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RESEARCH ARTICLE

Migraine and attention to visual events during mind wandering

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Abstract Although migraine is traditionally categorized as a primary headache disorder, the condition is also associated with abnormalities in visual attentional function in between headache events. Namely, relative to controls, migraineurs show both a heightened sensitivity to nominally unattended visual events, as well as decreased habituation responses at sensory and post-sensory (cognitive) levels. Here we used event-related potentials (ERPs) to examine whether cortical hypersensitivities in migraineurs extend to mind wandering, or periods of time wherein we transiently attenuate the processing of external stimulus inputs as our thoughts drift away from the on-going task at hand. Participants performed a sustained attention to response task while they were occasionally queried as to their attentional state—either "on-task" or "mind wandering." We then analyzed the ERP responses to task-relevant stimuli as a function of whether they immediately preceded an on-task versus mind wandering report. We found that despite the commonly reported heightened visual sensitivities in our migraine group, they nevertheless manifest a reduced cognitive response during periods of mind wandering relative to on-task attentional states, as measured via amplitude changes in the P3 ERP component. This suggests that our capacity to attenuate the processing of external stimulus inputs during mind wandering is not necessarily impaired by the class of cortical hypersensitivities characteristic of the interictal migraine brain.

Keywords Mind wandering · Migraine · EEG · Event-related potentials · Visual · Cortical hyperexcitability

Introduction

Migraine is a headache disorder characterized by moderate to severe pain, with sensitivity or intolerance to light and sound during the headache (Headache Classification Subcommittee of the International Headache Society). While the bulk of migraine research has focused on the headache, what it is to be a migraineur often goes well beyond the headache itself. A migraineur may feel that he/she is impacted in daily activities, even when not suffering from an attack. Many migraineurs anecdotally report that they feel sensitive to environmental stimuli (Sacks 1992). In fact, recent research has revealed attentional abnormalities in migraineurs in between headache attacks (Antal et al. 2005; Mickleborough et al. 2011a, b, 2013, 2014; Wagner et al. 2010). For instance, migraineurs do not show normal suppression of cortical responses to visual events outside their zone of attentional focus (Mickleborough et al. 2011b), and they have heightened reflexive visual–spatial orienting to sudden-onset peripheral events (Mickleborough et al. 2011a). In addition, migraineurs lack sensory and cognitive habituation to repetitive environmental stimuli (Brighina et al. 2009; Coppola et al. 2009; Evers et al. 1997, 1998, 1999; Mickleborough et al. 2013; Giffin and Kaube 2002). For example, when viewing a series of complex visual images, migraineurs showed an increasing

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cortical response across trial blocks, an effect consistent with lack of cognitive habituation to visual stimuli (Mickleborough et al. 2013). Given that these findings suggest migraineurs have an abnormally heightened visual sensitivity especially to unattended environmental stimuli, we examined whether migraineurs would also display attentional abnormalities during mind wandering.

Mind wandering is the regularly occurring experience of our attention directed away from an external task to an internal train of thoughts (Smallwood and Schooler 2006). During an attentionally demanding external task, such internally directed cognition can have negative practical consequences on our daily functioning. In terms of behavioral measures, mind wandering has been shown to impair reading comprehension (Schad et al. 2012; Schooler et al. 2004), memory encoding (Smallwood et al. 2006; Thomson et al. 2014), attentional task performance (Cheyne et al. 2006; Kam et al. 2013; McVay and Kane 2009), and specific aspects of executive functions (Kam and Handy 2013). In terms of electrophysiological measures, mind wandering has been tied to disruptions in a broad range of cognitive domains (see Kam and Handy 2013 for a review). This includes stimulus categorization (Barron et al. 2011; O'Connell et al. 2009; Smallwood et al. 2008a, b), performance monitoring (Kam et al. 2012), and affective processing (Kam et al. 2014). Taken together, periods of mind wandering have been associated with both disrupted behavioral performance and neural processing.

