Going AWOL in the Brain: Mind Wandering Reduces Cortical Analysis of External Events

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Abstract

■ Converging evidence from neuroscience suggests that our attention to the outside world waxes and wanes over time. We examined whether these periods of "mind wandering" are associated with reduced cortical analysis of the external environment. Participants performed a sustained attention to response task in which they responded to frequent "nontargets" (digits 0–9) and withheld responses for infrequent "targets" (the letter X). Mind wandering was defined both behaviorally, indicated by a failure to withhold a response to a target, and subjectively, via self-report at a thought probe. The P300 event-related potential component for nontargets was reduced prior to both the behavioral

and subjective reports of mind wandering, relative to periods of being "on-task." Regression analysis of P300 amplitude revealed significant common variance between behavioral and subjective markers of mind wandering, suggesting that both markers reflect a common underlying mental state. Finally, control analysis revealed that the effect of mind wandering on the P300 could not be ascribed to changes in motor activity nor was it associated with general arousal. Our data suggest that when trying to engage attention in a sustained manner, the mind will naturally ebb and flow in the depth of cognitive analysis it applies to events in the external environment. ■

INTRODUCTION

Our attention to the outside world has long been known to wax and wane over time, producing reliable oscillations between periods of comparatively high and low externally oriented attention (James, 1890). This latter state in particular—where attention is disengaged or *decoupled* from the constraints imposed by the task environment—has been described as "mind wandering" (Mason et al., 2007; Smallwood & Schooler, 2006), and is believed to reflect transient episodes during which ongoing thought competes with the processing of external, task-relevant information in working memory. One implication of this view is that mind wandering will compete with task-relevant information, and thus, reduce the cognitive analysis of external events (e.g., Smallwood & Schooler, 2006; Dehaene & Changeux, 2005).

Consistent with this model of mind wandering, recent neuroimaging evidence has revealed a network of task-related cortical areas that manifest reduced levels of activation during brief lapses in behavioral performance (e.g., Weissman, Roberts, & Woldroff, 2006). This net-

work includes the right inferior frontal gyrus, involved in stimulus-triggered attentional orienting (e.g., Corbetta & Shulman, 2002); the middle frontal gyrus, involved in maintaining task goals in working memory (e.g., Kerns et al., 2004; Miller & Cohen, 2004); and the anterior cingulate cortex, implicated in the detection and/or resolution of conflict (e.g., Boynton, Engel, Glover, & Heeger, 1996). However, at least two central questions remain regarding current models of mind wandering (e.g., Smallwood & Schooler, 2006; Dehaene & Changeux, 2005): Is cognitive analysis actually reduced for external events during periods of mind wandering, and can this transient effect be linked to the subjective reports of off-task thinking?

To address these questions, we adopted a paradigm designed to exploit the fact that mind-wandering episodes are frequent when tasks are simple or overlearned (e.g., Cheyene, Carriere, & Smilek, 2006; Giambra, 1995; Teasdale, Proctor, Lloyd, & Baddley, 1993; Antrobus, 1968). Specifically, participants performed a sustained attention to response task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), where a "nontarget" visual stimulus was presented once every 2 sec, on average, and required a simple manual response. Occasionally, a "target" stimulus was presented instead that required a manual response to be withheld. In this manner, the SART reverses the normal response contingencies of targets and nontargets, such that the former is signaled by response

inhibition and the latter by response execution. Importantly, the simple and rote nature of the SART is such that mind-wandering episodes during performance are frequent (e.g., Smallwood et al., 2004).

Given this paradigm, we operationally defined periods of mind wandering using two complementary approaches. In terms of objective behavior, an inability to withhold a response to a target stimulus can be taken as evidence of failing to adequately attend to the task (e.g., Manly, Lewis, Robertson, Watson, & Datta, 2002; Manly, Robertson, Galloway, & Hawkins, 1999; Robertson et al., 1997). We thus considered manual responses to the infrequent targets (an error) as a behavioral marker of mind wandering, whereas correctly withheld responses were taken as behavioral markers of being ''on-task.'' In terms of the subjective experience of mind wandering, research has documented that people can reliably report whether they were ''on task'' via verbal reports, a method that allows one to systematically categorize behavioral and psychophysiological data as reflecting different attentional states (for a review, see Smallwood & Schooler, 2006). Accordingly, to provide a subjective marker of mind wandering, we terminated each trial block with a ''thought probe'' at which participants were asked to report on the contents of consciousness *immediately* prior to the probe. A broad literature has indicated that, often, participants are unaware of these lapses (e.g., Smallwood et al., in press; Hester, Foxe, Molholm, Shpaner, & Garavan, 2005; Schooler, Reichle, & Halpern, 2005; Rabbit, 2002) and in this study we explored whether awareness of moderated the effects of mind wandering on the cortical processing of the task environment. To examine the role of awareness of mind wandering, participants were instructed to categorize their mental state at the time of the thought probe into one of three categories: ''on-task,'' ''tuned out'' (mind wandering with awareness), or ''zoned out'' (mind wandering without awareness).

To determine whether the cognitive analysis of external events does, in fact, decrease during mind-wandering episodes, we recorded the event-related potentials (ERPs) generated by the nontarget stimuli as a function of whether they immediately preceded a marker of mind wandering or being ''on-task.'' In particular, the amplitude of the P300 component indexes the extent to which stimulus context is updated in memory (e.g., Donchin & Coles, 1988) or more generally, the amount of attentional resources directed toward that stimulus at the time of presentation (e.g., Kramer & Strayer, 1988; Polich, 1986; Wickens et al., 1983). Moreover, dual-task conditions reduce the amplitude of the P300, suggesting that the component ''addresses a general aspect of working memory'' (Singhal & Fowler, 2004, p. 131). If episodes of mind wandering are, indeed, associated with decreases in the cognitive analysis of external events because working memory ceases to be constrained task-relevant information (e.g., Smallwood & Schooler, 2006;

Dehaene & Changeux, 2005), there should be a reduction in P300 amplitude for nontargets prior to both behavioral and subjective markers of mind wandering, relative to nontargets immediately preceding markers of being ''on-task.''

