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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.

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, Nortin, 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; Sereno & 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 Pulvermueller, 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; Sereno & 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 (Debruille, 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