Given that migraineurs show decreased attenuation of unattended visual stimuli and heightened attentional sensitivities in between headache events (relative to non-migraine controls), here we examined whether these sensitivities in migraine extend to periods of mind wandering, when there is a general attenuation of processing of external stimulus inputs. To address this question, we recorded event-related potentials (ERPs) while two groups of participants—migraineurs and non-migraine controls—performed a visual sustained attention to response task (SART) during which they were occasionally prompted to report their attentional state as either on-task or mind wandering. Previous research using this task has shown that the amplitude of the P3 ERP component elicited by task-relevant non-targets in the SART is attenuated during periods immediately preceding mind wandering reports, relative to on-task attentional reports in an undergraduate population (e.g., Kam et al. 2011; Smallwood et al. 2008a, b). At issue in our study was whether migraineurs would show a similar pattern of attenuation during periods of mind wandering or whether their profile of heightened attentional sensitivities extends to mind wandering epochs as well. Specifically, given that migraineurs have decreased attenuation of visual stimuli as compared to controls, and that mind wandering is characterized by attenuation of external stimuli processing, we predict that migraineurs will show less attenuation of the P3 during mind wandering than controls.

Methods

Participants

Two groups participated in this study: 14 were in the migraine group (11 women; age, mean = 24.4, SD = 5.1) and 14 were in the non-migraine control group (8 women; age, mean = 21.6, SD = 2.9). The migraine group consisted of individuals with aura ($n = 6$) and without aura ($n = 8$). Migraineurs experienced an average of 49 headaches per year, with each headache lasting 10 h on average. As a group, they had been having migraines for an average of 11.5 years. The non-migraine control group consisted of individuals who had only headaches of mild–moderate pain intensity with no nausea/vomiting associated with the headache, and who could only have symptoms of infrequent tension-type headache according to the international classification of headache disorders (Headache Classification Subcommittee of the International Headache Society 2004). All participants were right handed and received $20 for their participation. Informed consent was obtained from all individual participants included in the study. Testing procedures were approved by the Clinical Review Ethics Board at the University of British Columbia.

Paradigm and stimuli

The SART (Robertson et al. 1997) is a simple target detection task in which participants have to respond to frequent non-targets and withhold their response to rare targets. Successful performance in this task requires sustained attention, yet it makes minimal demands on other cognitive processes. This task has been extensively used in the mind wandering literature to elicit fluctuations in task-related attentional states given its repetitive nature (e.g., Christoff et al. 2009; Kam et al. 2011; Kirschner et al. 2012; McVay and Kane 2009; Smallwood et al. 2004). In addition to examining the P3 ERP component generated by non-targets, we also assessed reaction times and accuracy rates.

During the SART, a continuous stream of stimuli was presented at fixation. Participants were instructed to make a manual button press for frequently presented non-targets, which were single digit numbers (i.e., 0–9). They were to withhold their response when presented with the infrequent targets, which was the letter "X." Each target or non-target was presented for 500 ms followed by an interstimulus interval that varied between 400 and 600 ms. A task-irrelevant visual probe (i.e., a black square-wave grating) was then presented in the upper periphery for 100 ms, a manipulation previously included as a means of assessing the impacts of mind wandering on task-irrelevant stimuli in the visual periphery (see Kam et al. 2011); participants were instructed to ignore these probes, as they were irrelevant to the task. Following the visual probe was an intertrial interval (ITI) that also randomly varied between 800 and 1000 ms. Within each block, the probability of target occurrence was quasi-randomized, with the constraints that: (1) one to two targets were presented during each block; (2) for blocks having two targets, the targets would be separated by at least ten non-target events; and (3) targets did not appear in the last 12 s prior to the end of a trial block. Participants completed up to 50 blocks and were permitted breaks in between blocks, as requested. This task lasted approximately 60 min.

