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Where is my mind? Examining mind-wandering and vigilance performance

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Abstract

Vigilance is the ability to sustain attention to information for prolonged periods of time, particularly in environments where critical signals may be rare. Recent research in the domain of mind-wandering has suggested that processes associated with mind-wandering may underpin the typical decline in vigilance task performance. Current methods for measuring mind-wandering either disrupt vigils by asking probe questions throughout the task, or, require observers to reflect on how much mind-wandering occurred during the task upon conclusion of the vigil. Across three experimental studies, we treat mind-wandering as an individual difference, which was measured pre- and post-vigil. We argue this technique is a more holistic representation of mind-wandering and is less intrusive than probe measures, which serve to disrupt the vigil. The results of our first experiment challenge previous results in the literature: higher rates of mind-wandering were associated with improved correct detection performance. Interestingly, the second experiment suggests that increases in mind-wandering were not linked to vigilance performance deficits. However, significant differences in global workload emerged in the second experiment, implying individuals low in mind-wandering report greater workload. In a third experiment, wherein we manipulated event rate, mind-wandering typology had no significant effect on vigilance performance. We conclude with a discussion of the relevance of individual differences in mind-wandering in vigilance research considering the present findings.

Introduction

Vigilance, or the ability to sustain attention for extended periods of time and to respond to infrequent events, has been of interest to basic and applied researchers since the Second World War (Hancock and Warm 1989; Mackworth 1948; Warm and Jerison 1984). Nearly 50 years of research on vigilance has been supported by cognitive resource theory (Kahneman 1973; Moray 1967; Navon and Gopher 1979; Norman and Bobrow 1975). This theory has been used across a variety of paradigms to study the vigilance decrement, which is a decline in performance over time (Helton and Russell 2011, 2012; Helton and Warm 2008; Koelega et al. 1989; Mackworth 1948; Matthews et al. 1993; Parasuraman et al. 2009). Furthermore, a growing body of research suggests that vigilance tasks are high in workload and stressful for operators in both experimental and applied settings (Finomore et al. 2013; Grier et al. 2003; Grier 2015; Hancock and Warm 1989; Matthews and Davies 1998; Smit et al. 2004; Warm et al. 1996, 2008; Warm and Dember 1998). Changes in vigilance performance, as well as the stress and workload associated with the task, are proposed to stem from resource utilization depletion that occurs as a function of remaining vigilant to critical, but rare, information (Caggiano and Parasurman 2004; Helton and Russell 2013; Hirst and Kalmar 1987; Warm et al. 1996). More specifically, resource theory posits that more demanding vigilance tasks will more rapidly deplete cognitive resources due

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to operator overload. This finding has been especially prevalent in dual-task vigilance paradigms (Epling et al. 2016) and cognitive vigilance tasks (compared to sensory vigilance tasks; See et al. 1995).

In contrast to resource theory, mind-wandering theory postulates that declines in performance on vigilance tasks stem from underload, or underarousal, associated with the task (Robertson et al. 1997; Seli et al. 2016a; Thomson et al. 2014, 2015). Proponents of mind-wandering theory argue that vigilance tasks tend to be low in cognitive load (Thomson et al. 2015) and afford intentional or spontaneous mind-wandering, driving a decline in vigilance performance over time (Golchert et al. 2017; Seli et al. 2016a, 2017). Mind-wandering theory suggests that "simpler tasks should precipitate greater (or faster) attentional withdrawal relative to more demanding tasks" (Thomson et al. 2015, p. 85). Troublesome for this theoretical approach, however, is research indicating that performance deficits due to mind-wandering do not always occur in simple tasks (see Experiment One of Thomson et al. 2013). Moreover, the evidence insisting that mind-wandering intentionality is linked to performance is also inconsistent throughout this body of literature (Seli et al. 2015; cf; McVay and Kane 2012).

Given the differences in the proposed theoretical mechanisms underpinning cognitive resource theory and the underload hypothesis, the present research sought to examine the effects of mind-wandering on vigilance performance across three studies that manipulated task difficulty (i.e., simple vs. complex). We examined whether "decreases in detection accuracy over time" and simultaneous "increases in the frequency of reported mind wandering" were linked to performance decrements in a cognitive (complex) and sensory (simple) vigilance task, and difficult (high event rate) and easy (low event rate) vigilance tasks (Thomson et al. 2015, p. 87). The present set of experiments expanded upon previous research that has largely neglected the role of individual differences in mind-wandering across vigilance taxonomic factors, such as task type or event rate.

We measured mind-wandering as a pre- and post-vigil individual difference, rather than opting for a thought-probe design. In several studies of mind-wandering and vigilance, the thought-probe method has been used (Seli et al. 2016b, 2018); however, this method disrupts the vigil, and thereby thoughtfulness or thoughtlessness, which makes it difficult to conclude that mind-wandering affected vigilance performance. Furthermore, studies that have employed continuous mind-wandering thought probes have indicated that changes in task-unrelated thoughts (i.e., mind-wandering) did not predict performance lapses between vigilance periods (Head and Helton 2014). Thus, researchers have turned to self-report measures of mind-wandering, which remain reliable in their prediction of vigilance performance deficits (Matthews 2016; Seli et al. 2015a, b). In the present study, we measured mind-wandering using the thinking content questionnaire that accompanies the Dundee Stress State Questionnaire (DSSQ; Matthews 2016), as it is administered at pre- and post-task and does not interrupt the vigil.

We hypothesize that individuals low in mind-wandering will demonstrate better vigilance performance (i.e., correct detections, false alarms, response time to critical signals) given the previous findings from the literature on cognitive resource theory. For example, according to cognitive resource theory, it is likely that individuals low in mind-wandering have more cognitive resources to direct toward the task; individuals high in mind-wandering are distracted by inward and outward thoughts, which limits the resources they can direct toward the vigilance task. To reiterate, mind-wandering theorists suggest that simpler tasks will afford greater attentional withdrawal, resulting in greater mind-wandering, and thus poorer task performance (Thomson et al. 2015, p. 85).

Experiment one

Method

Observers

Data were collected from 71 observers at a large southeastern university in the US. Observers achieving a less than 60% correct detection rate in the first period on watch were excluded from the present analyses. Additionally, observers could commit no more than 15 false alarms in any given period on watch (i.e., Neigel et al. 2018). Twenty-four observers were removed from this sample due to performance deviations that did not meet inclusion criteria. It should be noted that removed observers did not significantly differ on measures of mind-wandering, workload, or stress relative to the overall sample.

This resulted in a sample of 47 (27 female; 20 male) observers with an average age of 19.98 years (median 19.00 years, SD 3.38 years, range 18–37 years) in the first experiment. All observers reported normal or corrected-to-normal vision. Observers indicated that they did not consume caffeine, stimulants, or depressants at least 24 h prior to participating in this study. Observers completed this study for partial course credit. Observers could only participate in one of the three experiments (i.e., all data is from unique samples).

Measures

Dundee stress state questionnaire The Dundee Stress State Questionnaire (DSSQ; Matthews 2016; Matthews et al. 2002) is a measure of perceived stress experienced prior to the experiment and immediately after the experiment. The

long version (Matthews et al. 2002) of the DSSQ yields 11 primary subscales that are related to stress. The subscales related to task-related thoughts and task-unrelated thoughts (i.e., Thinking Content; see the Appendix) were used to develop a set of mind-wandering typologies (described herein).