METHODS

Participants

Twenty-two participants (6 men, 16 women) completed the experiment in exchange for $20 (CAD). All participants were right-handed, with no history of neurological problems, and normal or corrected-to-normal vision. All gave informed consent according to the guidelines of the University of British Columbia Clinical Review Ethics Board.

Stimuli and Paradigm

Task stimuli where presented at the center of the screen sequentially. Participants were asked to respond to a stimulus if it was a number (0–9, the nontarget stimuli) and to withhold a response when presented with a letter (X, the target stimulus). The interstimulus interval (ISI) varied between 1900 and 2100 msec, and the duration of each stimulus (target and nontargets) was 500 msec. All participants signaled the presence of each nontarget letter via a manual finger press with the right hand via a hand-held game pad. Within each block of trials, target probability was quasi-randomized, with the constraints that (1) a minimum of one and a maximum of two targets were presented during each block, and (2) for blocks having two targets, the targets would be separated by at least 10 nontarget events. Participants received an equal number of one- and two-target blocks, with a total of at least 24 trial blocks per participant. The total duration of ERP testing lasted approximately 40 min.

Participants were instructed to expect a thought probe at the end of each block, thus block duration was randomly varied between 30 and 90 sec in order to (1) minimize predictability of block completion and (2) maximize variability of mind-wandering state at the time of the thought probe. At each probe, participants were asked to characterize their experiences immediately prior to the thought probe as either being ''on-task'' (fully attentive of performing the task at hand), ''tuned out'' (aware of mind wandering away from the task at the time the thought probe was presented), or ''zoned out'' (off-task but unaware of mind wandering away from the task at the time the thought probe was presented). Based on these operational definitions of mind-wandering states, ''tune-outs'' can be understood as the experience of knowing that you have been off-task, and ''zone-outs'' can be understood as the experience that you are surprised to find your were off-task (see Schooler et al., 2005). Importantly, participants

were provided with both written and verbal descriptions of these three ''mental'' states prior to beginning the testing session (see Smallwood et al., in press, for the complete instructions) and all readily reported a real-world familiarity with these three states via reflection on their own past cognitive experience. Responses to each thought probe were recorded by the investigator at the conclusion of each trial block.

Electrophysiological Recording and Analysis

Scalp potentials were recorded from 24 tin electrodes mounted in a custom elastic cap: standard sites O1, O2, Oz, T5, T6, T3, T4, P1, P2, P3, P4, P5, P6, Pz, C3, C4, Cz, F7, F8, Fp1, Fp2, Fz, along with PO1, PO2, and POz (midway between O1/O2/Oz and P1/P2/Pz), OL and OR (midway between O1/O2 and T5/T6); an additional channel recorded potentials from the right mastoid. All electroencephalographic (EEG) activity was recorded relative to the left mastoid, amplified (Grass Instruments, Model 12 Neurodata Acquisition System) with a band-pass of 0.1–30 Hz (1/2 amplitude cutoffs), and digitized on-line at a sampling rate of 256 samples-per-second. To ensure proper eye fixation, vertical and horizontal electro-oculograms (EOGs) were also recorded, the vertical EOG from an electrode inferior to the right eye, and the horizontal EOG from an electrode on the right outer canthus. All electrode impedances were kept below 5 kΩ. Off-line, computerized artifact rejection was used to eliminate trials during which detectable eye movements (>1°), blinks, muscle potentials, or amplifier blocking occurred; no participant had more than 7% of their total number of trails rejected due to these signal artifacts. For each participant, ERPs for each condition of interest were then averaged into 3000 msec epochs, beginning 1500 msec before stimulus onset. Subsequently, all ERPs were algebraically re-referenced to the average of the left and right mastoid signals, and filtered with a low-pass Gaussian filter (25.6 Hz half-amplitude cutoff) to eliminate any residual high-frequency artifacts in the waveforms. All statistical analyses of ERP waveforms were based on mean amplitude measures using repeated measures analyses of variance (ANOVAs), with specific time windows of analyses identified below as per each reported ANOVA. A −200 to 0 msec prestimulus baseline was used for all P300 measurements and displays.

RESULTS

Behavior

As the behavioral marker of mind wandering, the error rate for targets was 0.32 (SD = 0.14), averaged across participants. As the subjective markers of mind wandering, the self-report rate for ''zone-outs'' was 0.24 (SD = 0.12) and the self-report rate for ''tune-outs'' was 0.30

(SD = 0.16). These frequencies are in the typical range expected when using the SART to study mind wandering (Smallwood et al., 2004). In terms of validating participants' ability to reliably report their mind-wandering state, the proportion of tune-outs and zone-outs was in the approximate range of response inhibition errors that individuals did and did not report recognizing (Hester et al., 2005).

Event-related Potentials

Our primary ERP analysis centered on the P300, a component reliably elicited by target events and that is typically maximal over midline parietal–central scalp electrode sites (see Coles & Rugg, 1995). We thus constrained statistical analysis of the ERP data a priori to midline parietal and central electrodes Pz and Cz, respectively, along with four additional electrode pairs sampling the immediately adjacent scalp regions: left dorsolateral (electrodes P1 and C3), right dorsolateral (P2 and C4), left ventrolateral (PO1 and P5), and right ventrolateral (PO2 and P6). The repeated measures ANOVAs performed on the mean amplitude of the P300 reported below included scalp region (with 5 levels) as a factor.