Our approach to determine whether or not participants were in a mind wandering state at any given moment was based on experience sampling. Experience sampling is a direct measure of mind wandering that relies on our ability to report whether or not our attention is focused on the task at hand (e.g., McKiernan et al. 2006; Smallwood et al. 2003, 2008a, b). In using the report to categorize a participant's attentional state in the 10–15 s immediately prior to the report, this methodology has been used to demonstrate reliable and replicable differences in neurocognitive functioning between on-task and mind wandering states (e.g., Christoff et al. 2009; Franklin et al. 2011; Kam et al. 2011, 2012, 2013; Kirschner et al. 2012; Mason et al. 2007; McKiernan et al. 2006; Smallwood et al. 2008a, b; Stawarczyk et al. 2011).

In this method, participants were instructed to verbally report their attentional state when prompted as either being on-task or mind wandering. To facilitate this, participants were provided with standardized definitions of these attentional states prior to testing; on-task states were defined as when one's attention is firmly directed toward the task, and mind wandering states were defined as when one's attention has drifted away from the task. Attentional reports were recorded at the conclusion of each trial block, and these reports were then used to sort ERP data based on on-task versus mind wandering states. In order to maximize the variability of attentional states and minimize predictability of when an attentional report would be required, the duration of each trial block was randomly varied between 30 and 90 s, or 15–45 trials (c.f. Kam et al. 2011, 2012, 2014; Kirschner et al. 2012; Smallwood et al. 2008a, b).

Electrophysiological data recording and processing

During SART performance, EEG was recorded from 64 active electrodes mounted on a cap in accordance with the International 10–20 system using a Biosemi Active-Two amplifier system. Two additional electrodes located over medial–parietal cortex (Common Mode Sense and Driven Right Leg) were used as ground electrodes. EEG data were recorded using a high-pass filter of 0.05 Hz, digitized online at a sampling rate of 256 Hz, and then referenced off-line to the average of two mastoid electrodes. To ensure proper eye fixation and allow for the removal of events associated with eye movement artifacts, vertical and horizontal electrooculograms (EOGs) were also recorded.

EEG data processing and analyses were performed using ERPLAB (http://erpinfo.org/erplab/), a toolbox within MATLAB (2012a) used in conjunction with EEGLAB (Delorme and Makeig 2004). Continuous data were segmented into −200 to 800 ms epochs time-locked to stimulus presentation. Off-line artifact rejection was used to eliminate trials during which detectable eye movements and blinks occurred. Eye movements or muscle artifacts were automatically rejected from analysis, using the moving windows peak-to-peak option in ERPLAB, with amplitude thresholds customized for each participant (range 125–250 μV). An average of 19.61 % of total number of trials in migraineurs, and 19.63 % in controls, were rejected due to these signal artifacts. The percentage of trials rejected did not significantly differ between the two groups ($p = .998$), nor did they significantly differ between on-task and mind wandering states in both migraineurs ($p = .423$) and controls ($p = .558$). Data were then submitted to an IIR Buttersworth band-pass filter of 0.1–30 Hz.

Quantification of ERP data was based on mean amplitude measures using repeated-measures ANOVAs, with specific time windows of analyses centered on the components of interest as identified in the grand-averaged waveforms, as described below. These measures were all taken relative to a −200 to 0 ms pre-stimulus baseline. To compare ERP responses between on-task and mind wandering states, our ERP averages only included the six trials presented in the 12 s preceding each attentional report (on-task vs. mind wandering)—a time window we have used previously with ERP data (e.g., Kam et al. 2011, 2012, 2014; Kirschner et al. 2012; Smallwood et al. 2008a, b) that is designed to maximize the number of events that can be included in the ERP averages while still maintaining a reasonable fidelity to the attentional report (i.e., as the time window increases, the signal-to-noise ratio of the ERP averages improves, but the validity of the attentional report for individual events decreases).

