpern, 2004](#); [Smallwood, 2011](#); [Smallwood, Fishman, & Schooler, 2007](#); [Smallwood, McSpadden, & Schooler, 2008](#)). Because reading is a crucial ability in literate societies, it is important to better understand the neural manifestations of MW in this domain.

Previous psychophysiological research into MW while reading has used eye-tracking ([Reichle, Reineberg, & Schooler, 2010](#); [Schad, Nuthmann, & Engbert, 2012](#)) and pupillometry ([Franklin, Broadway, Mrazek, Smallwood & Schooler, 2013](#); [Smilek, Carriere, & Cheyne, 2010](#)) measures, finding detailed evidence of perceptual decoupling from the text and loss of meta-awareness. However, electrophysiological methods provide direct measures of cortical activation in real-time and therefore can provide additional and complementary information about the neurophysiological underpinnings of language comprehension ([Osterhout, McLaughlin, & Bersick, 1997](#); [Serenio & Rayner, 2003](#)). Toward this goal, the present research sought to identify electrophysiological correlates of MW in a reading task, examining brain activations in the form of event-related potentials (ERPs) and spectral power derived from the electroencephalogram (EEG).

1.1. EEG/ERPs while mind-wandering

Previous electrophysiological studies of MW have been conducted mostly within the context of the “sustained attention to response” task (SART; [Robertson, Manly, Andrade, Baddeley, & Yiend, 1997](#)). The SART is a continuous performance go/no-go task, in which participants must execute a single manual response to frequent non-targets (digits 1–9 excluding 3) and withhold this response to infrequent targets (digit 3). Previous studies have found that when individuals were MW during the SART ([Smallwood, Beach, Schooler, & Handy, 2008](#)), or for people with greater tendencies to MW during the SART ([Barron, Riby, Greer, & Smallwood, 2011](#)), ERP amplitudes were generally reduced in the P300 time-window, whether elicited by targets, non-targets, or task-irrelevant distractors. Outside of the SART paradigm, MW-related attenuation of P300 was observed in response to images of human hands receiving injuries, said to index-reduced perception of other people’s pain ([Kam, Xu, & Handy, 2014](#)).

Earlier ERPs have also been shown to be reduced in association with MW during the SART. [Kam, Dao, Farley, Fitzpatrick, Smallwood, Schooler, and Handy \(2010\)](#) found MW-related reduced amplitudes for visual P1 and auditory N1 components, evoked by task-irrelevant peripheral stimuli presented during the SART. Additionally, MW was associated with reduced P1 amplitudes to external events during the SART as well as reduced EEG phase-locking in theta frequency ([Baird, Smallwood, Lutz, & Schooler, 2014](#)). Outside the SART paradigm, [O’Connell and colleagues](#) found reduced steady-state-evoked-potential (SSVEP) responses evoked by flickering checkerboards were predictive of attentional lapses, i.e., failure to detect an infrequent target series of flickers ([Connell, Dockree, Robertson, Bellgrove, Foxe, & Kelly, 2009](#)). Additionally, [Braboszcz and Delorme \(2011\)](#) investigated EEG/ERP correlates of MW in a meditation task, finding generally reduced power in faster frequencies (alpha, beta) and enhanced power in slower frequencies (delta, theta) when people were MW, as well as reduced mismatch negativity (MMN) to task-irrelevant auditory stimuli played in the background, approximately 100 ms post-stimulus.

Together, these previous EEG/ERP investigations have shown that perceptual responses to external stimuli are reduced when people are MW. However, these studies have mostly concerned relatively low-level perceptual tasks and therefore have not shed

much light on MW-related differences in cortical processing during tasks that require higher-order, complex cognition. Furthermore, these studies have not demonstrated the relevance of MW-sensitive electrophysiological measures to a criterion ability of real-world importance, such as reading for comprehension. This limitation was addressed in the present study.

1.2. ERPs while reading

Psycholinguistic theories of reading comprehension posit a number of sequential processing stages, such as perceptual analysis, lexical access and selection, and semantic integration ([Carreiras, Armstrong, Perea, & Frost, 2014](#); [Just & Carpenter, 1980](#); [Lau, Phillips, & Poeppel, 2008](#)). The standard sequential account common to many theories of reading comprehension proposes that first perceptual analysis leads to recognition of a particular stimulus as a group of letters, then as a word, and then the specific identity of the word is determined (i.e., the word is recognized). Then the meaning of that word is accessed through a process of selection from representations in semantic or episodic memory, and then this meaning is integrated with other active meanings to support ongoing comprehension of complex representations, such as narratives or arguments. These processes are proposed to successively transform what is initially raw sensory input into increasingly complex representations, such as letters, words, propositions, and situational models ([Smallwood, 2011](#); [Zwaan & Radvansky, 1998](#)).

Long-running debates should be noted, concerning whether language processing stages are encapsulated and enacted serially, so that successive stages must wait for earlier stages to be completed before beginning, or in “cascade,” in which later processing stages can work on partial outputs (but the stages must still be run in order). Moreover, these “feedforward” theories can be contrasted with interactive models in which top-down feedback can bias or constrain the “earlier” stages ([Carreiras et al., 2014](#); [Price & Devlin, 2011](#)). And in *parallel* interactive theories, it is proposed that language processing stages are “nearly simultaneous,” extracting lexical, semantic, and other higher-order linguistic information within the first 250 ms after a word can be uniquely identified (for a review, see [Pulvermüller, Shtyrov, & Hauk, 2009](#); also [Barber & Kutas, 2007](#)). Because EEG/ERP techniques provide direct measures of cortical activation with fine-grained temporal resolution, they are well-suited for investigating the time-course of neural instantiations of the component processes of language comprehension that are proposed in cognitive theories ([Osterhout et al., 1997](#); [Serenio & Rayner, 2003](#)).

Electrophysiological investigation of language processing has been dominated by interest in relatively late-appearing ERPs like the N400 ([Kaan, 2007](#)). The N400, a broad negative-going wave initiated approximately 400 ms after word-onset, is more negative in response to semantic violations (e.g., “The pizza was too hot to cry”). According to different current proposals, the N400 reflects lexical access ([Lau et al., 2008](#)), semantic integration ([Franklin, Dien, Neely, Huber, & Waterson, 2007](#); [van Berkum, Hagoort, & Brown, 1999](#)), retrieval from semantic memory ([Kutas & Federmeier, 2000](#)), or inhibition of irrelevant semantic activations ([Debrulle, 2007](#)). In contrast, ERPs appearing earlier are thought to reflect more basic processes of perception and recognition of words and objects, and orthographic-to-phonological transformations (for a review, see [Dien, 2009b](#)).

[Smallwood, Fishman, and Schooler \(2007\)](#) presented a *cascade model of inattention* to describe the effects of MW on reading comprehension. Smallwood and colleagues proposed that through the mechanism of perceptual decoupling, MW affects reading comprehension at early stages of perceptual analysis and word recognition, which then “cascades” to influence subsequent more complex stages of language processing, such as

semantic-contextual integration and situation model building (see also Smallwood, 2011). Thus, this theory predicts that MW would affect both early and late ERPs related to reading. Indeed, Smallwood (2011) specifically predicted that MW would attenuate the late-appearing N400 (omitting, however, to make specific predictions concerning earlier ERPs). The present work investigated the general question by examining both early- and late-appearing ERPs related to MW while reading.

Early-appearing ERPs have been less often examined in relation to reading (for a recent review, see Dien, 2009b, as well as other articles appearing in the same special issue of *Biological Psychology* on early ERPs and language processing). One that has received much attention is the so-called “recognition potential” (RP; for a review, see Martín-Loeches, 2006). The RP is a negative deflection typically peaking in the range of 240–280 ms after word-onset, with occipital-temporal scalp topography, typically left-lateralized. The RP is evoked by recognizable images or words and is sensitive to lexical properties such as word concreteness and frequency. Moreover, RP latency has been found to predict individual differences in reading ability (Rudell & Hua, 1997). The RP currently has two main functional interpretations. According to one view, the RP reflects general processes of visual object recognition, attention, and conscious awareness (Rudell & Hua, 1995). Alternatively, it is proposed that the RP is more specialized to word recognition, reflecting processes such as lexical selection (Martín-Loeches, 2006) and orthographic-phonological translation (Dien, 2009b). In the linguistic interpretation, more negative amplitudes of the RP are said to reflect greater facilitation of lexical access and depth of semantic processing; thus, the RP has been called the “gate to reading” (Martín-Loeches, 2006, p. 89). It is thought that the RP is likely generated in or near ventrolateral occipitotemporal cortex, sometimes called the “visual word form area” (Dien, 2009b; Martín-Loeches, 2006; Price & Devlin, 2011).