The ERP waveforms for each condition of interest were themselves based on averaging together the EEG epochs for the six nontargets preceding each of the two target conditions (a correctly withheld response vs. a response error) and each of the three thought probe/mind-wandering conditions (on-task vs. zoned out vs. tuned out). Although we had no knowledge as to how long participants had actually been in a particular mind-wandering state at the time a behavioral or subjective marker was measured, our analyses were based on the assumption that the 15 sec prior to each marker would consistently fall within that mind-wandering state on average. Although a shorter premarker time window for averaging nontarget EEG epochs would more accurately capture mind-wandering states, it would also reduce the number of events in the ERP averages. The choice of how many premarker events to include in the averages was therefore an attempt to maximize the number of events per each waveform average while not extending the window back so far in time as to consistently capture the preceding mental state or transition period between states. The waveforms reported below for each condition of interest were based on the following number of events/EEG epochs (as averaged across participants): ''correct'' (176.6 events/epochs), ''error'' (82.6), ''on-task'' (98.6), ''zoned out'' (46.8), and ''tuned out'' (62.0).

We first examined the P300 amplitude elicited by nontargets preceding target events that either (1) correctly had a response withheld (''correct'') or (2) incorrectly engendered a response (''error''). We found that the P300 amplitude appeared to be larger for nontargets

in the "correct" relative to "error" condition (Figure 1A). This pattern was confirmed statistically via a repeated measure ANOVA on the mean amplitude of the P300 across a 300 to 600 msec poststimulus time window capturing the approximate peak of the P300 across the electrode sites of interest (Table 1, top). This analysis revealed a main effect of error condition [$F(1, 21) = 8.00$, $p = .0101$]. Although a main effect of scalp region indicated an expected overall difference in P300 ampli-

tude across regions [$F(4, 84) = 8.96$, $p = .0001$], there was no significant interaction between error condition and scalp electrode region [$F(4, 84) = 1.41$, $p = .2388$].

We then examined the P300 amplitude elicited by nontargets immediately preceding the thought probes as a function of self-reported mind-wandering state: "on-task," "zoned out," or "tuned out." We found that the amplitude of the P300 associated with nontargets in an "on-task" state appeared to be larger, relative to nontargets immediately preceding a self-report of "zoned out" and "tuned out" (Figure 1B). This pattern was also confirmed statistically via a repeated measures ANOVA on the mean amplitude of the P300, again across a 300 to 600 msec poststimulus time window (Table 1, bottom), which showed a main effect of self-report [$F(2, 42) = 3.65$, $p = .0347$]. Although a main effect of scalp region again indicated an expected overall difference in P300 amplitude across regions [$F(4, 84) = 9.10$, $p = .0001$], there was no significant interaction between self-report and scalp region [$F(8, 168) = 0.94$, $p = .4857$]. Simple main effects analysis indicated a reliable difference between "on-task" with "tuned out" ($p = .02$) and approached significance when comparing "on-task" with "zoned out" ($p = .07$), whereas the comparison between "tuned out" and "zoned out" was nonsignificant ($p = .72$).

Motor Controls

Although the ERP data converged on the finding of a reduced P300 amplitude to nontargets for both behavioral and subjective markers of mind wandering, we wanted to consider the possibility that these decreases in amplitude may have had two separate causes, rather than tapping into a common mental state. For example, the decrease in P300 amplitude observed prior to behavioral "errors" could perhaps be related to transient changes in motor control, whereas subjective off-task reports could be driven by a top-down division in attention. If so, there should be a relatively low correlation in P300 amplitude when comparing across the behavioral and subjective markers of mind-wandering state. On the other hand, if both mind-wandering markers are tapping into a common underlying attentional state, there should *only* be a reliable association between the P300 amplitude when both behavioral and subjective markers imply mind wandering, or alternatively, an "on-task" mental state.

Consistent with the latter possibility, we observed a high correlation in P300 amplitude between individuals' separate behavioral and subjective markers of mental state. In particular, the correlation in P300 amplitude between a verbal report of "on-task" and targets with a correctly withheld response (i.e., markers of non-mind wandering) was $R^2 = .651$ (Figure 2A). Likewise, the correlation in P300 amplitude between a verbal report of "zone-out" and "error" was $R^2 = .569$ (Figure 2B). Finally, the correlation in P300 amplitude between a
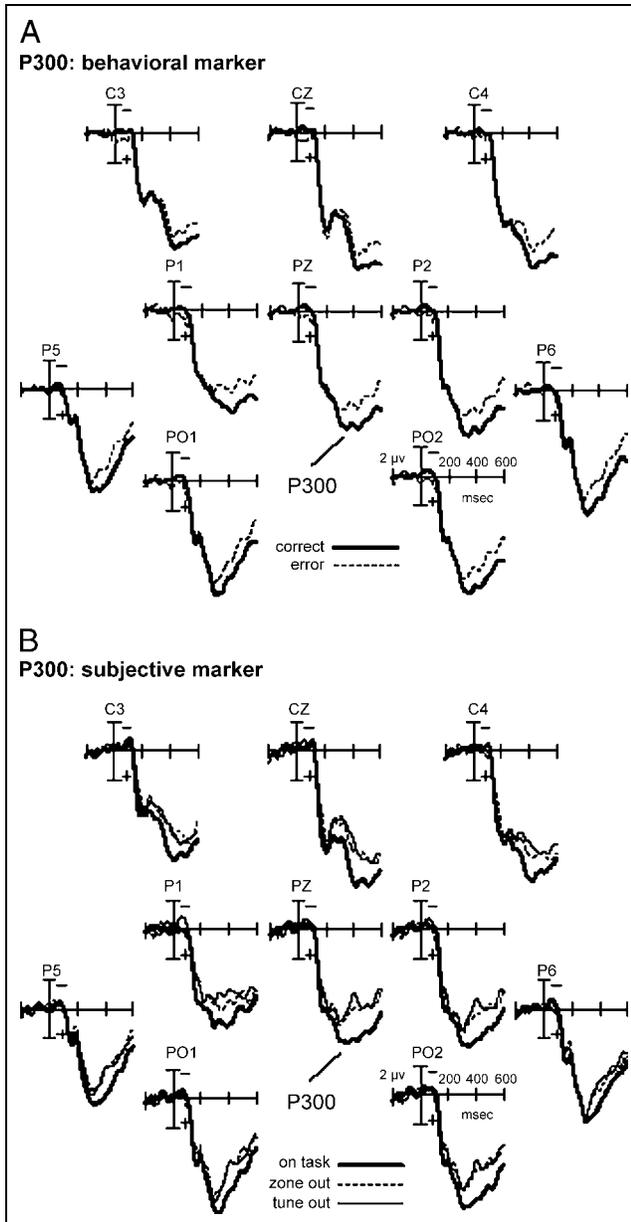
Figure 1. The P300 as a function of behavioral (A) and subjective (B) markers of mind-wandering state. In each figure, the P300 is the prominent positive going deflection dominant peaking around 400 msec poststimulus across the electrodes shown. For both markers of mind-wandering state, the amplitude of the P300 was significantly reduced when in states consistent with mind wandering ("error" in A and "zone-out" and "tune-out" in B).