Results

Attentional report

Participants completed an average of 42 trial blocks in the SART. The reported percentage of mind wandering

Table 1 Behavioral performance on the SART as a function of attentional states are shown separately for migraineurs and controls

	Migraineurs	Controls
RT to non-targets (ms)		
Overall	366 (30)	370 (43)
On-task	365 (26)	369 (49)
Mind wandering	370 (38)	366 (40)
Commission error rate	39.8 % (14.7 %)	39.5 % (13.6 %)

Standard deviations are presented in parentheses

between migraineurs ($M = 46$ %, SD = 20 %) and controls ($M = 53$ %, SD = 15 %) did not significantly differ from each other [$t(26) = 1.00$, $p = .326$].

Behavioral performance

We conducted independent samples t tests to examine group differences in behavioral performance. Table 1 presents the means and standard deviations of reaction times and commission error rates. There were no significant differences in reaction time to non-target trials between the migraine and control groups [$t(1,26) = 0.24$, $p = .811$]. We also examined reaction times for trials preceding on-task and mind wandering reports. There were no significant differences in reaction times between groups during periods of on-task [$t(1,26) = 0.28$, $p = .779$] and mind wandering [$t(1,26) = -0.27$, $p = .787$]. Commission error rates were also not significantly different the two groups [$t(1,26) = -0.06$, $p = .955$].

Electrophysiology

The overall P3 ERP waveforms and P3 as a function of attentional states, are shown in Figs. 1 and 2, respectively. Mean amplitudes of the P3 ERP component elicited by non-targets were taken across a 350- to 550-ms post-stimulus time window. This time window was chosen as it captured the P3 peak in both groups. Repeated-measures ANOVAs included a within-subject factor of electrode location (Fz, FCz, Cz, CPz, and Pz) and a between-subject factor of group (migraineurs, controls).

Normative analyses

We first evaluated the normative aspects of the cognitive response in the migraine group. Specifically, given previous studies showing heightened cognitive-level sensitivities to visual inputs (e.g., Evers et al. 1997, 1998, 1999; Mickleborough et al. 2013), we predicted a greater overall P3 response in migraineurs. Prior to examining group differences in the attentional modulations of the P3, we thus

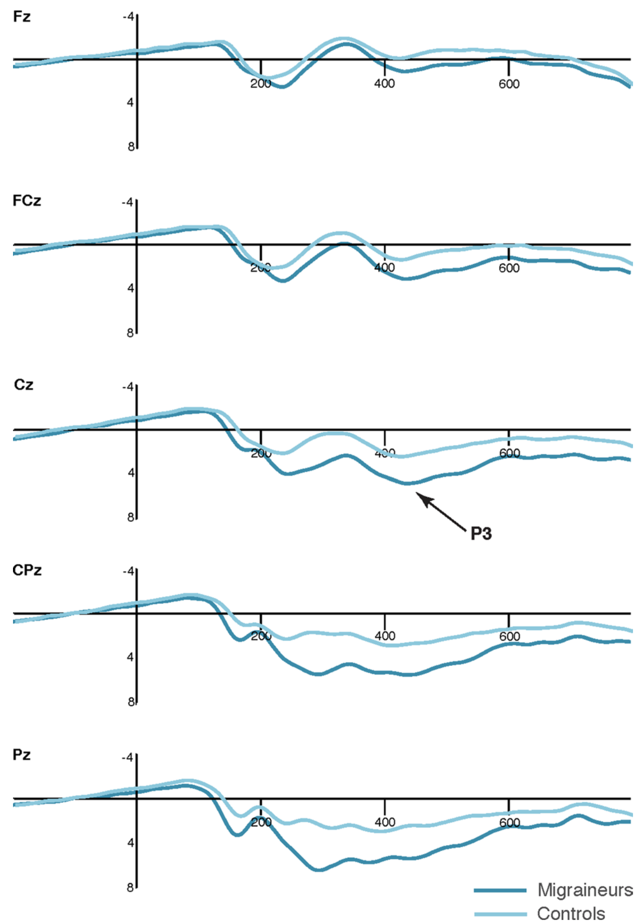

Fig. 1 P3 time-locked to all non-targets. Overall P3 in response to numbers (0–9) was recorded at midline separately for targets for both migraineurs (*dark blue lines*) and controls (*light blue lines*) (color figure online)

wanted to replicate this basic finding of the overall P3 component in response to non-targets. There was a significant main effect of group [$F(1,26) = 4.24$, $p = .050$], with overall P3 amplitudes being higher for the migraine group compared with the control group.