The present research examined effects of MW on an early ERP negativity evoked by words with scalp topography similar to that of the RP. However, it is noted that the RP is apparently related to a large “family” of negative ERPs occurring between 150 and 300 ms after stimulus-onset, with similar scalp topographies, and likewise implicated in early processes of word recognition and lexical access, such as the N170 (Dien, 2009b; Martín-Loeches, 2006). In this study, the negative ERP appearing earliest, peaking approximately 200 ms after word-onset and examined here in relation to MW, will be called “N1” for the sake of simplicity.

The P1 has not been examined much in the context of language processing although the phenomenon of perceptual decoupling suggests that P1 would be a good candidate to show effects of MW while reading. It has been shown that P1 can be modified by attention to orthographic properties of words (Proverbio & Adorni, 2009). Moreover, consistent with parallel-interactive theories of reading, effects of semantic-context and other linguistic parameters have been observed for the P1 (St. George, Mannes, & Hoffman, 1994) as well as other ERP responses observed about 100 ms after stimulus onset (Serenó, Brewer, & O’Donnell, 2003).

According to a recent review of ERP correlates of visual awareness (Raiio, Koivisto, & Revonsuo, 2011), P1 reflects pre-conscious processes of attentional selection that determine what information enters consciousness (while this latter process is reflected in a posterior negative ERP appearing around 200 ms). According to a related perspective (Klimesch, 2011, 2012), the P1 reflects processes of attentional filtering and perceptual categorization, supporting critical early access to a complex memory system encompassing the sum total of an individual’s personal knowledge, be it episodic, semantic, or procedural in nature (the so-called “knowledge system”). This theory assumes that P1 amplitudes are positively related to pre-stimulus activity in the alpha frequency band (8–12 Hz), which is proposed to reflect processes of top-down

modulation, attention, and conscious awareness (Klimesch, 2012; Palva & Palva, 2007). Indeed, positive relationships between pre-stimulus alpha activity and P1 amplitudes have been found (e.g., Fellinger, Klimesch, Gruber, Freunberger, & Doppelmayr, 2011).

It would be reasonable to expect that early attentional filtering processes reflected in P1 and pre-stimulus alpha would be less robust and less efficient when the brain is MW. And because these early processes of selection and inhibition are theorized to represent strong limiting factors with respect to accessing a personal knowledge system, it would be expected that through the mechanism of perceptual decoupling, MW would be detrimental to performance on many tasks requiring access to the knowledge system, such as reading for comprehension. Therefore, MW-related effects on P1 as well as pre-stimulus alpha power were examined in the present study.

1.3. Hemispheric asymmetries

Left-hemisphere specialization in the brain for language processing is well documented, but it is widely recognized that the right-hemisphere participates in language processing too (Federmeier, Wlotko, & Meyer, 2008; Hellige, 1993; Nemrodov, Harpaz, Javitt, & Lavidor, 2011). There have been many hypotheses about the nature of hemispheric differences in language processing (for a recent review, see Dien, 2009a; also Hellige, 1993). One current proposal is that left-hemisphere processes language in a more fine-grained fashion, at the word-level, while right-hemisphere processes language in a more coarse-grained fashion, at the message-level (Fiore & Schooler, 1997; Holtgraves, 2013; Jung-Beeman, 2005).

Hemispheric asymmetries were examined in the present study because it was reasoned that MW might differentially impair language-related competencies of one hemisphere versus the other. Furthermore, right-hemisphere dominant asymmetries have been regularly observed in tasks requiring sustained attention or vigilance (Langner & Eickhoff, 2012), spatial attention (Foxe, McCourt & Javitt, 2003; Shulman et al., 2010), and non-spatial attention (Connell, Schneider, Hester, Mattingley, & Bellgrove, 2011), each of which are likely to be impaired by MW and could thereby influence reading comprehension.

Notably, right-hemisphere enhancements of ERPs while reading sentences have been observed for early (P1) as well as late (N400) components (Kutas, Van Petten, & Besson, 1988). It is also noteworthy that a recent developmental study (Molfese, Fletcher, & Denton, 2013) reported that right-hemisphere P1 amplitudes effectively discriminated typically developing children from those with reading disabilities, while among the latter group, left-hemisphere P1 amplitudes discriminated “adequate responders” from “inadequate responders” to reading skills instruction. Additionally, they found that bilateral N2 amplitudes discriminated among all three groups. Thus, it was of special interest in this study to examine these early ERPs with respect to hemispheric differences and asymmetries.

1.4. Present research

To give an overview, participants read ordinary text passages presented word-by-word in the center of a display while continuous EEG was recorded. To assess MW, participants responded to numerous experience-sampling thought probes, asking them to report whether or not they were MW just before the probe. Tests of reading comprehension were administered after each text passage. ERPs evoked by words were examined depending on whether or not individuals reported they were MW. ERPs were examined in early (P1, N1) and late (P300, N400) time-windows. Pre-stimulus alpha power and hemispheric asymmetries were also examined.

1.4.1. Predictions

Based on the preceding literature review, it might be expected that any or all of these EEG/ERP measures might show effects associated with MW. In general it was expected that cortical responses to external stimuli (i.e., ERP amplitudes) would be attenuated when individuals were MW. However, it was decided in advance to constrain the investigation by evaluating the specificity to MW of any observed EEG/ERP differences, and to furthermore determine whether any MW-sensitive EEG/ERP variables were relevant to the criterion ability, reading for comprehension.

1.4.2. Criterion and covariate

It was important to show that MW-sensitive EEG/ERP variables would have consequences for a critical real-world activity, such as reading for comprehension; moreover, such effects should be specific to MW and not related to an unmeasured “third variable” that also varies with reading comprehension or the EEG/ERP measures. It was expected that reading comprehension as well as the electrophysiological responses would be influenced by individual differences in general intelligence (*g*) (Ackerman, Beier, & Boyle, 2002; Deary & Caryl, 1997). Furthermore, it has been found that significant variance in MW is related to general aptitude (Mrazek, Smallwood, Franklin, Chin, Baird, & Schooler, 2012). Therefore, a widely used measure of *g* was included in the design as a theoretically motivated covariate. It was reasoned that controlling the portion of between-person variance in *g* that was unrelated to MW would facilitate the identification of electrophysiological variables that were specifically related to within-person effects of MW; that were moreover, predictive of reading comprehension over-and-above prediction by *g*.

2. Method

2.1. Ethics statement

The research was conducted in accordance with the Declaration of Helsinki and with the approval of the Institutional Review Board of the University of California, Santa Barbara. Participants gave written informed consent and were compensated either with partial course credit or payment at a rate of \$10 per hour.

2.2. Participants

A total of 47 undergraduate students (33 female) participated in the experiment (age $M = 18.56$ years, $SE = 0.14$). Participants reported normal or corrected-to-normal vision and were proficient in written and spoken English. All participants reported to be right-handed.

2.3. Stimuli

Texts used as reading material were selected from a popular non-technical book about episodes in the history of science presented in an engaging biographical-narrative style (Bryson, 2003). Two separate passages about discoveries in the field of chemistry were presented (“The Atom” and “The Periodic Table”). Words ranged in length from one to 12 letters. The chosen texts have been used in previous studies of MW while reading (Smallwood, Nind, & O’Connor, 2009; Smallwood et al., 2013; Smilek et al., 2010). The texts were formally estimated to be “slightly easier than University-level material” in one of these previous studies (Smallwood et al., 2013; p 2); and participant interest-ratings were reported to be “near the middle of the scale” in another (Smallwood, Nind, & O’Connor, 2009; p 121).

2.4. Procedure

The experimental session lasted approximately 2 h including EEG set-up time. Participants performed the experiment in a partially shielded, sound-attenuating booth, while wearing noise-canceling foam earplugs, with the experimenter present. The reading task was programmed in the Psychophysics Toolbox (Brainard, 1997) and presented on a computer. EEG was recorded during the reading task. Participants sat at an ocular distance of approximately 57 cm from the display. Participants read two different text passages presented one word at a time in the center of the display. Order of text passages was counter-balanced across participants. Stimuli were presented in black against a white background in the center of the display. Word stimuli each appeared for 200 ms duration. The inter-stimulus interval between words was 800 ms. A central fixation cross was present during the

inter-stimulus interval. Word-stimuli subtended approximately 1.5° of visual angle vertically and 1–10° horizontally around central fixation.