Table 1. Mean P300 Amplitudes for Targets

	Electrode									
	Cz	Pz	C3	P1	C4	P2	PO1	P5	PO2	P6
Error	7.21 (1.07)	6.03 (0.62)	5.98 (0.92)	5.04 (0.79)	7.01 (1.01)	6.20 (0.63)	4.90 (0.49)	4.39 (0.49)	5.77 (0.63)	5.18 (0.50)
Correct	8.23 (1.19)	7.42 (0.73)	6.78 (1.02)	6.30 (0.84)	8.31 (1.03)	7.64 (0.73)	6.01 (0.56)	5.44 (0.51)	7.01 (0.67)	6.49 (0.59)
On-task	8.19 (1.49)	7.12 (1.13)	6.46 (1.18)	5.86 (0.96)	7.96 (1.29)	7.09 (0.95)	5.81 (0.71)	4.96 (0.59)	6.65 (0.92)	5.74 (0.63)
Zone-out	6.64 (1.07)	5.42 (0.57)	5.26 (0.86)	4.86 (0.71)	6.89 (0.87)	5.67 (0.52)	4.39 (0.45)	3.67 (0.43)	5.02 (0.52)	4.87 (0.36)
Tune-out	6.42 (1.07)	5.10 (0.64)	5.38 (0.92)	4.36 (0.76)	6.40 (1.05)	5.33 (0.67)	4.58 (0.48)	3.88 (0.43)	4.91 (0.58)	4.68 (0.55)

Behavioral (top) and subjective (bottom) markers of mind wandering are shown by condition (μV, with standard errors). Mean amplitudes were taken across a 300 to 600 msec poststimulus time window, measured relative to a −200 to 0 msec baseline.

verbal report of "tune-out" and targets having a response was $R^2 = .555$ (Figure 2C). Importantly, multiple regression confirmed these relationships were only reliable when both behavioral and subjective measures of mind wandering converged on the same hypothetical mental state (Tables 2 and 3). In other words, the beta values indicated that the P300 prior to correctly withheld response only overlapped with subjective reports of being on-task (Table 3, lower panel). On the other hand, the beta values indicated that P300 prior to a failure to withhold a response was only statistically associated with reports of "zoned out," although the experience of "tune-outs" showed a comparable trend (Table 3, upper panel).

Although these regression analyses were consistent with the conclusion that behavioral and subjective measures of mind wandering were tapping into similar underlying attentional states, they did not rule out the possibility that the small P300 when off-task was being driven by motor-related confounds. To assess this question, we examined the electrophysiological responses associated with motor activity itself across both mental states. In particular, when a hand movement is being prepared and executed, a negative scalp potential develops directly over the motor cortex (or electrode sites C3/C4) in the cerebral hemisphere contralateral to the responding hand—an electrophysiological indicator of central motor activation associated with the lateralized readiness potential (LRP; for a review, see Eimer, 1998). The degree to which central motor processes are activated during the preparation and execution phases of a unimanual response can thus be gauged by the amplitude of the negativity that response generates over the contralateral motor cortex. Given that all participants in the current study responded to nontargets via a manual response with the right hand, if motor activity associated with these responses was significantly different between mind-wandering states, then effects of mind wandering will be confounded with differences in motor activity in lateralized activity over electrode sites C3 and C4.

We thus examined the development of response-related motor negativity over C3 by deriving subtraction waveforms (the C3 ERP minus the C4 ERP) for both

behavioral and subjective markers of mind wandering. These subtraction waveforms were time-locked to two different events: (1) the onset of the nontarget signaling the need for a motor response and (2) the onset of the unimanual response itself (Figure 3). For subtraction waveforms associated with the behavioral marker of mind wandering, there appeared to be an increased negativity in the subtraction waveform for responses made to nontargets immediately preceding targets that correctly had a response withheld (Figure 3A, left). This interpretation was confirmed via a repeated measures ANOVA performed on the mean amplitude of the subtraction waveforms over the same 300 to 600 msec poststimulus time window used for P300 analyses reported above, relative to a −200 to 0 baseline (Table 4, top left), an analysis which revealed an effect of "correct" versus "error" that approached significance [$F(1, 21) = 3.34$, $p = .0819$]. On the other hand, the response-locked subtraction waveforms (Figure 3A, right) showed no significant differences in either the mean amplitude in the 200-msec time window immediately preceding the response [$F(1, 21) = 0.02$, $p = .8910$] or the mean amplitude in the 200-msec time window immediately following the response [$F(1, 21) = 0.51$, $p = .4835$], both measured relative to a −800 to −600 msec time window (Table 4, top right).