Higher scores on the thought-related subscales indicate more of that factor. For example, higher scores on task-related thought items indicate more focus on the task. Conversely, high scores on task-unrelated thought items indicate more distraction or mind-wandering during the task. The thinking content section DSSQ also demonstrated very high reliability at pre-task (Cronbach's alpha = 0.921, 16 items) and post-task (Cronbach's alpha = 0.910, 16 items).

NASA-task load index The NASA-Task Load Index (NASA-TLX; Hart and Staveland 1988) was used to measure the perceived mental workload associated with the vigilance task. The NASA-TLX includes six scales that measure mental demand, physical demand, temporal demand, performance, frustration, and effort. These six scales are used to calculate an overall, or "global", workload score. Higher scores are indicative of more global workload.

Task environment and stimuli

All stimuli were presented using SuperLab software (version 4.5) on a Dell OptiPlex 745 desktop computer and a Dell 18-inch computer monitor. Observers completed the experiment in a quiet, uniformly and dimly lit research laboratory. Observers were seated approximately 50.8 cm from a desktop computer monitor, which displayed the experimental stimuli (Hancock et al. 2015). A researcher was not present in the room for the vigil but was present to administer pre- and post-task questionnaires. All questionnaires were administered electronically using Qualtrics survey software.

Observers completed a 24-min, cognitive vigilance task. The vigilance task utilized in the present experiment was adapted from previous research investigating the effects of cognitive-based vigilance tasks and has reliably produced a vigilance decrement (i.e., Claypoole et al. 2018; Warm and Jerison 1984). Observers were required to monitor a single display that consisted of the repeated presentation of two-digit numbers (presented in black, 24-point Arial font upon a grey background). Observers were instructed to respond when a critical signal appeared on the screen. A critical signal occurred when the difference between the two digits was either zero, positive one, or negative one. For instance, "54", "66", and "10" were all critical signals, whereas "28", "09", and "42" were not.

Each stimulus was presented for 1000 ms and was followed by an interstimulus interval (ISI; a blank screen) that lasted 1500 ms, for a total stimulus duration of 2500 ms with an event rate of 24 events/min (signal probability ~ 3.5%). Observers were instructed to respond to critical signals by pressing the spacebar when a critical signal was perceived. Observers could respond to stimuli any time during the 2500 ms that the stimulus and the ISI were on-screen. In the 24-min vigilance task, there were five critical signals presented in each 6-min period of watch for a total of 20 critical signals across the four periods.

Procedure

Observers arrived at the laboratory and removed any timepieces (if worn) and surrendered cellular devices (i.e., Claypoole and Szalma 2018; Hancock 2017; Neigel et al. 2018). Observers were provided with an informed consent document. Next, observers completed a set of questionnaires (i.e., demographics questionnaire, pre-task DSSQ, in that order) prior to the vigil. After these questionnaires were completed, the researcher reviewed the instructions and example stimuli with the observer and answered any questions before exiting the room to allow the observer to complete the vigil alone (i.e., without supervision). Example stimuli were presented, and a 5-min practice vigil was provided to familiarize observers with the task (note that consistent with previous experiments, no feedback was provided during the practice session, i.e., Claypoole and Szalma 2018). Immediately after the practice session, the observers began the 24-min vigil. After the vigilance task was completed, the research assistant entered the room to administer the post-task questionnaires, which included the post-task DSSQ and NASA-TLX (in that order). Observers were then thanked for their time and left the research laboratory.

Results

Mind-wandering typologies

A hierarchical cluster analysis was performed to identify the typologies that corresponded to mind-wandering as measured by pre- and post-task task-related thoughts and task-unrelated thoughts (note: this is referred to as task-related interference and task-unrelated interference on the DSSQ, Matthews et al. 2002). A cluster analysis identified two groups: 14 observers low in mind-wandering (high task-related thoughts, low task-unrelated thoughts) and 35 observers high in mind-wandering (low task-related thoughts, high task-unrelated thoughts; see Table 1).

Global workload

An independent-samples *t* test was performed to examine differences in global workload between the mind-wandering clusters. The results did not yield any significant

**Table 1** Cluster centroids for the mind-wandering typologies (N=47)

	Low mind-wandering (N=14)	High mind-wandering (N=33)
Pre-task task-related thoughts	1.16	− 0.47
Post-task task-related thoughts	0.76	− 0.31
Pre-task task-unrelated thoughts	− 1.22	0.49
Post-task task-unrelated thoughts	− 1.14	0.46

findings. However, individuals low in mind-wandering noted slightly more workload (M 59.07, SD 18.41) associated with the task compared to individuals high in mind-wandering (M = 56.44, SD = 14.08, p = .16).

Correct detection performance

A two (mind-wandering typology) × four (number of watch periods) mixed measures analysis of variance (ANOVA) was performed with the proportion of correct detections as the dependent variable. The results indicated a significant main effect of period on correct detection performance, $F(3, 135) = 35.62$, $p < .001$, $\eta_p^2 = 0.442$ (i.e., the decrement). There was also a significant main effect of mind-wandering on correct detection performance, $F(1, 45) = 5.77$, $p = .020$, $\eta_p^2 = 0.114$. This main effect indicated that individuals high in mind-wandering, specifically task-unrelated thoughts, performed the cognitive task better than individuals low in mind-wandering. There were no additional significant main effects or interactions to report for this analysis. The proportion of correct detections for Experiment One are included in Fig. 1.