Participants were instructed to remain still, keep their eyes focused on the center of the display, and refrain from blinking except during the inter-trial intervals or rest breaks. Participants were instructed to read the text passages for comprehension in order to answer questions about them later. No overt responses were required during the reading task, except to respond to experience-sampling thought-probes. Sentences were presented in six blocks (three blocks for each text passage). Participants were given rest-breaks between blocks while the experimenter also checked and corrected electrode impedances.

2.4.1. Experience-sampling thought probes

The reading task was frequently interrupted by experience-sampling thought probes, presented visually as a message in black text against a cyan background, asking participants “Just now, were you mind-wandering?” Participants responded “yes” or “no” by pressing ‘Y’ or ‘N’ keys, respectively, on a standard computer keyboard. Thought-probe messages remained on-screen until the participant responded. Instructions to participants concerning thought probes emphasized the absence of a “correct” response and encouraged participants simply to respond as accurately and honestly as possible. No other special instructions were given concerning thought probes. Debriefing confirmed that participants interpreted the concept of MW according to everyday usage, as “thinking about something else.” Thought probes occurred according to a pseudo-random schedule, constrained to occur on average after every third sentence. When presented, thought probes were presented after the final word of a sentence. There were a total of 96 thought probes per person in the study.

2.4.2. Reading comprehension

When the participant reached the end of each text passage, a short pen-and-paper test of reading comprehension was administered for that passage. Questions tested recall of specific content that had been presented in the text. Tests for each passage comprised 10 multiple-choice questions, with four response options for each question. Reading comprehension scores were computed as the proportion of correct responses for both tests combined.

2.4.3. Individual differences

When the reading task was concluded, the EEG electrodes were removed and participants performed a short test of *g*, Raven’s Advanced Progressive Matrices (RAPM; Raven, Raven & Court, 1998), programmed in E-prime (Schneider, Eschman, & Zuccolotto, 2002) and presented on a computer. RAPM is widely regarded as a valid measure of *g* (Ackerman et al., 2002). Participants viewed matrices, each cell of which was composed of a complex combination of geometric shapes. One cell of each matrix was empty, and participants were to choose from an array of similar images, the item that would best complete the pattern. Participants were given 18 problems of increasing difficulty. One point was awarded for each problem solved correctly within a 10-min time limit. Scores could range from zero to 18.

After performing RAPM participants then performed a test of working memory capacity before responding to two short surveys about their tendencies to MW in daily life, before leaving the experiment. For the sake of brevity, results from these measures are not reported; none significantly predicted the criterion of reading comprehension after controlling for *g*.

2.5. EEG recording and offline processing

Continuous EEG was recorded from 129 electrodes during the reading task using the EGI Netstation hydrocell system (Electrical Geodesics Inc., 2004a) with 500 Hz sampling rate, 0.1 Hz high-pass filter, and vertex (Cz) reference. Impedances were kept below 60 k Ω throughout the experiment (re-checked by the experimenter during rest-breaks), which is within an acceptable range for high input-impedance systems (Feree, Luu, Russell, & Tucker, 2001). Offline, raw EEG data were pre-processed using EGI Waveform Tools (Electrical Geodesics Inc., 2004b), applying a 30 Hz low-pass filter before exporting into EEGLAB software (Delorme & Makeig, 2004) for further processing, first down-sampling the data to 250 Hz. To derive ERPs, data were segmented into epochs of 700 ms duration following word-onset, with 200 ms pre-stimulus baseline. ERP data epochs were back-sorted to construct two conditions (MW-yes, MW-no) based on participant-responses to thought probes. Specifically, depending on the response to a given thought probe (yes, no), ERPs to preceding words were categorized as MW-yes or MW-no, for up to 30 words preceding the probe (varying somewhat according to the length of sentences between thought probes).

2.6. Artifact rejection and data screening

The EGI Netstation hydrocell system is designed for quick and convenient application of a high-density electrode array, but this facility comes with a trade-off of relatively lower signal quality (Luck, 2005). To address the noisy quality of the EEG data, and consistent with work using similar recording systems (Frishkoff, Tucker, Davey, & Scherg, 2004), multiple criteria were applied to reduce noise and contamination in the data due to muscle and ocular artifacts, channel-pop, etc. Because the experiment was designed to yield upwards of 200 data epochs per person per

MW condition (varying according to individual differences in self-reported MW), and because a relatively high number of participants were tested, it was decided that experimental validity would be served best by applying strict criteria regarding inclusion of data epochs and participants.

Bad channels were replaced using a spherical interpolation algorithm before artifact-rejection. To reject artifacts, conservative thresholds were applied: (1) voltages exceeding $\pm 100 \mu\text{V}$ in any channel and (2) voltages exceeding $\pm 30 \mu\text{V}$ in the periocular channels, were considered to reflect artifacts and the corresponding data segments were discarded. Additionally, data segments and individual ERPs were inspected visually to screen for artifacts. After artifact rejection, remaining data were re-referenced to the average reference (replacing the vertex channel back into the data).

There were 20 participants who failed after artifact rejection to provide at least 50 epochs in each condition and their data were discarded from analyses. Additionally, data from three participants were found by visual inspection to be excessively contaminated by residual oscillatory activity and their data were discarded from analyses. EEG data from two participants were lost due to computer crashes.

The analyses reported in this article therefore included data from 22 individuals. The epochs contributing to the analyses for each MW condition were relatively numerous overall: MW-yes (before artifact rejection, $M = 342.50$, $SE = 37.36$; after artifact rejection, $M = 162.73$, $SE = 18.87$), and MW-no (before artifact rejection, $M = 485.91$, $SE = 31.11$; after artifact rejection, $M = 264.82$, $SE = 25.37$). Proportional data loss was not different on average between MW conditions, $t_{(21)} = 0.44$, $p = 0.67$.

3. Results

To give an organizational overview, behavioral measures are reported next, followed by within-person effects of MW on EEG/ERP measures (after controlling for g). These are followed by correlation/multiple-regression analyses, to examine prediction of individual differences in reading comprehension by EEG/ERP measures that were found in the preceding analyses to be sensitive to MW.

3.1. Behavioral measures

Reading comprehension scores were on average relatively low ($M = 0.62$, $SE = 0.04$), consistent with results of a previous study using these texts (Smallwood et al., 2013), but significantly better than chance (i.e., 0.25), $t_{(21)} = 10.37$, $p < 0.01$. The distribution showed a relatively uniform representation of scores across a range of 0.40–0.95. Moreover, individual differences in reading comprehension were strongly related to g : As expected, reading comprehension was positively correlated with RAPM, $r = 0.55$, $p = 0.01$. Thus, the measure of reading comprehension was judged to be valid for use as criterion in subsequent analyses, with RAPM as covariate.

Responses to thought probes were of interest in this study primarily as the means for classifying the EEG data segments according to self-reported MW. On average, participants reported to be MW about a third of the time that they were probed ($M = 0.33$, $SE = 0.03$), consistent with a previous study using these texts (Smilek et al., 2010). MW rate was not correlated with individual differences in reading comprehension, either before or after controlling for g (before, $r = -0.15$, $p = 0.51$; after, *partial*- $r = -0.23$, $p = 0.32$; neither was MW rate correlated with g , $r = 0.08$, $p = 0.73$).

3.2. EEG/ERP measures

Time-windows for examination were chosen based on common parameters reported in the literature and visual inspection of grand-average ERPs and individual-average ERPs, as well as scalp topographies, to ensure that the chosen time-windows would contain the activities of interest across participants. ERP amplitudes (μV) at each electrode were averaged across time samples during four time-windows of interest (100–150, 175–225, 300–400, and 400–500 ms after word-onset), corresponding to typical latency ranges for the ERP components of interest (referred to in the following analyses as P1, N1, P3, and N4, respectively). Based on prior expectations of lateral-posterior distributions for

the ERP components of interest and visual inspection of scalp topographies, 11 lateral-posterior electrodes in each hemisphere (left, right) were selected for statistical examination (electrode arrays shown in Fig. 2, upper panel).

ERP amplitudes in these electrodes were averaged for each lateral-posterior array to make hemisphere-average variables (left, right) for each MW condition (MW-yes, MW-no), for each time-window of interest (100–150, 175–225, 300–400, and 400–500 ms after word-onset). These hemisphere-average variables were the primary ERP data submitted to statistical analyses. Additionally, hemispheric asymmetry scores for ERPs were computed using the hemisphere averages (right-hemisphere minus left-hemisphere), such that more positive scores resulted from more positive ERPs in right-hemisphere versus left-hemisphere.