The identical set of comparisons for the subtraction waveforms associated with the subjective marker of mind wandering showed no main effect of mind wandering for the responses to the nontargets in the mean amplitude over the 300 to 600 msec time window poststimulus (Figure 3B, left, and Table 4, bottom left) relative to a −200 to 0 baseline [$F(1, 21) = 1.75$, $p = .1862$]. The response-locked waveforms also failed to show any significant differences in either the mean amplitude in the 200-msec time window immediately preceding the response [$F(1, 21) = 0.96$, $p = .3906$] or the mean amplitude in the 200-msec time window immediately following the response [$F(1, 21) = 0.53$, $p = .5933$], both again measured relative to a −800 to −600 msec time window (Figure 3B, right, and Table 4, bottom right). In summary, these analyses of lateralized
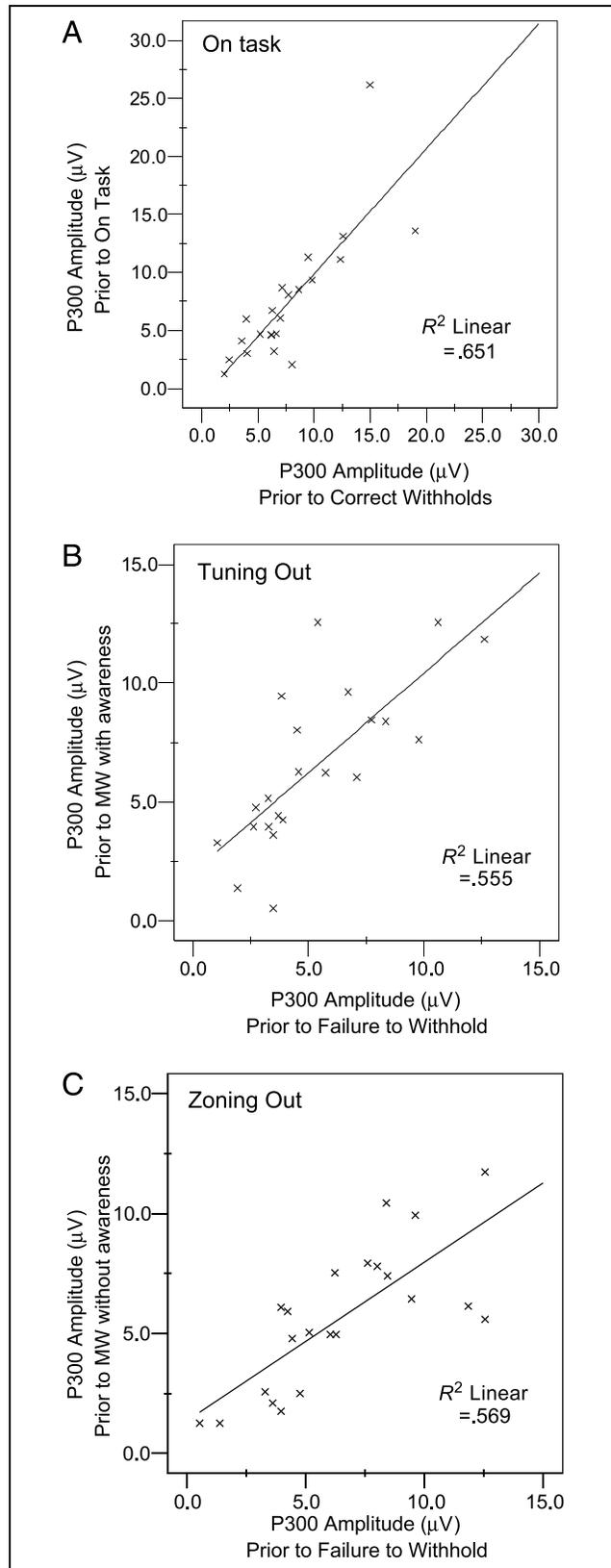
motor-related negativity revealed no consistent effects of mind wandering; although a difference did approach significance in one of the conditions studied, if motor-related influences were, in fact, driving the P300 effects

Figure 2. Scatterplots demonstrating statistical convergence in the amplitude of the P300 waveform (μV) prior to different measures of mind wandering. Plots present the consistency between the P300 (μV) prior to behavioral and verbal indications of decoupling under three conditions: (A) attention is focused on the task, (B) attention is off-task but participants are aware, a state of divided attention, and (C) attention is off-task and the individual is unaware of this fact.

reported above, mind wandering should have produced reliable difference in lateralized motor activity for both markers of mind wandering, and for non-target-locked and response-locked waveforms. In other words, it is unlikely that the limited differences in motor-related activity observed account for the consistent differences in cortical processing across both measures of mind wandering implied by the difference in the P300.

Early Components

As a final set of control analyses, we wanted to examine whether there were any reliable or consistent effects of mind wandering on the amplitudes of the early, visually evoked ERP components. If so, one interpretation would be that participants' general level of arousal may have negatively covaried with mind-wandering state, a possibility that might call into question the overall conclusion of our P300 data: that the decreased P300 during mind wandering was driven by a decrease in cognitive analysis of external events. That is, might a decrease in general arousal during mind wandering also produce such an effect on the P300? Given this question, if arousal was, in fact, biasing the ERP responses to nontarget events, it predicted that these effects should be manifest in the visually evoked components—for example, via a change in pupil diameter altering the intensity of light stimulating the retina.

We thus analyzed the mean amplitude of the ERP waveforms from occipital–temporal scalp sites—T5, OL, Oz, OR, and T6—via repeated measures ANOVAs for both behavioral and subjective markers of mind wandering across three contiguous time windows, approximately capturing the C1 (50–100 msec poststimulus), P1 (100–150 msec poststimulus), and N1 (150–200 msec poststimulus) ERP components, all measured relative to a −200 to 0 baseline. For behavioral markers (Figure 4, top, and Table 5), factors in the ANOVAs included mind wandering (error vs. correct) and electrode (5 levels); no significant effects of mind wandering were observed in any of the three time windows [50 to 100 msec: $F(1, 21) = 2.23, p = .1505$; 100 to 150 msec: $F(1, 21) = 2.26, p = .1115$; 150 to 200 msec: $F(1, 21) = 0.37, p = .5504$]. As well, no interactions between mind wandering and electrode were observed in any time window (all F values < 0.94, all p values > .44). For subjective markers (Figure 4, bottom, and Table 6), factors in the ANOVAs included mind wandering (on-task vs. zone-out vs. tune-out) and electrode (5 levels); again, no significant effects