False alarm performance
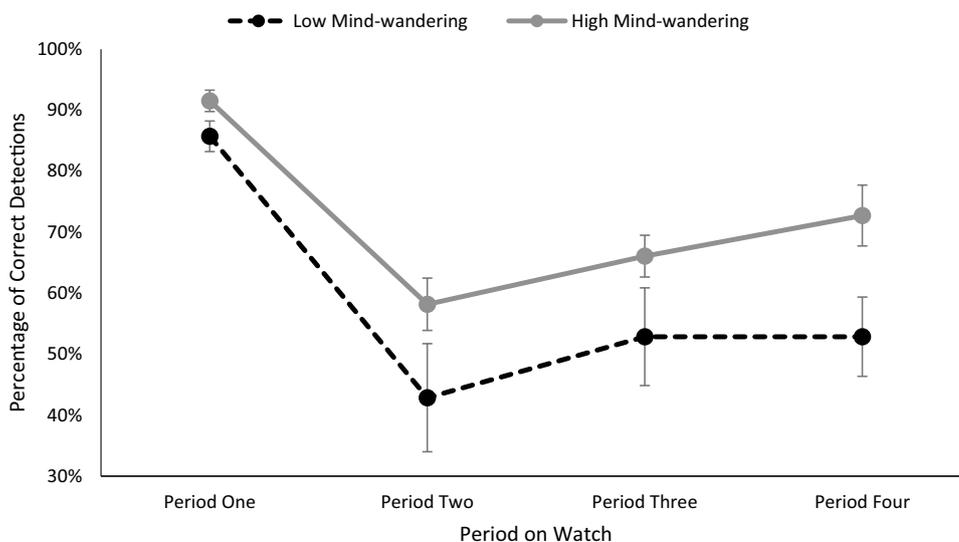
A two (mind-wandering typology) × four (number of watch periods) mixed measures ANOVA was performed with a number of false alarms as the dependent variable. The test of sphericity was violated and the Huynh–Feldt epsilon statistic is reported where appropriate. The results indicated a significant main effect of period, $F(3, 135) = 8.37$, $p < .001$, $\eta_p^2 = 0.157$, $\varepsilon = 0.708$. There were no additional significant main effects or interactions to report for this analysis. The number of false alarms committed over time is included in Fig. 2.
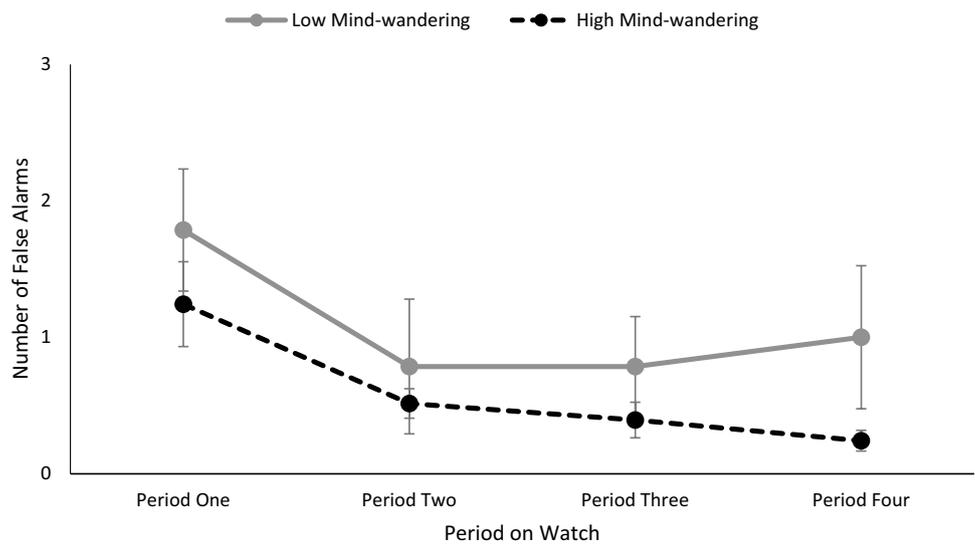
Response time

A two (mind-wandering typology) × four (number of watch periods) mixed measures ANOVA was performed with mean response time (in milliseconds) to critical stimuli as the dependent variable. The test of sphericity was violated and the Huynh–Feldt epsilon statistic is reported where appropriate. The results indicated a significant main effect of period on watch, $F(3, 129) = 12.42$, $p < .001$, $\eta_p^2 = 0.224$, $\varepsilon = 0.673$. There were no additional significant main effects or interactions to report for this analysis. Mean response time is included in Fig. 3.

Discussion

Experiment One examined the effects of pre- and post-task reports of mind-wandering on cognitive vigilance performance. The present experiment demonstrated that individual difference measures of mind-wandering were linked to correct detection performance. Interestingly, individuals higher in mind-wandering correctly detected more target stimuli than individuals who were low in

Fig. 1 Percentage of correct detections across observers high and low in mind-wandering. Error bars represent standard error of the mean

Fig. 2 Number of false alarms committed across observers high and low in mind-wandering. Error bars represent standard error of the mean

Fig. 3 Mean response time to critical signals across individuals high and low in mind-wandering. Error bars represent standard error of the mean
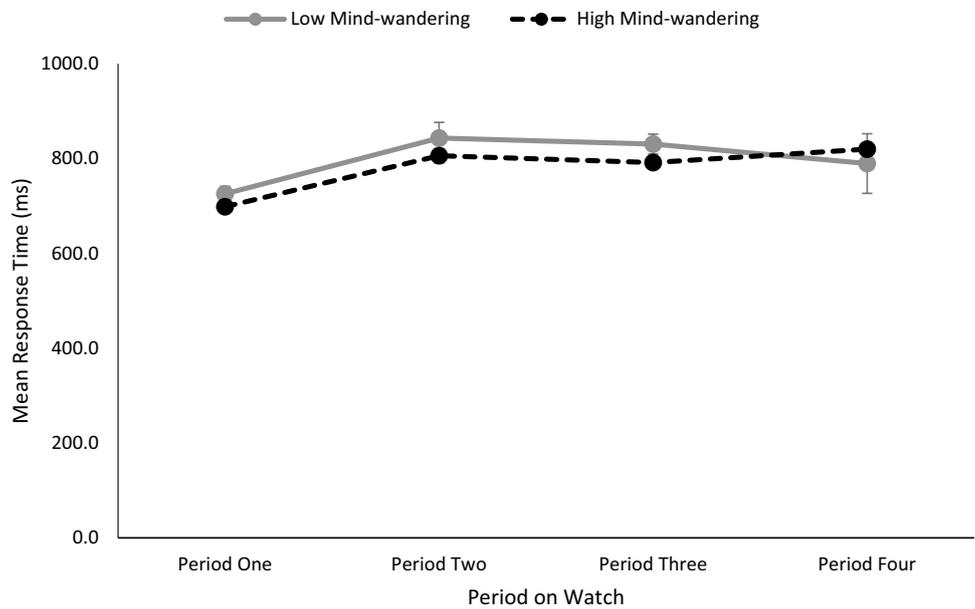
mind-wandering. Individuals lower in mind-wandering (i.e., more task-related thoughts and fewer task-unrelated thoughts) performed worse on the cognitive vigilance task relative to the high mind-wandering observers. While this result contradicts much of the mind-wandering literature, it supports the idea that individuals higher in mind-wandering may have better resource allocation strategies and thus can better oscillate between focusing on the task at hand and active mind-wandering, which has recently been suggested by some mind-wandering theorists (Golchert et al. 2017). Moreover, advocates of mind-wandering theory argue that a more difficult vigilance task, like the cognitive task used in the present experiment, should result in lower levels of mind-wandering because it is mentally stimulating (Thomson et al. 2015). However, the current results indicated that over half of the observers reported high levels of mind-wandering and high levels of global workload. Again, the results indicated that mind-wandering is neither linked to the vigilance decrement nor associated with changes in false alarm performance or response time to critical signals.

Other than the difference found in correct detection performance, Experiment One indicated that time on task was driving the declines in detection performance. Mind-wandering was not linked to false alarm performance or response time. To better understand these results and replicate the relationship between mind-wandering and performance, we conducted a second experiment that manipulated task type, which enabled us to determine whether mind-wandering is affected by task complexity.

To reiterate, mind-wandering suggests two main assumptions in relation to performance: (1) a decrease in correct detection performance is related to an increase in mind-wandering, and (2) tasks that are simple, or easy, should result in higher rates of mind-wandering due to cognitive underload (Robertson et al. 1997; Seli et al. 2014; Thomson et al. 2015). The results of the first experiment did not support either assumption of mind-wandering theories, thus, the second experiment was conducted to directly compare differences between simple and complex vigilance tasks.

Experiment two

Method

Observers

Data were collected from 79 observers at a large southeastern university in the US. As in the first experiment, observers achieving a less than 60% correct detection rate in the first period on watch were excluded from the present analyses. Additionally, observers could commit no more than 15 false alarms in any given period on watch (i.e., Neigel et al. 2018). Fourteen observers were removed from the sample because of performance deviations that did not meet the inclusion criteria. Of the two task types, observers tended to be removed from the cognitive task more often than the sensory task.