For examining pre-stimulus EEG power, the same electrode arrays and data epochs were included as in the ERP analyses. A fast Fourier transform using the Welch method was performed on channel voltages (μV^2) in a pre-stimulus baseline time-window (–100 to –50 ms). Mean spectral power was computed in the alpha frequency band (8–12 Hz). As in the ERP analyses, hemisphere averages across electrodes were computed for each MW condition, and hemispheric asymmetry scores were computed using these hemisphere-averages (right-hemisphere minus left-hemisphere).

3.2.1. Within-person effects: MW while reading

3.2.1.1. ERPs. ERP waveforms for MW conditions (MW-yes, MW-no) are shown in Fig. 1 at two representative lateral-posterior electrodes (left hemisphere 66/PO7 and right electrode 85/PO8). These show the P1 as an early positive deflection sharply peaking approximately 100 ms after word-onset, and at right-hemisphere electrode 85/PO8, apparently less positive for MW-yes versus MW-no conditions. The N1 is observed here as an early negative deflection, sharply peaking approximately 200 ms after word-onset and somewhat left-lateralized, and at left-hemisphere electrode 66/PO7, apparently less negative for MW-yes versus MW-no conditions. The P3 is seen here as a later positive deflection in the range of 300–400 ms after word-onset, and the N4 as the subsequent negative-going deflection in the range of 400–500 ms after word-onset; neither apparently differing across MW conditions. These observations were confirmed by the following analyses. Huynh-Feldt ϵ was used to correct p -values as necessary for violations of sphericity. Uncorrected degrees of freedom are reported.

The hemisphere-average variables were submitted to an omnibus $4 \times 2 \times 2$ repeated-measures analysis of covariance (ANCOVA), depending on the within-subjects factors of time-window (100–150, 175–225, 300–400, and 400–500 ms), MW (MW-yes, MW-no), and hemisphere (left, right), and controlling for individual differences in g by evaluating the covariate RAPM at its mean ($M = 9.14$, $SE = 0.74$). The three-way interaction of time-window \times MW \times hemisphere was significant in the ANCOVA, $F_{(3,60)} = 4.27$, $p = 0.01$, $\eta_p^2 = 0.18$, $\epsilon = 1$. This interacted with the covariate, $F_{(3,60)} = 3.02$, $p = 0.04$, $\eta_p^2 = 0.13$, $\epsilon = 1$, because in general P1-asymmetry was negatively (although not significantly) correlated with RAPM (MW-yes, $r = -0.16$, $p = 0.47$; MW-no, $r = -0.36$, $p = 0.10$). This means that individuals with lower g showed greater P1-asymmetry than individuals with higher g (especially when they were not MW). No lower-order effect was significant except for the main effect of time-window, $F_{(3,63)} = 6.13$, $p < 0.01$, $\eta_p^2 = 0.235$, $\epsilon = 0.85$, simply reflecting that ERP amplitudes varied over time.

To clarify the three-way interaction, separate 2×2 ANCOVAs were performed on the hemisphere-averages for each time-window, again depending on the within-subjects factors of MW (MW-yes, MW-no), and hemisphere (left, right) and controlling for individual differences in g . Results are summarized in Table 1. P1 amplitudes were more positive in right- versus left-hemispheres when participants were not MW (right $M = 1.26$, $SE = 0.20$, left

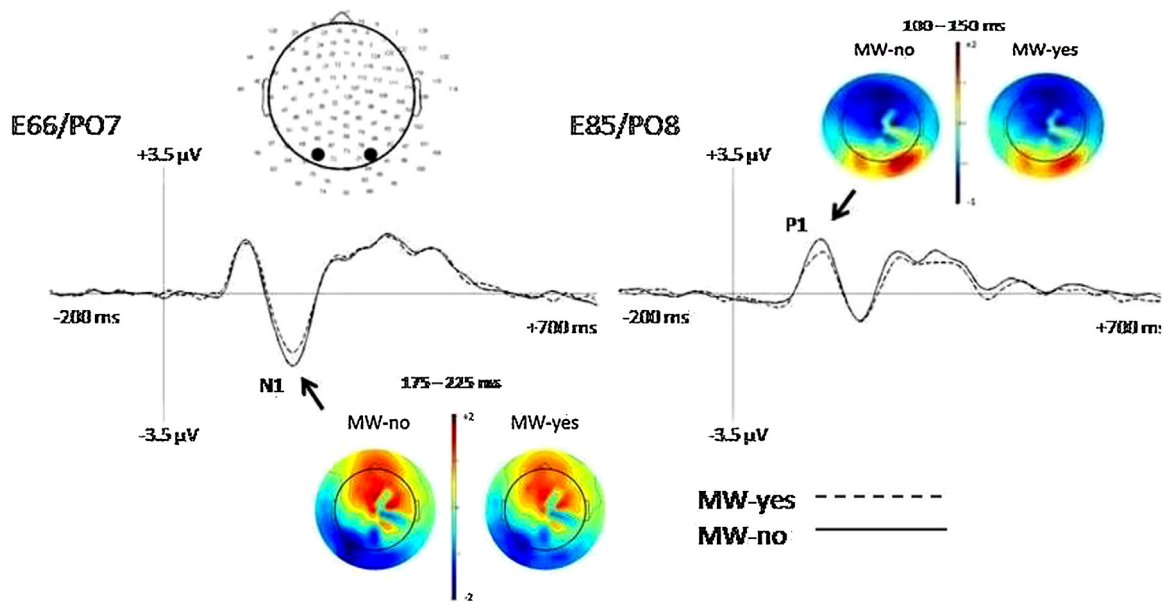


Fig. 1. ERPs evoked by words at two representative lateral-posterior electrodes in left (66/PO7) and right (85/PO8) hemispheres, for MW-yes (dashed lines) and MW-no conditions (solid lines). Arrows indicate ERP components of interest for which significant MW effects were observed (P1, N1). Scalp topographies during the P1 and N1 time-windows are shown for each mind-wandering condition.

$M = 0.86$, $SE = 0.20$), compared to when they were MW (right $M = 1.08$, $SE = 0.19$, left $M = 0.94$, $SE = 0.22$). N1 amplitudes were more negative bilaterally when participants were not MW (averaged across hemispheres, $M = -1.25$, $SE = 0.25$), compared to when they were MW ($M = -1.10$, $SE = 0.24$). Neither P3 nor N4 amplitudes differed by MW, hemisphere, or in the interaction.

Hemispheric asymmetry scores for P1 and N1 amplitudes are plotted in Fig. 2 (bottom panel left). Statistical tests showed that P1-asymmetry was significantly greater than zero when participants were not MW, $t_{(21)} = 2.12$, $p = 0.04$, but was not so when they were MW, $t_{(21)} = 0.73$, $p = 0.47$. In contrast, N1-asymmetry was significantly greater than zero when participants were MW, $t_{(21)} = 4.44$, $p < 0.01$, as well as when they were not MW, $t_{(21)} = 5.45$, $p < 0.01$, confirming the general left-lateralization of the N1 apparent in the scalp topographies (Fig. 1).

Results showed that P1 and N1 were sensitive to within-person changes in MW. For the P1, the within-person MW effect was reflected in greater hemispheric asymmetry (right-hemisphere more positive than left-hemisphere) when individuals were not MW. For the left-lateralized N1, ERPs were more negative overall when individuals were not MW.

3.2.1.2. Pre-stimulus alpha. Scalp topographies for pre-stimulus EEG power in the alpha frequency band (8–12 Hz) are shown in Fig. 2 (bottom panel right, scale in dB). As expected, these show a posterior distribution for pre-stimulus alpha. A 2×2 ANCOVA performed on alpha power depending on the within-subjects factors MW (MW-yes, MW-no) and hemisphere (left, right), and with RAPM as covariate, did not show a significant effect of MW or a significant MW \times hemisphere interaction, $F < 1$. The main effect of hemisphere was significant, $F_{(1,20)} = 4.60$, $p = 0.04$. Left-hemisphere alpha ($M = 0.65$, $SE = 0.09$) was greater than right-hemisphere alpha ($M = 0.64$, $SE = 0.11$). However, this interacted with the covariate, $F_{(1,20)} = 5.55$, $p = 0.03$, indicating that between-person variance in alpha-asymmetry was related to variance in RAPM (MW-yes, $r = -0.54$, $p = 0.01$; MW-no, $r = -0.36$, $p = 0.10$, n.s.). Alpha variables were combined across MW conditions in subsequent analyses.