Table 2. Summary of Two Regression Equations Examining the Unique Predictors of Behavioral Measures of Mind Wandering

Model		Sum of Squares	df	Mean Square	F	Sig.
P300 amplitude prior to a correct withhold	Regression	266.280	3	88.760	17.941	.000(a)
	Residual	89.050	18	4.947		
	Total	355.331	21			
P300 amplitude prior to failure to correctly withhold a response	Regression	159.964	3	53.321	12.068	.000(a)
	Residual	79.530	18	4.418		
	Total	239.494	21			

Alpha value, $p < .05$. In both cases, the following predictors were entered into the equation: (i) P300 amplitude (µV) prior to reports of on-task, (ii) P300 amplitude (µV) prior to reports of tune-outs, and (iii) P300 amplitude (µV) prior to reports of zone-outs.

of mind wandering were observed [50 to 100 msec: $F_{(2, 42)} = 2.27$, $p = .1154$; 100 to 150 msec: $F_{(2, 42)} = 0.17$, $p = .8457$; 150 to 200 msec: $F_{(2, 42)} = 1.19$, $p = .3134$], nor were any significant interactions observed between mind wandering and electrode site (all F values < 1.96, all p values $> .13$). In short, no evidence was found in support of the hypothesis that the early visual-evoked ERP components were being influenced by mind-wandering state. Taken together, our analysis of the ERP suggests that both subjective and behavioral measures of mind wandering are associated with a specific reduction in the cognitive analysis of the task environment, and were not related to either motor deficits in processing or overall shifts in arousal state.

DISCUSSION

In this study, we found direct evidence that when the mind wanders, there is a reduction in the depth of the cognitive analysis that is applied to the task environment. In particular, the amplitude of the P300 was significantly reduced for nontargets presented during periods of mind wandering defined via both behavioral and subjective markers, relative to periods identified as being on-task. Although mind wandering may have effects on cortical function that extend beyond those associated with cognitive analysis—such as motor behavior and general arousal—our data suggest that these potential influences were not contributing to the observed pattern of P300 behavior. Rather, it appears that attention to external events itself ebbs and flows as the mind wanders. Given this conclusion, several questions follow.

First, to what extent did behavioral and subjective markers of mind wandering converge? Although both behavioral and subjective markers of mind wandering yielded the same pattern of reduced P300 amplitude, our statistical analyses indicate that the subjective markers were associated with greater variance. This

Table 3. Summary of the Proportion of Variance in the P300 Amplitude (µV) Prior to Failures to Withhold a Response Accounted for by the P300 Amplitude (µV) Prior to Subjective Reports of Mental State

Dependent Variable	Independent Variable	Unstandardized Coefficients B	Standardized Coefficients SE	Beta	t	Sig.
Failure to withhold a response	(Constant)	0.937	1.026		0.913	.373
	On-task	−0.038	0.143	−0.063	−0.268	.792
	Zone-out	0.523	0.213	0.458	2.453	.025*
	Tune-out	0.542	0.302	0.481	1.794	.090
Correctly withheld response	(Constant)	1.316	1.085		1.213	.241
	On-task	0.351	0.152	0.469	2.315	.033*
	Zone-out	0.367	0.226	0.263	1.624	.122
	Tune-out	0.327	0.320	0.239	1.023	.320

In both cases, the subjective and behavioral descriptions show converging evidence that the deflections of the P300 amplitude observed in this study result from a common cause.

*Significant predictor at $p < .05$.
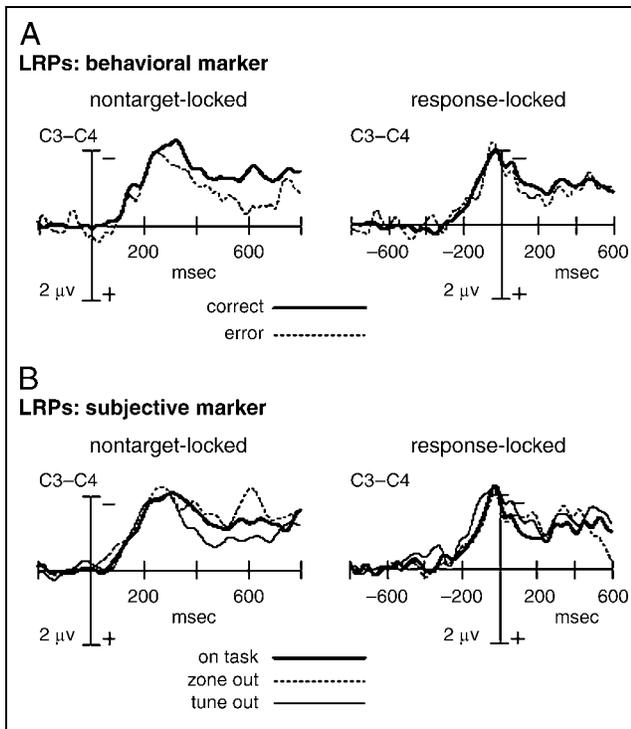
Figure 3. Lateralized motor-related activity associated with behavioral (A) and subjective (B) markers of mind wandering. Shown are the subtraction waveforms derived by subtracting ERP waveforms at electrode site C4 from the ERP waveforms at electrode site C3, time-locked to both the presentation of nontargets (left) and manual responses (right). These data suggest that there were no consistent effects of mind-wandering state on the motor activity associated with the preparation and execution of manual responses (see Results).