This resulted in a sample of 65 (42 female; 23 male) observers with an average age of 19.09 years (median 19.00 years, SD 1.57 years, range 18–27 years). All observers reported normal or corrected-to-normal vision and were asked to abstain from the consumption of caffeine, stimulants, or depressants at least 24 h prior to participating in the study. Observers completed this study for partial course credit. Observers could only participate in one of the three experiments (i.e., all data is from unique samples).

Measures

The DSSQ and NASA-TLX were also administered in Experiment Two. The thinking content section DSSQ demonstrated very high reliability at pre-task (Cronbach's alpha = 0.914, 16 items) and post-task (Cronbach's alpha = 0.891, 16 items) in this experiment.

Task environment and stimuli

Observers could be randomly assigned to one of two vigilance tasks: a cognitive task ($N = 26$) or a sensory task ($N = 39$). Each vigilance task consisted of four blocks of 123 neutral events and five critical signals, which were presented over the course

of a 21-min vigil (signal probability ~ 3.9%). Stimuli were presented for a total of 2500 ms using SuperLab 4.0 software on a Dell Optiplex 745 desktop computer. The stimuli are adapted from Szalma and Teo (2012) and have reliably produced a vigilance decrement in previous research.

Sensory task In the sensory task, critical stimuli occurred when one digit in a two-digit pair was bolded, but the other digit was not. Observers were instructed to press the spacebar on the keyboard whenever this difference was perceived. All other two-digit pairs were considered neutral events (i.e., no digits in the pair were bolded) and observers were instructed to withhold responses to these non-signals.

Cognitive task The same cognitive vigilance task that was utilized in Experiment One was used in Experiment Two.

The same experimental laboratory setup was utilized in Experiment Two.

Procedure

As in the first experiment, all observers powered down any electronic devices (e.g., cellphones, tablets, laptops, etc.) and surrendered watches (if worn) to the researcher prior to beginning the experiment (Hancock et al. 2015). Observers arrived at the research laboratory and were provided with an informed consent document.

Next, observers completed the pre-task DSSQ. Observers then completed a short set of practice trials (approximately 2 min in duration) related to the vigilance task to which they were assigned. Practice trials were designed to provide more information about the critical signals and provide a brief opportunity for practicing responding to the stimuli. During this practice period, observers were instructed to press the spacebar on a keyboard if they encountered a critical signal and withhold response to all neutral stimuli. As in the first experiment, no feedback was provided during the practice session.

After practice, the vigil began, and the research assistant left the room. When the vigil concluded, observers completed the post-task DSSQ and NASA-TLX, which were counterbalanced to control for order effects. Demographic information was collected after the DSSQ and NASA-TLX were administered. Finally, observers were given a post-participation form and thanked for their participation in the study.

Results

Mind-wandering typologies

The same hierarchical cluster analysis was performed to identify high or low mind-wandering. This cluster analysis

indicated that 20 observers were low in mind-wandering (12 sensory, 8 cognitive) and 45 observers were high in mind-wandering (27 sensory, 18 cognitive; see Table 2).

Global workload

A two (mind-wandering typology) × two (task type) ANOVA was performed with global workload as the dependent variable. The results yielded a significant main effect of mind-wandering typology on workload, $F(1, 64) = 5.46$, $p = .023$, $\eta_p^2 = 0.082$. Pairwise comparisons indicated that significantly greater global workload was reported by observers low in mind-wandering (M = 43.66, SD = 14.67) compared to observers high in mind-wandering (M = 35.53, SD = 12.91, $p = .023$). Average global workload scores are included in Fig. 4.

Correct detection performance

A two (mind-wandering typology) × two (task type) × four (number of watch periods) mixed measures ANOVA was performed with the proportion of correct detections as the dependent variable. For these analyses, the test of sphericity was violated and the Huynh–Feldt epsilon statistic is reported where appropriate. The results indicated a significant main effect of period on watch, $F(3, 183) = 6.01$, $p = .002$, $\eta_p^2 = 0.090$, $\varepsilon = 0.805$ (i.e., the decrement), which is consistent with Experiment One. Observers higher in mind-wandering tended to perform better than individuals lower in mind-wandering across conditions, albeit no significant main effects emerged. There were no additional significant main effects or interactions to report for this analysis. The proportion of correct detections for Experiment Two are included in Fig. 5.

False alarm performance

A two (mind-wandering typology) × two (task type) × four (number of watch periods) mixed measures ANOVA was performed with number of false alarms as the dependent variable. The test of sphericity was violated and the Huynh–Feldt epsilon statistic is reported where appropriate. Consistent with Experiment One, the results indicated a significant main effect of period, $F(3, 183) = 11.31$, $p < .001$, $\eta_p^2 = 0.156$, $\varepsilon = 0.622$. There were no additional significant main effects or interactions to report for this analysis. The number of false alarms committed over time is included in Fig. 6.

Response time

A two (mind-wandering typology) × two (task type) × four (number of watch periods) mixed measures ANOVA was performed with mean response time to critical signals as the dependent variable. The test of sphericity was violated and

Table 2 Cluster centroids for the mind-wandering typologies (N = 65)

|	Low mind-wandering (N = 20)	High mind-wandering (N = 45)
Pre-task task-related thoughts	0.49	− 0.38
Post-task task-related thoughts	0.11	− 0.25
Pre-task task-unrelated thoughts	0.04	0.16
Post-task task-unrelated thoughts	− 0.55	0.33