Likewise, to confirm previous reports that migraineurs also show heightened visual sensory responses (e.g., Brighina et al. 2009; Coppola et al. 2009), we analyzed the amplitude of the lateral occipital P1 ERP component elicited by the task-irrelevant probes. We used the task-irrelevant visual probes for this analysis because stimuli in the visual periphery present a better test of visual-evoked sensory sensitivity than stimuli at fixation (see Handy and Khoe 2005). The overall P1 ERP waveforms are shown in Fig. 3. Mean amplitudes of the P1 ERP component elicited by task-irrelevant visual probes were taken across a 100- to 150-ms post-stimulus time window, as this window captured the P1 peak in both groups. Repeated-measures ANOVAs included a within-subject factor of electrode lobe

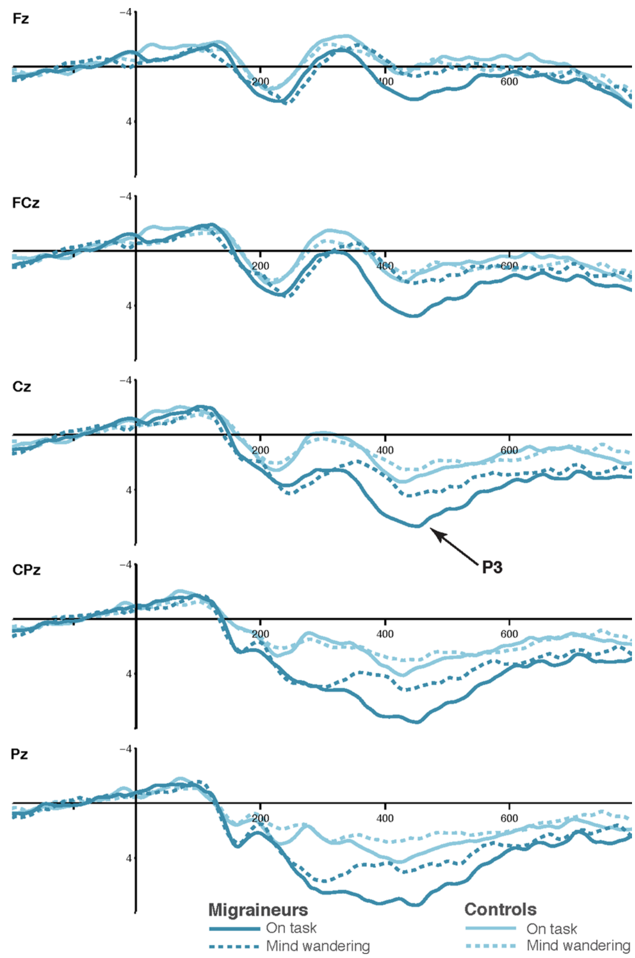

Fig. 2 P3 time-locked to non-targets as a function of attentional states. Non-targets (or numbers) preceding attentional report recorded at midline were averaged separately for on-task (*solid lines*) and mind wandering reports (*dotted lines*) for migraineurs (*dark blue lines*) and controls (*light blue lines*) (color figure online)

(parietal, occipital), electrode location (left, middle, right) and a between-subject factor of Group (migraineurs, controls). Consistent with these prior reports, we found a significant main effect of group [$F(1,26) = 4.91$, $p = .036$], with the migraineurs showing greater P1 amplitude than controls. None of the interaction effects involving group were significant ($p > .300$).