apparent supremacy of the behavioral marker for mind wandering is, perhaps, not surprising given the disreputable status of self-reports in cognitive psychology (e.g., Nisbet & Wilson, 1977). However, on the other hand, the fact that subjective reports did yield reliable differences in P300 behavior may come as a surprise to neuroscientists who have traditionally relied on behavioral measures of attentional states. Moreover, it was actual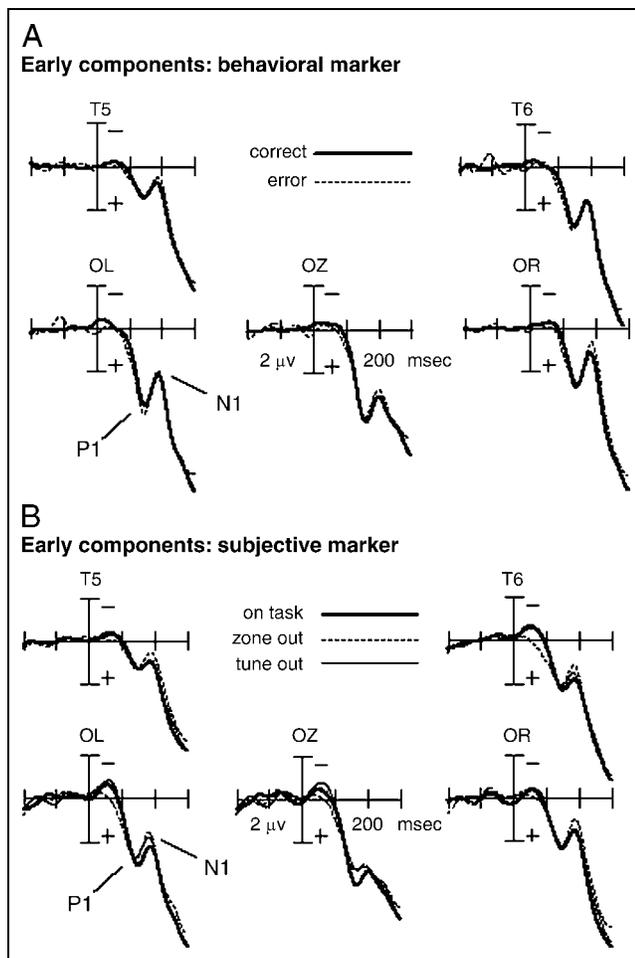ly the behavioral markers of mind wandering that showed a slight difference in motor-related processing according to our analyses of lateralized motor negativities, suggesting that the subjective markers may even have some advantages over the behavioral counterpart (see Smallwood & Schooler, 2006). In short, however, although minor differences were present in our two markers of mind wandering, our data suggest that self-report measures, when applied correctly, can provide an essential adjunct to the standard behavioral measures used in cognitive neuroscience.

Second, what effects, if any, did awareness of mind wandering have on cognitive analysis? The evidence on this point was mixed. Irrespective of awareness, the subjective markers of being off-task were both associated with a reduced P300, relative to being on-task. Nevertheless, regression analysis suggested only reports of mind wandering without awareness ("zone-outs") yielded a P300, which reliably overlapped with the same measure prior to response inhibition errors. Reports of mind wandering with awareness ("tune-outs") showed a comparable relation, although, in this instance, the difference did not achieve statistical significance. A cautious interpretation of these data would imply that similar to divisions of attention, simply being off-task is associated with reduced processing of events in the external environment. Within this context, an absence of awareness that one is actually off-task, however, could mediate the extent to which one can rapidly reconfigure attention in order to withhold a response to a target stimulus. Such an interpretation is consistent with previous behavioral work indicating that information processing is comparable prior to "zone-outs" and failures in response inhibition (Smallwood et al., in press), whereas simply being off-task is associated with impaired or reduced encoding from the task environment (Smallwood et al., in press, 2007). This notion is consistent with Hester et al. (2005), who suggest that "momentary inattention to task demands might prevent the unconscious detection of an error" (p. 606). Although inconclusive, our data do suggest that future work may wish to consider the importance of awareness

Table 4. Lateralized Motor Activity for Behavioral (Top) and Subjective (Bottom) Markers of Mind Wandering are Shown by Condition (μV, with Standard Errors) for Both Target-locked and Response-locked Subtraction Waves

Condition	Target-locked	Response-locked	
	300 to 600 msec	−200 to 0 msec	0 to 200 msec
Error	−1.05 (0.40)	−1.31 (0.25)	−1.07 (0.53)
Correct	−1.54 (0.27)	−1.35 (0.27)	−1.32 (0.35)
On-task	−1.50 (0.41)	−1.34 (0.30)	−1.16 (0.45)
Zone-out	−1.63 (0.30)	−1.25 (0.30)	−1.43 (0.43)
Tune-out	−1.02 (0.37)	−1.70 (0.29)	−1.54 (0.40)

The reported time windows indicate the window over which mean amplitudes were taken. Target-locked waveforms were measured relative to a −200 to 0 msec baseline, and response-locked waveforms were measured relative to a −800 to −600 msec baseline.

Figure 4. Early visual ERP components over occipital–temporal scalp electrode sites for behavioral (A) and subjective (B) markers of mind wandering.

of the task environment as mitigating the most costly lapses in attention.

Third, if there is a reduction in the cognitive analysis of the external environment which accompanies periods of mind wandering, what brain networks might under-

pin the expression of these stimulus-independent experiences? When the human mind is deprived of stimulation, functional neuroimaging indicates it often recruits discrete network of brain regions commonly referred to as the "default" network (Mazoyer et al., 2001; Raichle et al., 2001; Shulman et al., 1997). The areas implicated in this network include the medial posterior cingulate extending caudally into the anterior precuneus and the paracentral lobule, the bilateral inferior parietal cortex, the angular gyri bilaterally, portions of the inferior frontal cortex, bilateral superior and middle frontal gyri, and a sizable cluster spanning dorsal medial frontal regions. The link between this network and mind wandering has come from functional magnetic resonance imaging, where behavioral lapses have been tied to increased blood oxygenation level-dependent (BOLD) activity in default network structures (Weissman et al., 2006). Likewise, default network activity has been shown to correlate with periods of mind wandering during both easy (McKiernon, D'Angelo, Kaufman, & Binder, 2006) and well-practiced tasks (Mason et al., 2007). Finally, during a passive sensory task, Grecius and Menon (2004) reported that the accompanying sensory processing was inhibited by default network activity, implying that subjects were dividing "their attentional resources between simple external stimuli and the default mode" (p. 1488).