Fig. 4 Workload across observers high and low in mind-wandering and across conditions. Error bars represent standard error of the mean
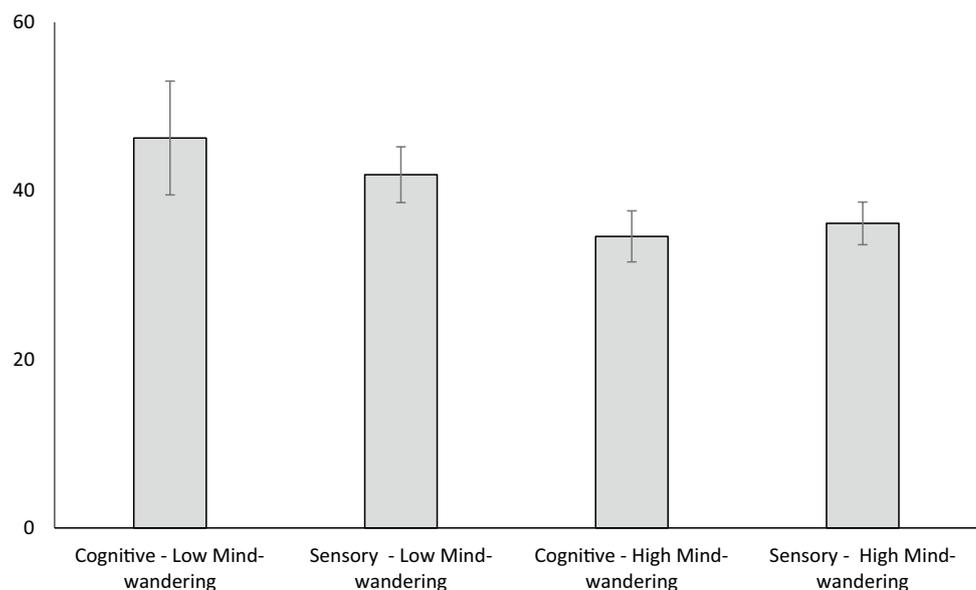
Fig. 5 Percentage of correct detections across observers high and low in mind-wandering and across conditions. Error bars represent standard error of the mean
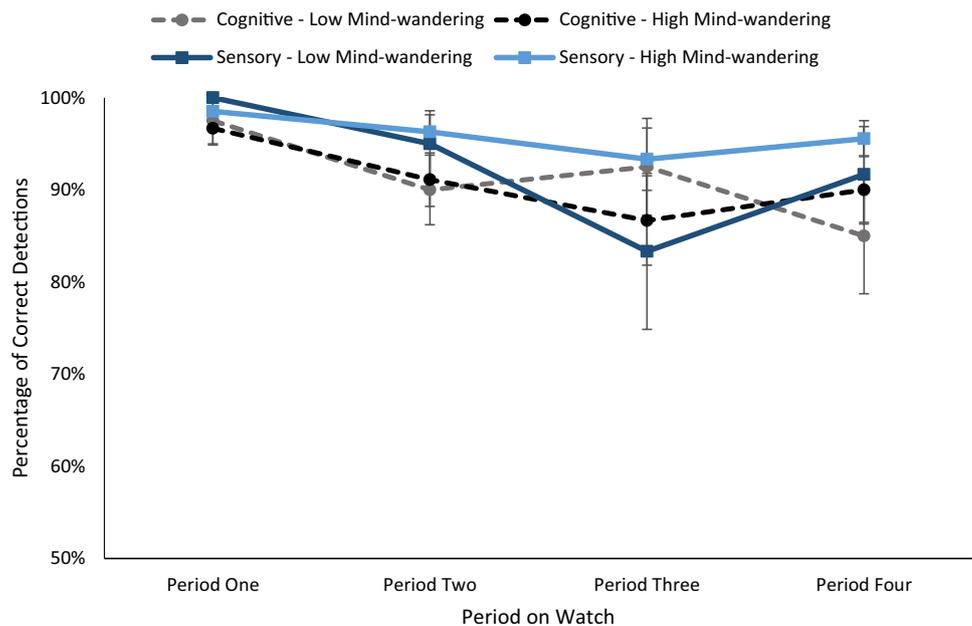
Fig. 6 Number of false alarms across observers high and low in mind-wandering and across conditions. Error bars represent standard error of the mean
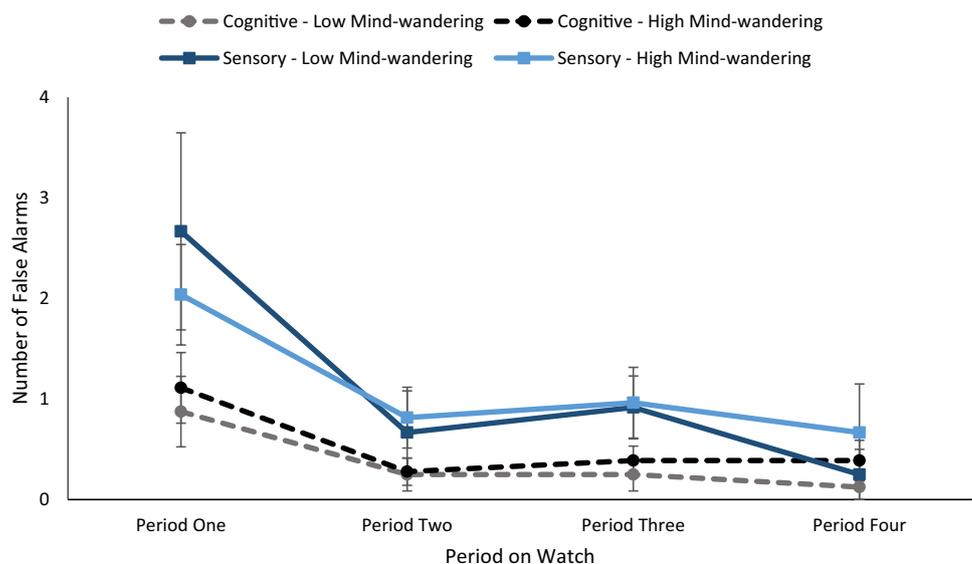

the Huynh–Feldt epsilon statistic is reported where appropriate. The results indicated a significant main effect of task type, $F(1, 60) = 17.98$, $p < .001$, $\eta_p^2 = 0.231$, which suggests that observers in the sensory vigilance task responded to critical signals more rapidly than observers in the cognitive vigilance task. The results also indicated a significant main effect of period on watch, $F(3, 180) = 3.87$, $p = .014$, $\eta_p^2 = 0.061$, $\varepsilon = 0.960$, such that response time increased as a function of period on watch, a finding which is consistent with Experiment One and the previous research (e.g., Warm et al. 2008). Finally, the results indicated a significant interaction between task type and period on watch, $F(3, 180) = 3.08$, $p = .031$, $\eta_p^2 = 0.049$, $\varepsilon = 0.960$. This interaction

indicated that response time to critical signals tended to increase overall in the sensory vigilance task but decreased overall in the cognitive vigilance task. There were no additional significant main effects or interactions to report for this analysis. Mean response time is included in Fig. 7.

Discussion

Experiment Two sought to replicate and extend the results of Experiment One by examining the effects of mind-wandering on vigilance performance in a sensory (i.e., simple) and cognitive (i.e., complex) paradigm. The results of the second experiment indicated that mind-wandering was not

Fig. 7 Mean response time (ms) to critical signals across observers high and low in mind-wandering and across conditions. Error bars represent standard error of the mean
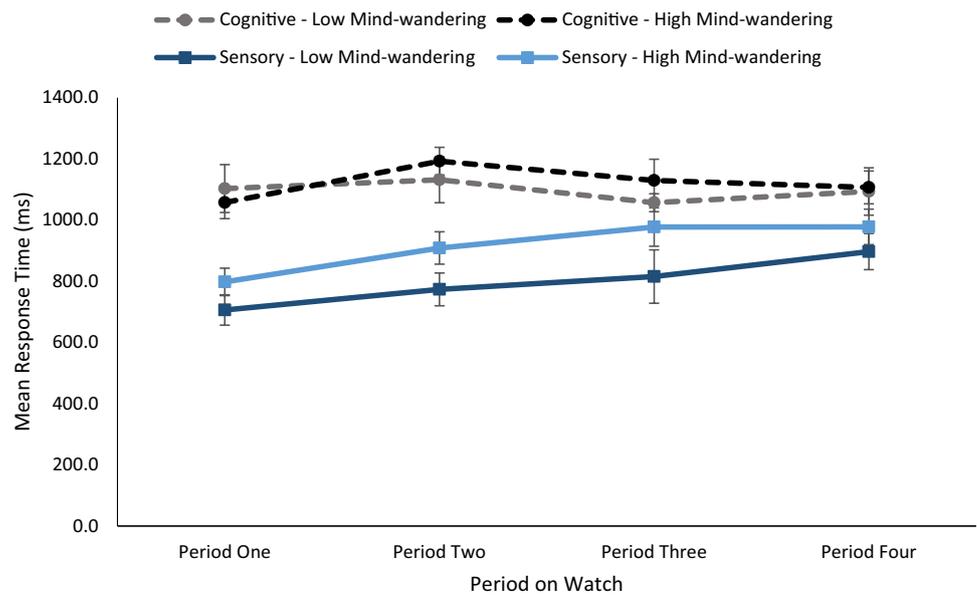
significantly related to several aspects of vigilance performance, including correct detection, false alarm response, and response time. However, the results of Experiment Two did indicate that aspects of the vigilance task, such as task type, drive differences in performance. The results partially replicated Experiment One, in that individuals higher in mind-wandering slightly outperformed observers low in mind-wandering, but this was not significant. While these results are inconsistent, we can argue that mind-wandering does not significantly exacerbate the vigilance decrement, which is suggested by proponents of the mind-wandering hypothesis (i.e., Robertson et al. 1997; Thomson et al. 2015).