3.2.2. Individual differences: predicting reading comprehension

ERP variables that had shown within-person effects of MW in the preceding analyses were next evaluated with respect to predicting variance in the criterion measure of reading comprehension, while controlling for individual differences in g. Pre-stimulus

Table 1
Summary of effects on ERP amplitudes.

	TW	F	p	η_p^2	TW	F	p	η_p^2
MW	100–150	0.05	0.83	0.00	300–400	0.55	0.47	0.03
MW \times RAPM		0.23	0.64	0.01		0.13	0.73	0.01
Hem		2.86	0.11	0.13		0.02	0.90	0.00
Hem \times RAPM		1.54	0.23	0.07		0.00	0.96	0.00
MW \times Hem		6.22*	0.02	0.24		0.67	0.42	0.03
MW \times Hem \times RAPM		2.67	0.12	0.12		0.10	0.75	0.01
MW	175–225	4.49*	0.05	0.18	400–500	0.62	0.44	0.03
MW \times RAPM		2.63	0.12	0.12		0.08	0.78	0.00
Hem		2.50	0.13	0.11		1.27	0.27	0.06
Hem \times RAPM		0.06	0.80	0.00		0.14	0.72	0.01
MW \times Hem		3.07	0.10	0.13		0.33	0.57	0.02
MW \times Hem \times RAPM		1.34	0.26	0.06		1.03	0.32	0.05

Notes. $N = 22$. Results of analysis of covariance (ANCOVA) performed separately for each time-window (100–150, 175–225, 300–400, and 400–500 ms) on the ERP hemisphere averages (μV). RAPM was evaluated in the ANCOVA models at its mean = 9.14. Abbreviations: TW = time-window, MW = mind-wandering, Hem = hemisphere, RAPM = Raven's Advanced Progressive Matrices. $df = (1,20)$.

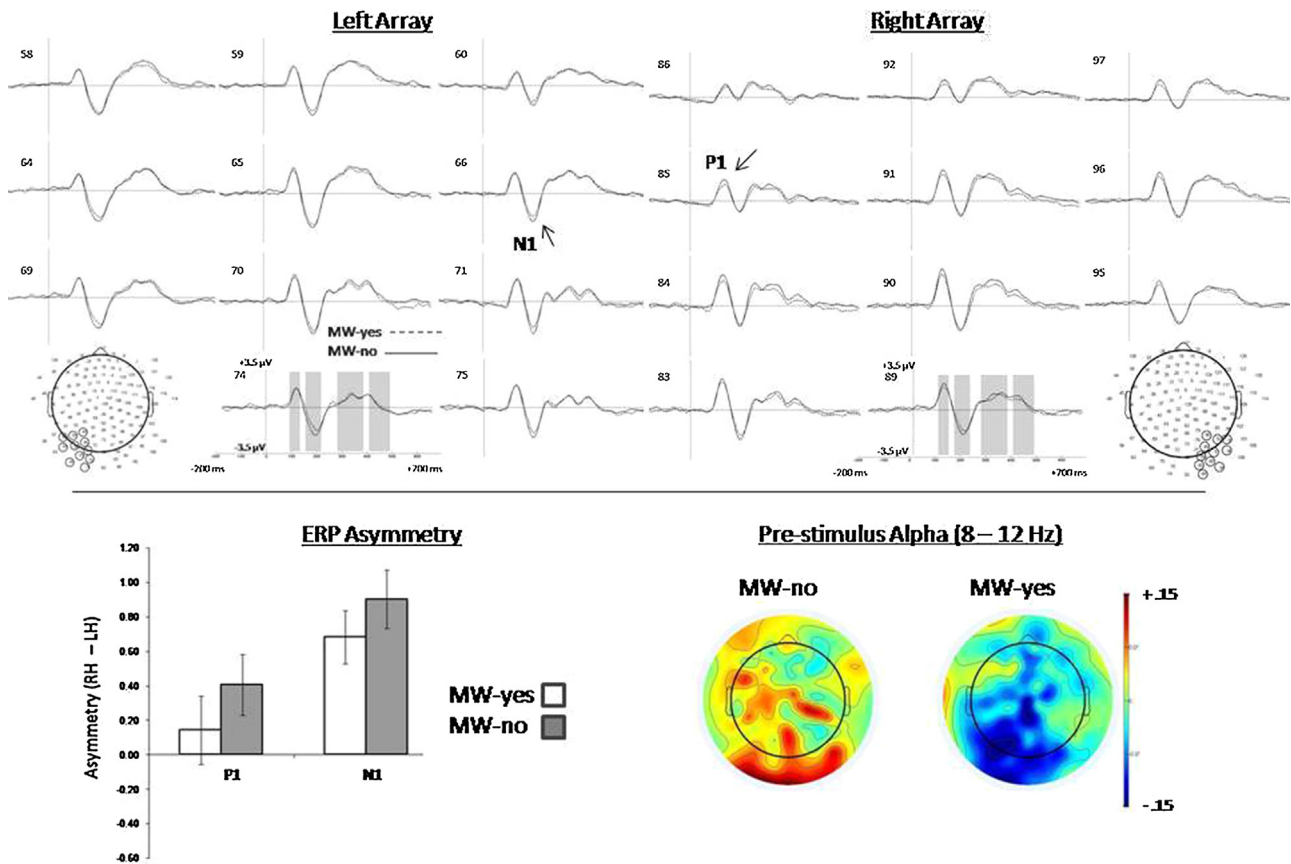


Fig. 2. ERPs for 11-electrode posterior arrays in left- and right-hemispheres. Upper panel: ERPs for MW-yes (dashed lines) and MW-no conditions (solid lines). Scales for amplitude (μV) and time (ms) are shown for electrodes 74 and 89 (shaded areas schematically represent time-windows included in analyses). Electrode locations for left- and right-hemisphere arrays are indicated on head-plots. Bottom panel, left: Hemisphere-asymmetry scores (right-hemisphere minus left-hemisphere) for MW-yes (white bars) and MW-no (gray bars) conditions. More positive values reflect greater positivity in right- versus left-hemisphere; more negative values reflect greater positivity in left- versus right-hemisphere. Error bars represent the standard error of the mean. Bottom panel, right: Scalp topographies for EEG power (dB) in pre-stimulus alpha frequency (8–12 Hz) for MW conditions (scale: -0.15 to $+0.15$ db).

alpha was evaluated as a potential predictor of reading comprehension on account of its interaction with g in the preceding ANCOVA. Pre-stimulus alpha examined separately by hemisphere did not show differential relationships to other variables to be entered as predictors in the regressions. Therefore, pre-stimulus alpha data were combined both across MW conditions and across hemispheres in subsequent analyses. Pre-stimulus alpha power overall was negatively correlated with reading comprehension after controlling for g , $\text{partial-}r = -0.44$, $p = 0.05$, and was positively correlated with MW-rate, $\text{partial-}r = 0.48$, $p = 0.03$. Therefore, regression models predicting reading comprehension included pre-stimulus alpha as well as g , in addition to the ERP variables that had shown within-person effects of MW.

3.2.2.1. MW-no. Next, the ERP variables that were sensitive to within-person changes in MW were evaluated for predictive relationships to reading comprehension. Results are summarized in Table 2, for four hierarchical regression models predicting reading comprehension, progressively including: (1) the g measure RAPM, (2) pre-stimulus alpha (combined across MW conditions and hemispheres), (3) P1-asymmetry (MW-no), and (4) left-hemisphere N1 amplitudes (MW-no). As can be seen, each predictor accounted for a significant increment of variance in reading comprehension after controlling for the predictors entered in preceding steps, accounting for approximately 82% of criterion variance in total. A fifth model additionally including right-hemisphere N1 (MW-no condition) did not account significantly for additional criterion variance, $F < 1$.

To summarize, individual differences in the same ERP variables that were sensitive to within-person changes in MW (P1-asymmetry and left-hemisphere N1) uniquely accounted for about 38% of the variance in reading comprehension after controlling for individual differences in g and pre-stimulus alpha, when individuals were not MW.

Entering left- and right-hemisphere P1 amplitudes (MW-no) in two successive steps (rather than entering P1-asymmetry in a single step), followed by entering left-hemisphere N1, resulted in a regression model that accounted for slightly more total variance in reading comprehension (approximately 83%) than the corresponding model that entered P1-asymmetry in a single step (Model 4, Table 2). Notably, left- and right-hemisphere P1 each significantly accounted for unique increments of predictive variance (approximately 13 and 17%, respectively, $p < 0.01$), adding up to just slightly more predictive variance than was accounted for by P1-asymmetry in the corresponding model (approximately 30 versus 28%, respectively). Thus, results show that P1-asymmetry (MW-no) was robust and efficient at predicting reading comprehension, but when evaluated separately, left-hemisphere and right-hemisphere P1 amplitudes (MW-no) each made unique contributions to prediction.