In short, the default network is a strong candidate system for providing the neural substrates which support off-task thinking because these structures show the essential properties of mind wandering observed in this study—namely, they are active under circumstances when attention ceases to be constrained by task-relevant information. Importantly, similar to the apparent modulation of cortical processing of the task environment by mind wandering described here, the evidence that default network activity underpins the experience of off task thinking is based on a convergence between behavioral (e.g., Weissman et al., 2006) and subjective markers of the experience (Mason et al., 2007; McKiernon et al., 2006).

Table 5. Early ERP Components: Behavioral Markers

| Window | Condition | Electrode | | | |
		T5	T6	OL	OR
50 to 100 msec	Error	0.12 (0.17)	0.17 (0.13)	0.43 (0.21)	0.24 (0.20)
	Correct	−0.08 (0.11)	0.11 (0.13)	0.16 (0.14)	−0.09 (0.14)
100 to 150 msec	Error	1.08 (0.26)	2.03 (0.39)	2.80 (0.56)	2.12 (0.37)
	Correct	0.95 (0.27)	1.67 (0.39)	2.29 (0.54)	1.82 (0.34)
150 to 200 msec	Error	0.87 (0.61)	2.05 (0.53)	2.66 (0.75)	1.32 (0.82)
	Correct	1.01 (0.48)	2.07 (0.57)	2.69 (0.79)	1.62 (0.66)

Mean amplitudes across lateral occipital–temporal scalp sites are shown by condition (μV, with standard errors) and time window of analysis. All measures were taken relative to a −200 to 0 msec baseline.

Table 6. Early ERP Components: Subjective Markers

		Electrode			
Window	Condition	T5	T6	OL	OR
50 to 100 msec	On-task	−0.32 (0.23)	−0.44 (0.36)	−0.37 (0.34)	−0.18 (0.21)
	Zone-out	−0.02 (0.21)	0.38 (0.23)	0.32 (0.25)	0.11 (0.24)
	Tune-out	−0.23 (0.17)	−0.41 (0.28)	−0.58 (0.28)	−0.28 (0.13)
100 to 150 msec	On-task	0.69 (0.32)	1.41 (0.45)	2.12 (0.62)	1.61 (0.45)
	Zone-out	0.76 (0.27)	1.68 (0.39)	2.32 (0.53)	1.70 (0.35)
	Tune-out	0.83 (0.23)	1.54 (0.40)	2.04 (0.47)	1.64 (0.30)
150 to 200 msec	On-task	1.05 (0.45)	1.94 (0.47)	2.47 (0.74)	1.71 (0.68)
	Zone-out	0.74 (0.48)	1.41 (0.48)	1.85 (0.71)	1.38 (0.69)
	Tune-out	1.03 (0.36)	1.69 (0.42)	2.02 (0.63)	1.77 (0.53)

Mean amplitudes across lateral occipital/temporal scalp sites are shown by condition (μV, with standard errors) and time window of analysis. All measures were taken relative to a −200 to 0 msec baseline.

A final point to consider is that our data add to a growing body of evidence that attention ebbs and flows between two dichotomous states. During task performance, attention is often strongly coupled to the external world, presumably affording fast and effective responses to events in the immediate environment. But at the same time, attention can be, either intentionally or unintentionally, decoupled from the immediate environment and directed instead to the internal or private experiences of the individual. Among other things, this state allows the individual to entertain goals and thoughts which extend well beyond their immediate circumstances—a phenomenon termed mental time travel (e.g., Buckner & Vincent, 2007; Addis, Wong, & Schacter, 2007; Mason et al., 2007; Suddendorf & Busby, 2005).

Recent work from a variety of different disciplines within neurosciences has begun to demonstrate converging measures of these dichotomous influences on attention. For example, Castellanos et al. (2005) observed systematic fluctuations in response time in the performance of individuals with ADHD—a client group shown to experience frequent periods of mind wandering (e.g., Shaw & Giambra, 1993). These systematic changes in attention were argued to represent a transient "catecholaminergic deficit in the ability to appropriately modulate such oscillations in neuronal activity" and were suggested to underpin failures in sustained attention in individuals with ADHD and, more generally, in the population at large (Castellanos et al., 2005, p. 1416). Similarly, using seed analysis, Fox, Corbetta, Snyder, Vincent, & Raichle (2005) and Fransson (2005) demonstrated that default activity during the resting state shows a systematic fluctuation between two brain networks: one largely involving default network structures, the other involving the engagement of task-relevant structures. Mirroring the behavioral data of Castellanos et al., these fluctuations in BOLD activity were interpreted as "a dynamic interplay within and between large spatially distributed systems representing opposing components of our mental lives" (Fox et al., 2005, p. 9677). Based on this converging evidence, it seems that one fruitful avenue for future research would be to examine whether the subjective measures of mind wandering and their accompanying behavioral and physiological correlates (see Smallwood & Schooler, 2006 for a review) can be mapped directly onto these transient fluctuations in BOLD activity and thus providing a comprehensive neural model of the ebb and flow of attention to external events reported here.

APPENDIX 1

Instructions given to participants

During this experiments you will be asked at various points whether your attention is firmly directed toward the task, or alternatively, you may be aware of other things than just the task. Occasionally, you may find as you perform the task that you begin thinking about something completely unrelated to what you are doing; this is what we refer to as "mind wandering." We believe there are two forms of mind wandering:

TUNING OUT: Sometimes when your mind wanders, you are aware that your mind has drifted, but for whatever reason you still continue to perform the task. This is what we refer to as "tuning out"—i.e., when your mind wanders and you know it all along.

ZONING OUT: Other times when your mind wanders, you don't realize that your thoughts have drifted away from the text until you catch yourself. This is what we refer to as "zoning out"—i.e., when your mind wanders, but you don't realize this until you catch it.

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