Interestingly, Experiment Two did reveal a significant effect of mind-wandering on average global workload. This finding indicated that observers low in mind-wandering, regardless of task type, reported greater global workload associated with the task than individuals high in mind-wandering, which is in line with the first experiment. Because workload scores are moderately high (see Grier 2015) across observers low in mind-wandering, it could be argued these individuals are more focused on the task and devoting greater effort to it. It is also possible that mind-wandering serves as a possible coping mechanism to offset some of the workload induced by the vigilance task, but this is a postulation that will require further investigation, and this would have to be thoughtfully implemented into real world settings.

While the results of Experiments One and Two were similar in terms of the effects of mind-wandering on correct detection performance, these novel results were not statistically identical. For instance, Experiment One produced significant patterns of correct detection performance based on mind-wandering typology, while Experiment Two only suggested a numerical difference in correct detection

performance based on the same typologies. Interestingly, there were several key differences between the first and second experiment, namely in terms of the descriptive statistics. For instance, in the first experiment, the proportion of correct detections, regardless of mind-wandering typology, declined to approximately a 45% correct detection rate. Conversely, in Experiment Two, the proportion of correct detections, regardless of mind-wandering typology or task type, only declined to approximately an 85% correct detection rate. This is further highlighted in the differences in the cluster centroids between the two experiments. The first experiment produced more extreme cluster centroids while the second experiment contained more moderate cluster centroids. It is possible the sample of undergraduates from each experiment differed in some other factor not measured by these experiments, such as personality or working memory which is known to be related to vigilance task performance (i.e., Caggiano and Parasuraman 2004; Finomore et al. 2009; Helton and Russell 2011, 2013; Matthews et al. 2014; Shaw et al. 2010). Future work should seek to investigate which individual difference variables affect mind-wandering in vigilance paradigms.

The purpose of Experiment Two was to determine if simple and complex vigilance tasks resulted in different patterns of mind-wandering and examine how these patterns affect vigilance performance. Importantly, Experiment Two did not provide support for either of the two main assumptions of mind-wandering in relation to performance (i.e., Robertson et al. 1997; Seli et al. 2014; Thomson et al. 2015): decreased correct detection performance was not related to an increase in mind-wandering, and the complex task (i.e., cognitive vigil) was not associated with lower levels of mind-wandering. Instead, the

results of the second experiment provide further empirical support for cognitive resource theory. Decreased detection performance was attributed to time on task and performance was most affected by task complexity.

Experiment Two operationalized task complexity in terms of task type: sensory (i.e., simple) and cognitive (i.e., complex). Although this distinction is prominently supported in the literature (i.e., See et al. 1995), previous research has indicated that vigilance task difficulty may be manipulated through other factors such as signal conspicuity, source complexity, and event rate (i.e., Parasuraman 1979; Parasuraman and Davies 1977; See et al. 1995).

Since there are several mechanisms to induce task difficulty and since the assumptions of mind-wandering theories rely heavily on task difficulty, we conducted a third experiment to further test the effects of mind-wandering on vigilance task performance. The third experiment manipulated event rate, which is argued to be one of the most important factors affecting vigilance performance (Parasuraman and Davies 1977), as well as one of the most reliable indictors of task difficulty in vigilance paradigms (i.e., Claypoole et al. 2018; Guralnick 1973; Jerison and Pickett 1964; Meuter and Lacherez 2016; Mouloua and Parasuraman 1995; Parasuraman 1979).

Experiment three

Method

Observers

Data were collected from 123 observers at a large southeastern university in the US. As in the first two experiments, observers achieving a less than 60% correct detection rate in the first period on watch were excluded from the present analyses. Additionally, observers could commit no more than 15 false alarms in any given period on watch (i.e., Neigel et al. 2018). Twenty-seven observers were removed from this sample due to performance deviations that did not meet inclusion criteria.

This resulted in a sample of 96 (67 female; 29 male) observers with an average age of 19.96 years (median 19.00 years, SD 3.57 years, range 18–41 years). All observers reported normal or corrected-to-normal vision. Observers indicated that they did not consume caffeine, stimulants, or depressants at least 24 h prior to participating in this study. Observers completed this study for partial course credit. Observers could only participate in one of the three experiments (i.e., all data are from unique samples).

Measures

Consistent with the first two experiments, the DSSQ and NASA-TLX were also administered in Experiment Three. The thinking content section DSSQ demonstrated high reliability at pre-task (Cronbach's alpha = 0.891, 16 items) and post-task (Cronbach's alpha = 0.869, 16 items) in this third experiment.

Task environment and stimuli

The task environment and stimuli were adapted from previous research examining the effects of event rate of cognitive vigilance tasks (i.e., Claypoole et al. 2018). The stimuli are the same stimuli used in the cognitive vigilance task from Experiments One and Two. However, this iteration of the cognitive vigilance task employed two levels of event rate, which were manipulations of task difficulty (see Parasuraman and Davies 1977). Participants were either randomly assigned to a difficult task (i.e., high event rate; 40 events per minute with signal probability ~ 2.1%) or an easy task (i.e., low event rate; 24 events per minute, signal probability ~ 3.5%). In the difficult condition ($N = 59$), each stimulus was presented for 1000 ms and was immediately followed by a 500 ms interstimulus interval (i.e., ISI). In the easy condition ($N = 37$), which was identical to the task parameters outlined in the first experiment, each stimulus was presented for 1000 ms and was immediately followed by a 1500 ms ISI. In both conditions, participants were able to respond at any time during the 1500 ms (i.e., difficult condition) or 2500 ms (i.e., easy condition) trial duration.

The same experimental laboratory setup and procedure outlined in Experiment One was also utilized in Experiment Three.

Results

Mind-wandering typologies

The same hierarchical cluster analysis used in the previous experiments was performed to identify high or low mind-wandering. This cluster analysis indicated that 35 observers were low in mind-wandering (16 low event rate; 19 high event rate) and 61 observers were high in mind-wandering (21 low event rate; 40 high event rate; see Table 3).