3.2.2.2. MW-yes. For comparison purposes, Table 3 shows four hierarchical regression models that are the same as those shown in Table 2, except that ERP variables in the MW-no condition were changed to their MW-yes counterparts. As can be seen, less total variance was accounted for in reading comprehension

Table 2
Regression models (MW-no) predicting reading comprehension.

	Model 1		Model 2		Model 3		Model 4	
	B (SE)	<i>t</i>	B (SE)	<i>t</i>	B (SE)	<i>t</i>	B (SE)	<i>t</i>
RAPM	0.03 (0.01)	2.97**	0.03 (0.01)	3.11**	0.04 (0.01)	5.51**	0.04 (0.01)	6.99**
α			-0.14 (0.07)	-2.13*	-0.14 (0.05)	-2.89**	-0.14 (0.04)	-3.58**
No-P1 _{asym}					0.11 (0.03)	4.24**	0.12 (0.02)	5.56**
No-N1 _{left}							-0.04 (0.01)	-3.16**
df ₁ , df ₂	1, 20		1, 19		1, 18		1, 17	
R ²	0.31		0.44		0.72		0.82	
R ² _{adj}	0.27		0.38		0.67		0.78	
R ² _{chng}	0.31		0.13		0.28		0.10	
F _{chng}	8.85**		4.53*		18.00**		10.00**	

Notes. *N* = 22. Hierarchical linear regression models predicting reading comprehension by *g* (RAPM) and electrophysiological variables: pre-stimulus alpha (α) power, P1-asymmetry (MW-no), and left-hemisphere N1 amplitudes (MW-no). ***p* < 0.01. **p* < 0.05.

(approximately 62%) by the models including MW-yes instead of MW-no. MW-yes P1-asymmetry accounted for only about 1.32% of incremental variance in reading comprehension, and left-hemisphere N1 amplitudes were not significantly predictive. Thus, while P1-asymmetry was significantly predictive of reading comprehension even when individuals were MW, it was more strongly predictive when individuals were not MW. Also, left-hemisphere N1 amplitudes were predictive only when individuals were not MW.

To quantify the prediction of reading comprehension by the within-person effect of MW on P1-asymmetry, an additional regression model was evaluated in which P1-asymmetry (MW-yes) was entered in a fifth step after the variables in Model 4, Table 2. After controlling for *g*, alpha, P1-asymmetry (MW-no), and left-hemisphere N1 (MW-no), P1-asymmetry (MW-yes) accounted for an increment of approximately 4.60% of variance in reading comprehension ($F_{(1,17)} = 3.30, p = 0.09$). This estimates the incremental amount of between-person variance in reading comprehension accounted for uniquely by the within-person difference in P1-asymmetry associated with MW.

To help visualize key relationships among individual differences in the data, scatter-plots are shown in Fig. 3, showing the prediction of reading comprehension by RAPM (left plot), and by P1-asymmetry, MW-no (right plot). Scalp topographies for high/low groups for *g* and P1-asymmetry (determined by median-split) are shown under the *x*-axis of the respective plot, and scalp topographies for reading comprehension, low/high groups, are shown vertically along the *y*-axis of the left plot. (Note that high/low groups were formed only for these visualizations). These images show: (1) the extremes of the range of variation in P1-asymmetry, (2) that P1-asymmetry was greater for participants demonstrating better reading comprehension, and (3) that (when not MW) individuals with lower *g* showed more P1-asymmetry than those with higher *g*. Indeed as noted earlier, the correlation between RAPM and P1-asymmetry when participants were not

MW was negative (approaching statistical significance, $r = -0.36, p = 0.10$). Thus, the within-person effect of MW on P1-asymmetry interacted with individual differences in *g*.

3.3. Results summary

When statistically controlling for individual differences in *g*, a cognitive ability expected to predict reading comprehension, ERP results showed specific within-person effects of MW, such that P1 amplitudes were more positive in right-hemisphere versus left-hemisphere when participants were not MW. Furthermore, N1 amplitudes, left-lateralized, were more negative when participants were not MW. Pre-stimulus alpha power did not significantly differ between MW conditions. Furthermore, individual differences in the ERP variables that had shown within-person effects of MW were significantly predictive of reading comprehension, especially when individuals were not MW. When individuals were not MW, P1-asymmetry, left-hemisphere and right-hemisphere P1 amplitudes, and left-hemisphere N1 amplitudes, each robustly accounted for significant variance in reading comprehension, over and above prediction by *g* and pre-stimulus alpha. The within-person effect of MW on P1-asymmetry accounted for approximately 4% of the variance in reading comprehension.

4. Discussion

The first goal of the research was to identify electrophysiological correlates of MW while reading. The second goal was to assess psychometric prediction of reading comprehension by the same EEG/ERP variables that were sensitive to MW. After controlling for individual differences in *g*, it was revealed that selectively when individuals were not MW, posterior P1 amplitudes were more positive over right- versus left-hemisphere sites, 100–150 ms after word-onset. Immediately after, in the 175–225 ms time-window, the N1 component was more negative bilaterally when

Table 3
Regression models (MW-yes) predicting reading comprehension.

	Model 1		Model 2		Model 3		Model 4	
	B (SE)	<i>t</i>	B (SE)	<i>t</i>	B (SE)	<i>t</i>	B (SE)	<i>t</i>
RAPM	0.03 (0.01)	2.97**	0.03 (0.01)	3.11**	0.03 (0.01)	3.80**	0.03 (0.01)	3.67**
α			-0.14 (0.07)	-2.13*	-0.14 (0.06)	-2.37*	-0.13 (0.03)	-2.31*
Yes-P1 _{asym}					0.07 (0.03)	2.36*	0.02 (0.03)	2.25*
Yes-N1 _{left}							-0.03 (0.02)	-1.39
df ₁ , df ₂	1, 20		1, 19		1, 18		1, 17	
R ²	0.31		0.44		0.57		0.62	
R ² _{adj}	0.27		0.38		0.50		0.53	
R ² _{chng}	0.31		0.13		0.13		0.04	
F _{chng}	8.85**		4.53*		5.54*		1.92	

Notes. *N* = 22. Hierarchical linear regression models predicting reading comprehension by *g* (RAPM) and electrophysiological variables: pre-stimulus alpha (α) power, P1-asymmetry (MW-yes), and left-hemisphere N1 amplitudes (MW-yes). ***p* < 0.01. **p* < 0.05.

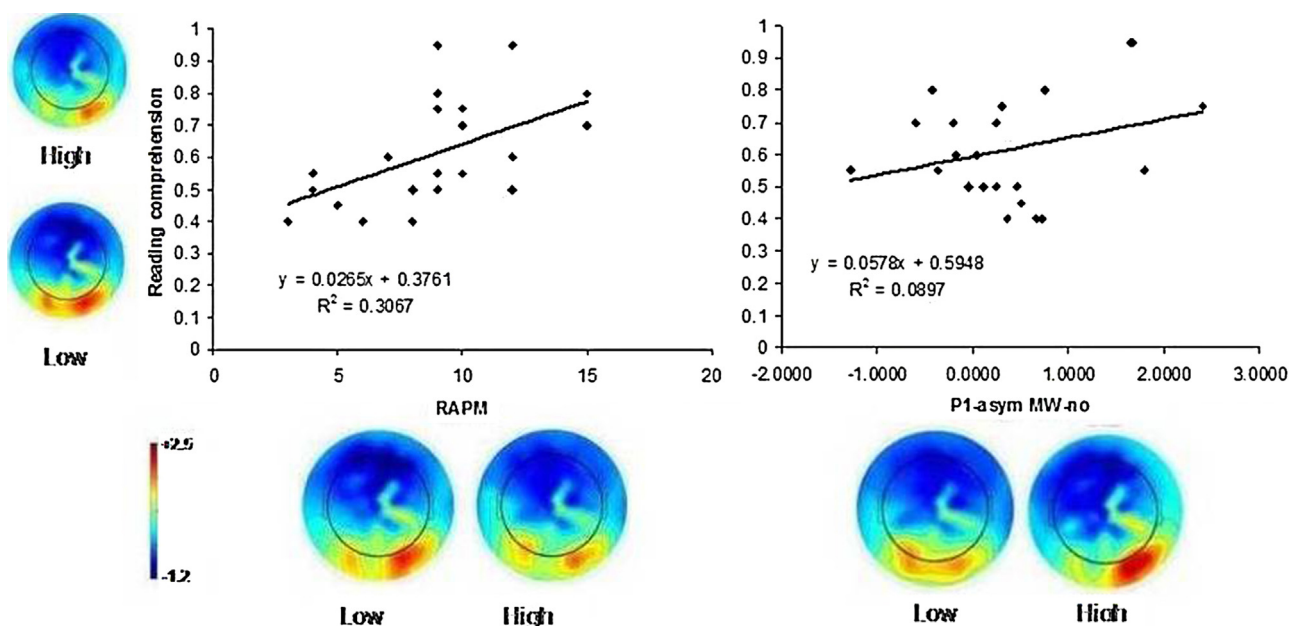


Fig. 3. Plots depicting relationships between reading comprehension (y-axis both panels) and (1) *g* (RAPM; x-axis left panel) and (2) P1 asymmetry, MW-no condition (x-axis right panel). Scalp topographies (scale in μV) are also shown, corresponding to MW-no condition, low/high groups (determined by median-split) for reading comprehension, RAPM, and P1-asymmetry (shown alongside respective plot axes).