Effects of mind wandering

With respect to our primary question of interest, we examined the P3 response to non-targets as a function of whether the stimulus immediately preceded on-task or mind wandering reports. Thus, repeated-measures ANOVAs included an additional within-subject factor of attentional states (on-task vs. mind wandering). The main effect of attentional states was significant [$F(1,26) = 9.68$, $p = .004$], with reduced P3 amplitude during mind wandering relative to on-task periods. There was a near-significant main effect of group [$F(1,26) = 3.82$, $p = .062$], with lower P3 amplitudes found in controls compared with migraineurs. Importantly, there was a significant interaction between attentional states and group [$F(1,26) = 4.48$, $p = .044$]. Follow-up analyses revealed that the P3 amplitude was significantly reduced during mind wandering relative to on-task periods in migraineurs [$F(1,13) = 8.99$, $p = .010$]. Although the same pattern was observed in controls, this effect was not significant [$F(1,13) = 1.03$, $p = .328$].

Discussion

The present study used migraineurs as a neuropsychological approach to examine the question of whether cortical hyperexcitabilities to visual inputs alter our ability to attenuate the processing of external stimuli during periods of mind wandering. Using ERPs, we found that despite the commonly reported increase in neural response to visual stimuli in our migraine group, they nevertheless manifest an attenuation in the neurocognitive response to task-relevant visual events as they mind wandered, a decrease previously reported in study populations not screened for migraine status (e.g., Kam et al. 2011; Smallwood et al. 2008a, b). Given this finding, at least three key questions and issues follow.

First, although our migraineur group was found to manifest decreased P3 responses to target stimuli during mind wandering, our control group did not replicate this effect as seen in previous studies that have also employed the SART (i.e. Kam et al. 2011; Smallwood et al. 2008a, b). In other words, task conditions and sample sizes sufficient to produce a significant effect in migraineurs were insufficient to produce an effect in controls. How might this be explained? One possibility is that despite their known cortical hyperexcitabilities, migraineurs might be particularly prone to cognitive attenuation of external stimulus inputs while mind wandering, relative to the non-migraine population. Consistent with this, the habituation responses impaired in migraine are believed to normally protect the cortex against stimulus overload (e.g., Brighina et al. 2009; Fumal et al. 2006; Groves and Thompson 1970; Stankewitz and May 2009). As such, a heightened capacity or more consistent propensity for engaging in attenuation during mind wandering states may provide migraineurs with an alternative mechanism or compensatory strategy for reducing stimulus overload in cortex.

Paralleling this line of reasoning are issues of individual variability introduced by accounting for migraine status in study participants. Namely, it has been estimated that the general Canadian population contains approximately