Global workload

A two (mind-wandering typology) × (task difficulty) ANOVA was performed with global workload as the dependent variable. The analyses yielded a significant main effect of event rate on global workload, $F(1, 92) = 6.25$, $p = .014$, $\eta_p^2 = 0.064$. Pairwise comparisons indicated that

Table 3 Cluster centroids for the mind-wandering typologies ($N=96$)

	Low mind-wandering ($N=35$)	High mind-wandering ($N=61$)
Pre-task task-related thoughts	0.81	−0.46
Post-task task-related thoughts	0.91	−0.53
Pre-task task-unrelated thoughts	−0.61	0.35
Post-task task-unrelated thoughts	−0.57	0.33

significantly greater global workload was reported by observers in the difficult condition (M = 64.46, SD = 15.12), which is consistent with previous research (i.e., Claypoole et al. 2018). No other main effects or comparisons were statistically significant. Average global workload scores are included in Fig. 8.

Correct detection performance

A two (mind-wandering typology) × two (task difficulty) × four (number of watch periods) mixed measures ANOVA was performed with thw proportion of correct detections as the dependent variable. The results indicated a significant main effect of period on watch, $F(3, 276)=32.30$, $p<.001$, $\eta_p^2=0.260$ (i.e., the decrement), which is consistent with Experiments One and Two. In addition, there was a significant main effect of condition on proportion of correct detections, $F(1, 92)=62.80$, $p<.001$, $\eta_p^2=0.460$, such that observers who completed the easy vigilance task correctly detected more critical signals than those who completed the difficult vigilance task, which is consistent with previous

research (i.e., Claypoole et al. 2018; Guralnick 1973; Jerison and Pickett 1964; Meuter and Lacherez 2016; Mouloua and Parasuraman 1995; Parasuraman 1979). There was also a significant interaction between difficulty and period on watch, $F(3, 276)=14.77$, $p<.001$, $\eta_p^2=0.138$. Observers in the difficult condition demonstrated an accelerated vigilance decrement over time, compared to observers in the easy condition. The proportion of correct detections for Experiment Three are included in Fig. 9.

False alarm performance

A two (mind-wandering typology) × two (difficulty) × four (number of watch periods) mixed measures ANOVA was performed with number of false alarms as the dependent variable. There were no significant main effects or interactions to report for this analysis.
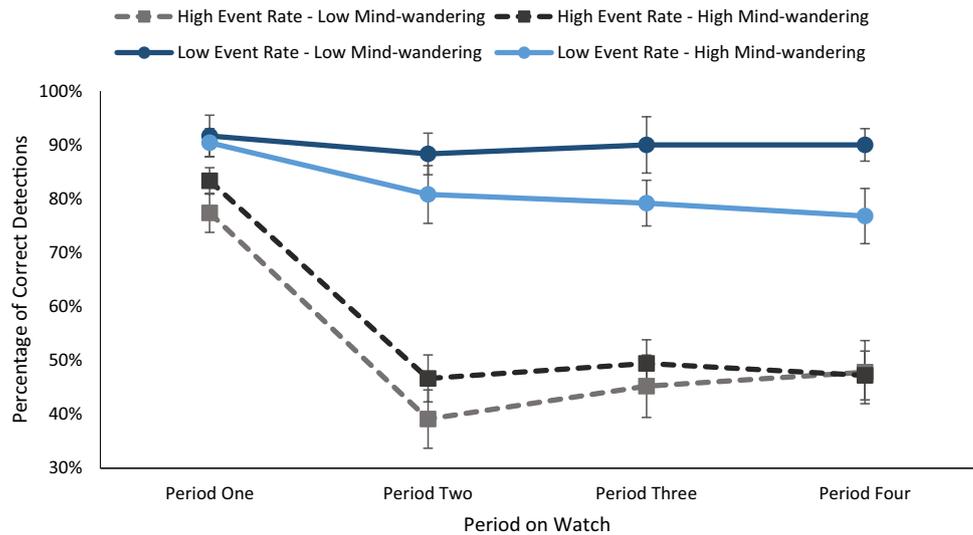
Response time

A two (mind-wandering typology) × two (difficulty) × four (number of watch periods) mixed measures ANOVA was performed with mean response time to critical signals as the dependent variable. The results indicated a significant main effect of period on watch on response time, $F(3, 231)=23.02$, $p<.001$, $\eta_p^2=0.230$, such that response time increased as a function of period on watch, a finding which is consistent with Experiments One and Two and the previous research (i.e., Warm et al. 2008). There was also a significant main effect of difficulty on response time, $F(1, 77)=6.78$, $p=.011$, $\eta_p^2=0.081$. Observers in the easy condition were

Fig. 8 Workload across observers high and low in mind-wandering and across event rates. Error bars represent standard error of the mean
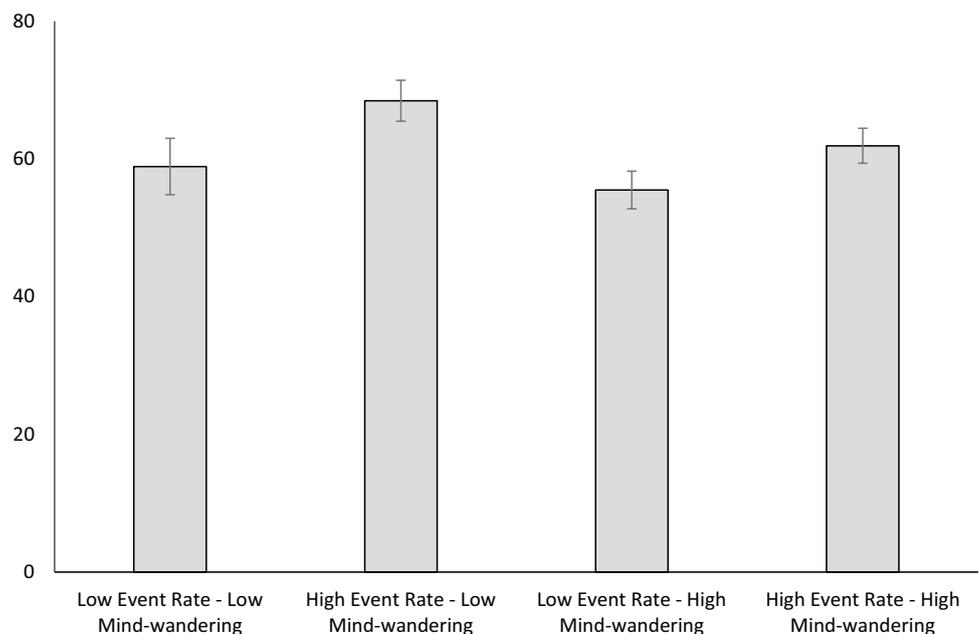
Fig. 9 Percentage of correct detections across observers high and low in mind-wandering and across high and low event rate. Error bars represent standard error of the mean

slower in their response to critical signals. Mean response time is included in Fig. 10.

Discussion

The purpose of the third experiment was to replicate and extend the results of Experiments One and Two to further clarify the effects of mind-wandering on vigilance task performance. Experiment Three examined the effects of mind-wandering on vigilance performance in an easy (i.e., low event rate) and difficult (i.e., high event rate) vigilance task. A key assumption of the mind-wandering hypothesis is that increasing task difficulty results in lower rates of mind-wandering. However, this assumption was not

supported in the present experiment, which utilized one of the most reliable indicators of task difficulty in vigilance paradigms (Claypoole et al. 2018; Guralnick 1973; Jerison and Pickett 1964; Parasuraman 1979). Instead, most observers, regardless of the level of event rate, reported high levels of mind-wandering.