individuals were not MW, although this component was generally left-lateralized like the RP, N170 and other early negative ERPs associated with reading.¹

Later, ERPs in the P300 and N400 time-windows did not show MW-related effects. Pre-stimulus alpha did not show an MW effect but was related negatively to reading comprehension and positively to MW-rate; therefore, pre-stimulus alpha power was included in subsequent hierarchical regressions as a further statistical control on individual differences, in addition to *g*. It was shown that individual differences in the MW-sensitive ERPs were significantly predictive of reading comprehension, accounting for approximately 38% of criterion variance, over-and-above prediction by *g* and pre-stimulus alpha.

The MW-related effects for the early-appearing ERPs, P1 and N1, are consistent with the process of perceptual decoupling as a general accompaniment of MW, and with results of previous EEG/ERP studies that found MW-related attenuation of the P1 to visual stimuli presented during the SART (Baird et al., 2014; Kam et al., 2010). However, the present results are novel in showing the relevance of early visual processing to a real-world ability involving complex, higher-order cognition, i.e., reading for comprehension.

No MW effects were observed later than about 225 ms in the present results, although MW effects on the later-appearing P300 have been reported consistently in studies using the SART (Barron et al., 2011; Smallwood et al., 2008a,b) and other procedures (Kam et al., 2014) in which participants must detect rare or salient targets in a stream of non-targets. In the present study, however, participants read ordinary nonfiction prose passages one word at a time and were not required to overtly execute or withhold any responses during the reading task. It is known that passive-viewing conditions attenuate the P300 (Benington & Polich, 1999). Moreover, the analyses were not sensitive to effects of any particular surprising or inciting elements that might have been contained in the reading material. These key differences between stimulus- and task-characteristics likely explain the discrepancy concerning the P300 across the present results and those from previous ERP studies of MW.

The present results did not support the additional prediction of the “cascade model of inattention” concerning MW while reading (Smallwood, 2011), i.e., that attenuation of early ERPs would “cascade” to attenuate later ERPs like the N400. However, it should be noted that the N400 is modulated by similar parameters as the P300 (Arbel, Spencer, & Donchin, 2010), i.e., stimulus probability and salience. Therefore, it is likely that the present paradigm was not sensitive to MW-related effects on the N400. However, results suggest that MW-related differences in late-appearing language-related ERPs such as the N400 were not necessary in order to observe significant consequences for complex semantic processing, such as reading for comprehension.

Notably, the early ERPs related to perceptual analysis and word recognition (P1 and N1), when individuals were not MW, were sufficient to account for significant variance in reading comprehension. Thus, results would seem to pose challenges for serial or cascade interpretations of ERP correlates of language processing, in which early- and late-appearing components are assumed to reflect progressively more complex levels of language processing. In contrast, results are generally consistent with parallel-interactive models of word reading, in which “nearly-simultaneous” access to lexical and semantic-contextual information is acquired within the first 250 ms after word-onset (Pulvermueller et al., 2009). Moreover, this perspective is consistent with results from eye-tracking studies showing that eye-fixations while reading are typically around 250 ms in duration (Rayner & Clifton, 2009). In this framework, late-appearing ERPs like N400 and P600 (widely associated with detecting semantic and syntactic violations respectively; Kaan, 2007) reflect “post-comprehension” or “re-analysis” processes, that become necessary in the face of linguistic anomalies (Pulvermueller et al., 2009).

Individual differences in left- and right-hemisphere P1 amplitudes as well as P1-asymmetry were significantly predictive of reading comprehension. This would seem to implicate the P1 as making important contributions to complex cognition depending on perceptual analysis. Thus, results appear to support an interpretation of the P1 in which it reflects complex processes of perceptual analysis and categorization that are critical to accessing

a general personal knowledge-base (Klimesch, 2011, 2012). The present finding that P1 amplitudes in left- and right-hemisphere each made independent and unique contributions to predicting reading comprehension suggests the existence of dissociable language processing functions for the hemispheres (Federmeier et al., 2008; Hellige, 1993), which were affected by MW. Notably in this connection, present results are convergent with those of a recently reported developmental study (Molfese et al., 2013), in which right-hemisphere P1 amplitudes effectively discriminated “typically developing” children from those with reading disabilities, while among this latter group, left-hemisphere P1 amplitudes discriminated “adequate responders” from “inadequate responders” to reading skills instruction. Additionally, they found that bilateral N2 amplitudes discriminated among all three groups.

Present results suggest that critical right-hemisphere functions related to attention and/or language processing were differentially engaged depending on whether or not individuals were MW. With respect to language processing, the differential right-hemisphere engagement might have reflected greater involvement of relatively coarse-grained semantic processing (Fiore & Schooler, 1997; Holtgraves, 2013; Jung-Beeman, 2005), which could have supported more complete comprehension at multiple levels of communication. Effects of semantic and other higher-order linguistic parameters have been shown as early as approximately 100 ms after word onset (Bayer, Sommer, & Schacht, 2012; Fields & Kuperberg, 2012; St. George, Mannes, & Hoffman, 1994; Sereno et al., 2003). The present findings are consistent with existing evidence that early ERPs can be affected by higher-order linguistic parameters such as semantic context.

Alternatively, greater right-hemisphere engagement might have reflected greater engagement of a right-hemisphere-dominant cortical network for controlling spatial (Foxe et al., 2003; Shulman et al., 2010), non-spatial (O’Connell, Schneider, Hester, Mattingley, & Bellgrove, 2011), and/or vigilant attention (Langner & Eickhoff, 2012), each of which would support more efficient perceptual categorization and word recognition and could therefore lead to better comprehension. Attentional effects on P1 are fairly commonplace (Luck, Woodman, & Vogel, 2000). Indeed, it is possible to articulate a purely attention-based explanation for the MW-related effect on P1-asymmetry, by noting that the word stimuli in the present study were centered on central fixation so that initial letters extended into the left visual field. Therefore, it is plausible to suppose that participants in this study developed an attentional bias for processing the left visual field. This attentional bias could easily result in enhanced P1 in the contralateral (right) hemisphere (Luck et al., 2000), and this would likely be modulated by MW (inattention). However, this explanation is countered by observing right-hemisphere P1-enhancements to words presented vertically along the visual-field midline (Rosazza, Cai, Minati, Paulignan, & Nazir, 2009), indicating that right-hemisphere dominant P1-asymmetry does not depend on a left visual-field attentional bias. Furthermore, this purely attention-based account would not lessen the utility of P1-asymmetry as a sensitive marker of MW while reading, which was moreover predictive of comprehension.

Individual differences in early MW-sensitive processes reflected in the P1–N1 complex (when individuals were not MW) accounted for approximately 38% of the variance in performance on subsequent tests of reading comprehension. Thus, it appears that brain responses within about 250 ms after word-onset had far-reaching consequences for higher-order language processing, depending especially on whether or not individuals were MW. Results also showed that when individuals were MW, these same ERP measures were weakly related if at all to reading comprehension. The stronger prediction by MW-no ERP variables confirms that neural processes underlying task performance and reflected in ERPs were more closely supporting ongoing word recognition and reading

comprehension when individuals were not MW. In classical psychometric terms this means that MW-no ERPs reflect more “true score” and less error variance (or noise).