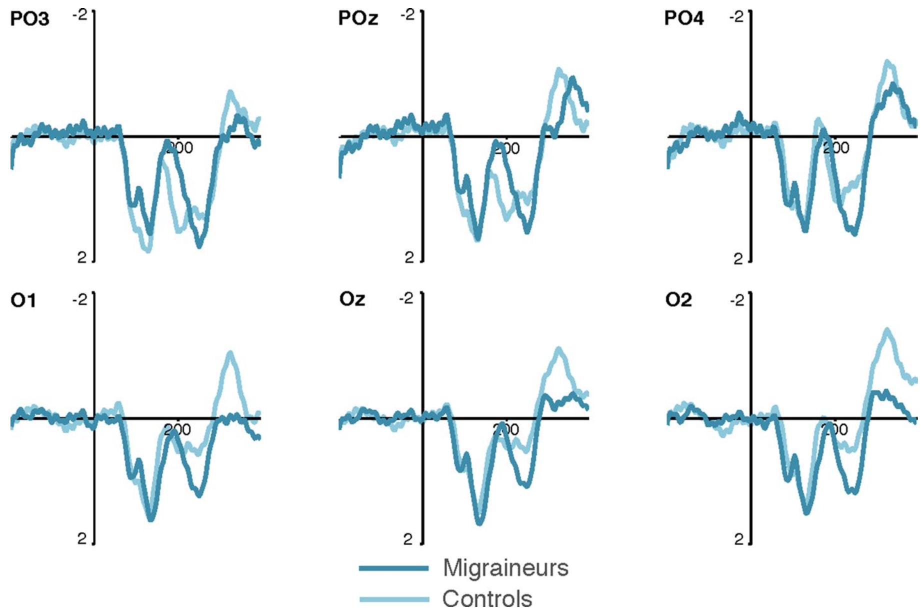

Fig. 3 P1 time-locked to all task-irrelevant visual probes. Overall P1 was recorded at parieto–occipital sites for both migraineurs (*dark blue lines*) and controls (*light blue lines*) (color figure online)

16 % migraineurs (Obrien et al. 1994). If migraineurs have a heightened propensity to attenuate the neurocognitive response to sensory inputs while mind wandering relative to non-migraineurs, their likely inclusion in the cohorts studied in prior ERP investigations of mind wandering (e.g., Kam et al. 2011; Smallwood et al. 2008a, b) could help account for the positive results reported, while their exclusion here could help explain our null findings in controls. Of note, our non-migraine control group is not a headache-free control group because finding individuals who do not suffer from any tension-type headaches at all is very difficult. It would be interesting to have a control group that is entirely headache free and see how that differs from our non-migraine controls who may have tension-type headache. At the same time, because they are screened for a dominant neurological characteristic, any migraine group likely manifests a smaller degree of individual variability in neurocognitive characteristics, relative to control groups screened only for the absence of the condition. This again would help explain why experimental parameters sufficient for finding a significant effect in migraineurs here were insufficient for finding a comparable effect in controls.

A second issue concerns our findings of neural differences between migraineurs and non-migraineurs in the absence of behavioral differences. In particular, the increased P3 response found in migraineurs did not correspond with faster reaction times or higher accuracy rates, leaving some ambiguity in the interpretation of the neural differences. In this particular study, one possibility is that the reaction time and commission error measures in the SART may not be sensitive enough to detect any differences between groups. Another possibility is that reaction times and accurate rates in the SART may be differentially sensitive to two types of mind wandering, spontaneous and deliberate (Seli et al. 2014), which have been recently shown to correlate with different behavioral measures (Carriere et al. 2013; Seli et al. 2015). The current study did not make such a distinction at time of testing; however, we believe this would be an interesting and useful distinction to make in future studies. Of importance, the lack of group differences in our behavioral measures underscores the utility of ERP measures in revealing the underlying neural processes engaged by migraineurs that may not manifest as behavioral differences. Future studies could benefit from using other experimental paradigms to examine which behavioral measures would be more sensitive to differences between migraineurs and non-migraineurs.

Lastly, what do our findings reveal about mind wandering and its neural basis, independent of its possible idiosyncrasies in migraineurs? Recent ERP and behavioral data have led to the proposal that our ability to attenuate the processing of external stimulus inputs during mind wandering depends on our basic mechanisms of selective attention in cortex, mechanisms that we use to highlight task-relevant aspects of the external environment during on-task (or non-mind wandering) attentional states (Kam and Handy 2013). Yet despite migraineurs' hyperexcitable responses in these attentional mechanisms in between headache attacks (Mickleborough et al. 2011a, b, 2013; Wagner et al. 2010; Antal et al. 2005), in a migraine population that showed these hyperexcitable responses, we found significant mind wandering-related attenuation in the amplitude of the P3 ERP component elicited by task-relevant events. While the details of how mind wandering exerts comprehensive control over our basic attentional mechanisms remains somewhat unclear (see Kam and Handy 2013), our current results indicate that mind wandering can effectively attenuate external stimulus processing at these stages despite a propensity for hyperexcitability during non-mind wandering states.

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Conflict of interest All authors have no conflict of interest to declare.

Ethical standard All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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