Consistent with Experiment Two, the results of the present experiment indicated that mind-wandering was not associated with correct detection performance, false alarm rates, or response time to critical signals. Thus, as in the previous two experiments, higher rates of mind-wandering did not result in poorer vigilance performance, as theorized by mind-wandering proponents. Instead, the results

Fig. 10 Mean response time to critical signals across observers high and low in mind-wandering and across event rate. Error bars represent standard error of the mean
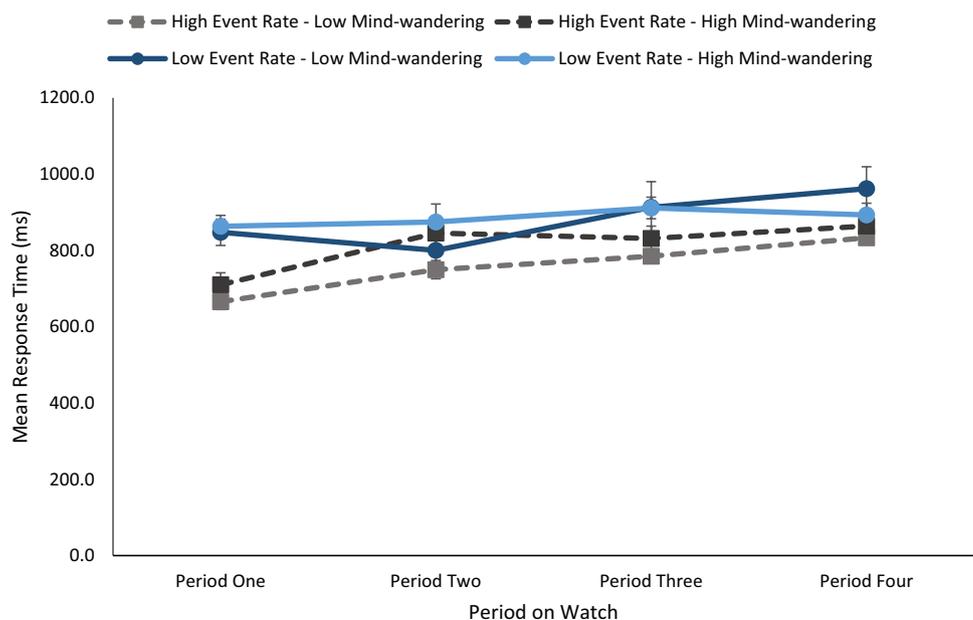
indicated that the taxonomic factor of event rate was the driving force in the reported performance differences.

This result provides further empirical support for cognitive resource theory over the mind-wandering hypothesis. An inverse relationship between event rate and performance was observed: as event rate increased, performance declined. This result is best explained by cognitive resource theory rather than the mind-wandering hypothesis; a more difficult task, which requires the use of more cognitive resources, resulted in poorer performance and greater perceived workload.

General discussion

Two competing theories attempt to explain the vigilance decrement, which is a decline in performance over time. These theories include cognitive resource theory (Fraulini et al. 2017; Helton and Russell 2011, 2012; Helton and Warm 2008; Kahneman 1973; Norman and Bobrow 1975; Parasuraman et al. 2009) and mind-wandering theory (Robertson et al. 1997; Seli et al. 2016a; Thomson et al. 2014, 2015). In the first experiment, the results indicated that observers high in mind-wandering can outperform observers low in mind-wandering, especially when individual differences in task-related and task-unrelated thoughts are considered simultaneously. This finding contradicts the mind-wandering approach: greater mind-wandering should not be linked to improved vigilance task performance. On the contrary, the results of Experiments Two and Three indicated that as complexity or difficulty increase, mind-wandering no longer impacts vigilance performance. Importantly, mind-wandering was not associated with any declines in detection performance across all three experiments and the level of mind-wandering (i.e., high versus low) was not dependent on task type or difficulty as assumed by the theories of mind-wandering. Thus, the results of all three experiments fail to support the key assumptions of the mind-wandering hypothesis: increased task difficulty did not result in lower mind-wandering and higher mind-wandering was not associated with decreased detection performance.

While these results seem contradictory, they actually reflect the broader research on mind-wandering quite well. That is, mind-wandering has not been a reliable predictor of performance (see Experiment One of Thomson et al. 2013), a finding that was further supported by the inconsistent results across the present three experiments. Although mind-wandering was associated with better correct detection performance in the first experiment (a novel result which has not been previously reported), this effect was not reliable in the subsequent experiments. These conflicting results further support the contention of resource theory proponents: mind-wandering is an unreliable predictor and vigilance performance is best explained in terms of resource utilization and allocation.

Furthermore, observers reported moderately high (see Grier 2015) levels of workload associated with the vigilance tasks across all three experiments. This suggests the vigilance tasks across all three experiments, regardless of task-type or event rate, were hard work and effortful, which is consistent with the broader literature (i.e., Warm et al. 2008). In the first two experiments, observers higher in mind-wandering reported lower levels of global workload, which may be evidence for the performance-workload disassociation (Hancock 1996). The direction of this disassociation (i.e., no performance effects, but lower perceived workload) may reflect shifts in attention strategies that result in fewer resources required to perform the task (Claypoole and Szalma 2018; Hancock 1996; Yeh and Wickens 1988), which would align with the cognitive resource theory view of the vigilance decrement. However, this effect did not emerge in the third experiment. Instead, perceived workload was affected by event rate rather than mind-wandering. As event rate increased, perceived workload also increased; this resulted in a performance–workload association (i.e., performance declined, workload increased). This effect reflects the hallmark assumptions of cognitive resource theory: as more resources are required to complete a task, performance will suffer and workload will increase if no resource allocation strategies are employed. Thus, rather than encouraging purposeful mind-wandering, perhaps future research efforts can be directed toward understanding attentional strategies and resource allocation during vigilance tasks.

Compliance with ethical standards

Appendix: Thinking content items from the DSSQ

This set of questions concerns the kinds of thoughts that go through people's heads at particular times, for example, while they are doing some task or activity. Below is a list of thoughts, some of which you might have had recently. Please indicate roughly how often you had each thought during the last 10 min or so, by circling a number from the list below

(1 = Never, 2 = Once, 3 = A few times, 4 = Often, 5 = Very often).

Task-related thought items:

- I thought about how I should work more carefully.
- I thought about how much time I had left.
- I thought about how others have done on this task.
- I thought about the difficulty of the problems.
- I thought about my level of ability.
- I thought about the purpose of the experiment.
- I thought about how I would feel if I were told how I performed.
- I thought about how often I get confused.

Task-unrelated thought items:

- I thought about the members of my family.
- I thought about something that made me feel guilty.
- I thought about personal worries.
- I thought about something that made me feel angry.
- I thought about something that happened earlier today.
- I thought about something that happened in the recent past (last few days, but not today).
- I thought about something that happened in the distant past.
- I thought about something that might happen in the future.

Note: There is a present tense version of the DSSQ which is worded slightly differently and administered at pre-task. The version included in the "Appendix" is the post-task version of the DSSQ and worded as though the vigil has been completed.

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