However, it was desired to estimate the potential cost of mind-wandering to individuals, not just at the group level. Therefore, the prediction of reading comprehension by the within-person effect of mind-wandering on P1-asymmetry was estimated in regression models. These suggested that, to the extent that a person can refrain from mind-wandering while reading, individual differences in reading comprehension between that person and a more skilled reader (who did not so constrain her/his mind-wandering) would be significantly reduced, perhaps by as much as about 4.6% across a population of such pairs of individuals.

To put these findings in wider perspective, it is instructive to look at what variables are commonly used to predict reading comprehension in the developmental literature addressed to reading and literacy, and how much criterion variance is typically accounted for by these predictors. In large-sample developmental studies (Hoover & Gough, 1990) typically about 70–85% of variance in reading comprehension is explained by combinations of multiple measures of “decoding” and “comprehension” constructs (Hoover & Gough, 1990; Jenkins, Fuchs, van den Broek, Espin, & Deno, 2003; Klauda & Guthrie, 2008). These tests are directly measure component processes of reading ability, such as reading words and pseudowords aloud, or listening to a story and then answering questions about it. Notably, a comparable total amount of variance in reading comprehension was explained in the present work by: (1) a non-verbal measure of *g*, (2) pre-stimulus alpha, (3) P1-asymmetry (MW-no), and (4) left-hemisphere N1 (MW-no). In contrast to standard measures of fluency and comprehension, these predictor variables would seem to have very little surface-similarity to the criterion of reading for comprehension, and yet about the same amount of criterion variance was explained. Moreover, incremental predictive variance in comprehension explained by the within-person effect of MW on P1-asymmetry (4.6%) was comparable in size to that explained by behavioral measures of component abilities of reading, as in Klauda and Guthrie (2008): inferencing (8%), word reading speed (10%), syntactic processing (5%), and passage-level processing (2%). Thus, the MW-sensitive ERP measures in the present work appeared as strongly related to reading comprehension as standard behavioral measures that much more directly assess component abilities of reading.

In a recent meta-analysis, Fletcher and colleagues reported that *g* did not strongly predict response-to-treatment in reading instruction programs (Stuebing et al., 2009). Thus, especially because the present ERP predictors of comprehension were independent of individual differences in *g*, they would appear to have practical utility augmenting traditional psychometric prediction of reading ability and response to reading instruction. In particular, the present findings suggest that the efficiency of decoding processes could be sensitively assessed by P1–N1 measures, particularly when individuals were not mind-wandering. Moreover, these signals could be targeted in neurofeedback training to enhance attention while reading and to increase comprehension.

The present results add to a growing literature on early brain responses (<250 ms) while reading (for reviews see. e.g., Dien, 2009a,b; Pulvermüller et al., 2009), suggesting these are important for higher-order complex cognition, quite beyond processing physical and orthographic characteristics of words. The current findings also add to a relatively heterogeneous literature on ERP predictors of reading ability per se. Korinth, Sommer, and Breznitz (2012) recently reported that individual differences in reading speed among young adults were predicted by N170 latencies in a word recognition task. Earlier Rudell and Hua (1997) found that RP latencies in a word-recognition task predicted scores on the verbal portion of the Graduate Record Examination. In contrast, the present

study found that early ERP amplitudes, rather than latencies, predicted comprehension (of the naturalistic text passages eliciting the ERPs). Among developmental studies not already mentioned, [Silva-Pereyra, Bernal, Rodriguez-Camacho, Yanez, and Rodriguez \(2010\)](#) recorded EEG while children performed a cued go/no-go task, finding reduced right-hemisphere P2 amplitudes among children identified as poor readers. Similarly, attenuated lateralization of early ERPs has been reported for dyslexic children ([Schulte-Körne, Bartling, Deimel, & Remschmidt, 1999](#)). In a lifespan developmental study with children, younger adult, and middle-aged adult participants, [Spironelli and Angrilli \(2009\)](#) reported left-lateralization of the N150 in adults, but right-lateralization in children. And in a study of adolescents, [Segalowitz, Wagner, and Menna \(1992\)](#) reported that good readers showed P300 hemispheric asymmetries while poor readers did not. The present study found generally convergent results, in that more negative left-hemisphere P1 and N1 amplitudes, as well as greater P1-asymmetry (right-hemisphere more positive than left), were each significantly predictive of better reading comprehension among younger adults. Altogether, present results add to substantial evidence that early ERPs and hemispheric asymmetries can be used as diagnostic signals of individual differences in reading ability, implicating the roles for attention and functional lateralization in comprehending written language.

The electrophysiological literature concerning *g* is heterogeneous; however, ERP differences between high- and low-*g* individuals, emerging between 140 and 240 ms after stimulus-onset, have been consistently reported using a range of elementary cognitive tasks correlating positively with *g* (for a review, see [Deary & Caryl, 1997](#)). Early ERPs (<200 ms) evoked even by simple auditory and visual stimuli have been reported to predict individual differences in *g* ([Brumback, Low, Gratton, & Fabiani, 2004](#)). ERP differences related to *g* in the present study were likely related to differences in the anatomy or efficiency of cortical networks ([Langer, Pedroni, Gianotti, Hanggi, Knoch, & Jancke, 2012](#)), here manifested in relation to language processing and attention. Apparently, individuals with lower *g* had to work harder to achieve the same level of cortical engagement with the text passages as did individuals with higher *g*. This idea is consistent with PET studies reporting negative correlations between *g* and regional glucose uptake (for a review, see [Deary & Caryl, 1997](#)). However, results showed that when not MW, the ERPs of individuals with lower *g* more closely resembled the ERPs of better readers (showing more P1-asymmetry). This suggests a potential strategy by which individuals with lower *g* might boost their performance on cognitive tasks like reading for comprehension (namely, refraining from MW).

4.1. Limitations and caveats

It should be noted that the FFT to derive pre-stimulus alpha measures was performed on a very short segment of data (50 ms) per trial and that even with a large number of trials the alpha results should be interpreted with caution. Additionally, the artifact-rejection process resulted in discarding a large portion of data, which is not optimal ([Keil et al., 2014](#)). Finally, possible overlap of ERP components during the chosen time-windows should be considered ([Keil et al., 2014](#)). There may have been electrophysiological activity during the time-windows that reflected ERP components besides those discussed in this article ([Keil et al., 2014](#); [Luck, 2005](#)).

4.2. Summary and conclusions

Consistent with parallel-interactive theories of language processing ([Carreiras et al., 2014](#); [Price & Devlin, 2011](#);

[Pulvermueller et al., 2009](#)), results suggest the following scenario. Individual differences in pre-stimulus alpha were associated with tonic differences in task-set and temporal attention, in anticipation of viewing the individual words presented successively in the text passages. When individuals were MW, preconscious processes of attentional filtering and perceptual categorization reflected in P1 were less robust. This likely contributed to inefficient access to the personal “knowledge system” ([Klimesch, 2011, 2012](#)). Additional ramifications of MW were evident immediately following P1, in a diminished N1 response. The attenuated N1 likely reflected diminished effectiveness of word-recognition ([Dien, 2009b](#); [Martín-Loeches, 2006](#)) and decoding processes ([Hoover & Gough, 1990](#)). Thus, MW-related inattention and deficiencies in word-reading fluency led to poorer ongoing comprehension and integration of word-meanings into higher-level semantic structures at sentence- and discourse-levels (indicated by poorer comprehension).

Results confirmed again the phenomenon of perceptual decoupling as a general accompaniment of MW; and went further than previous EEG/ERP studies of MW in this respect, by demonstrating the relevance of perceptual decoupling for higher-order complex cognition. Results have theoretical implications toward better understanding of the effects of MW while reading and its neural bases; and more generally, the functional meaning of the P1–N1 complex. Furthermore, results have practical implications for the covert detection of MW and the development of brain-based interventions to remediate MW, as well as enhance reading comprehension and general cognitive functioning. Accounting for mind-wandering in future studies of dyslexia and reading disorder may provide an important clue to distinguishing those individuals who would be most ready to benefit immediately from reading instruction, versus those who would likely to benefit after a preliminary intervention to enhance attentional-control skills.

Note

¹ The N1 observed in this study appears earlier than usually reported for the RP, although the scalp distributions are similar, and the present procedure was not optimal for observing the RP according to some experts ([Martín-Loeches, 2006](#)). It is possibly an N170, also associated with lexical access, and again the scalp topographies are similar. Because of the possibility of component-overlap, the “N1” in this study is probably best characterized simply as a left-lateralized posterior negativity peaking at approximately 200 ms after word onset; that was moreover, predictive of reading comprehension when individuals were not MW.

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