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A Resource-Control Account of Sustained Attention: Evidence From Mind-Wandering and Vigilance Paradigms

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Abstract

Staying attentive is challenging enough when carrying out everyday tasks, such as reading or sitting through a lecture, and failures to do so can be frustrating and inconvenient. However, such lapses may even be life threatening, for example, if a pilot fails to monitor an oil-pressure gauge or if a long-haul truck driver fails to notice a car in his or her blind spot. Here, we explore two explanations of sustained-attention lapses. By one account, task monotony leads to an increasing preoccupation with internal thought (i.e., mind wandering). By another, task demands result in the depletion of information-processing resources that are needed to perform the task. A review of the sustained-attention literature suggests that neither theory, on its own, adequately explains the full range of findings. We propose a novel framework to explain why attention lapses as a function of time-on-task by combining aspects of two different theories of mind wandering: attentional resource (Smallwood & Schooler, 2006) and control failure (McVay & Kane, 2010). We then use our "resource-control" theory to explain performance decrements in sustained-attention tasks. We end by making some explicit predictions regarding mind wandering in general and sustained-attention performance in particular.

Keywords

vigilance, mind wandering, sustained attention, executive control, attentional resources

Sustaining the focus of one's attention over long durations can be challenging at the best of times, but it can seem exponentially more difficult when the challenge is to "stay sharp" in case a possible, but unlikely, event occurs. This scenario is common to many occupations, and it characterizes the daily lives of radar operators, nuclear power plant operators, air traffic controllers, security screeners, x-ray technicians, truck drivers, and pilots, to name but a few. It has long been known that attention, and consequently performance, wanes over time (both empirically and anecdotally) in situations in which there is typically little for the observer to do, as in the monitoring of automated systems (Parasuraman, 1996). This sustained-attention (or vigilance) decrement can result in costly oversights, such as failing to identify an enemy submarine or allowing a passenger to carry a weapon onto an airplane. As a result, the study of sustained attention is an important pursuit for cognitive psychologists interested in the basic mechanisms of attention as well as for human factors researchers interested in optimizing the performance of human monitors across a range of settings.

Here, our goal is to understand why it is so difficult for humans to stay focused on the task at hand beyond the first few minutes. We first describe the phenomenon known as the *vigilance decrement* (N. H. Mackworth, 1948), in which performance in sustained-attention tasks declines as a function of time-on-task. We then discuss leading theoretical accounts of the vigilance decrement, which fall into two broad categories: (a) *underload theories*, which maintain that vigilance tasks are mundane and monotonous, causing attention to drift away from

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the external environment, resulting in an inability to detect critical events, and (2) *overload theories*, which hold that vigilance tasks are effortful and result in the depletion of a limited pool of information-processing resources, thus impairing one's ability to detect critical events. We then examine the empirical evidence on vigilance performance to date, and we argue that neither theory in its current form can readily handle the full range of findings. Finally, we propose a novel theoretical framework that can make sense of seemingly conflicting findings. We draw on aspects of "resource" (Smallwood & Schooler, 2006) and "control-failure" (McVay & Kane, 2010, 2012) theories of attention lapses to explain the full range of empirical findings concerning vigilance decrements. We discuss the implications of this *resource-control theory* with respect to sustained attention, mind wandering, and the vigilance decrement before making novel empirical predictions and suggesting avenues for future work.

The Phenomenon

Starting just after the end of World War II, N. H. Mackworth (1948, 1950) was tasked with explaining why British naval radar operators displayed an increasing tendency to miss critical radar signals (enemy combatants) as their watch periods progressed. Laboratory tasks were devised that were intended to mirror the monotony of a standard radar-monitoring task. In one such task, participants were required to monitor a simplified clock in which the clock hand moved 1/12th of the way around the clock face each second or so. The critical signals to be detected were "skips" in the clock hand in which the hand moved 1/6th of the way around the clock in a single move. With a low signal frequency (i.e., when skips were rare), Mackworth observed significant decrements in detection accuracy over time, confirming real-world observations.

The conditions under which vigilance decrements occur have been made explicit in a "taxonomy" (Parasuraman & Davies, 1977; see also Parasuraman, 1979; Parasuraman, Warm, & Dember, 1987). This taxonomy has allowed researchers to create abbreviated vigilance tasks that are relatively short in duration (e.g., 8 min; Nuechterlein, Parasuraman, & Jiang, 1983), and yet, the vigilance decrement is quite pronounced. These abbreviated tasks have spurred increased research in recent years. However, surprisingly, despite more than 60 years of investigation, researchers have yet to agree on the underlying mechanisms that promote declining performance over time in tasks—be they simple or complex—requiring sustained attention.

Current Theoretical Accounts of the Vigilance Decrement

Although the theoretical accounts of the vigilance decrement in the early years after the work of N. H. Mackworth (1948, 1950) were numerous and varied (see Frankmann & Adams, 1962, for a review), modern theoretical accounts typically take one of two forms: overload and underload theories. Both accounts have received considerable attention in recent years, and there is some debate in the literature as to which theory best accounts for the extant data. We first briefly outline these two contrasting theories then unpack the empirical evidence supporting them.

The overload account: Resource depletion

The leading variant of the overload account of the vigilance decrement is known as the *resource-depletion hypothesis*, which is premised on the fact that humans are limited in terms of their information-processing abilities at any given moment in time. The depletion account holds that vigilance tasks are quite taxing and effortful (Warm, Dember, & Hancock, 1996), and the vigilance decrement derives from the depletion of information-processing resources over time. Thus, the depletion hypothesis holds that (a) the amount of resource depletion depends on the nominal demands of the primary task, as well as on the amount of time one is required to sustain the focus of attention on that task (Caggiano & Parasuraman, 2004), and (b) when resources become too low, there is insufficient attention directed toward the task, resulting in a reduced ability to detect critical target events.

The underload account: Mindlessness versus mind wandering

One popular instantiation of the underload account is known as the *mindlessness hypothesis*. This hypothesis holds that vigilance tasks, by their very nature, are monotonous and understimulating (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Consequently, as time progresses, there is a withdrawal of attention from the perceptual input, resulting in an automatic, or "mindless," approach to the task at hand. As time-on-task increases, infrequent targets are responded to as if they were frequent nontargets. The mindlessness account, however, does not specify the fate of attention after it becomes withdrawn from the task. It could be that attention is directed nowhere, that is, the individual is literally

Table 1. Predictions of the Resource-Depletion and Mind-Wandering Accounts With Respect to the Four Key Lines of Inquiry Related to the Vigilance Decrement

	Theoretical account	
Line of inquiry	Resource-depletion	Mind-wandering
1. Are vigilance tasks effortful?	Yes	No
2. How should increasing task demands affect the decrement?	Decrement should get larger	Decrement should get larger or remain unchanged
3. How should increasing task engagement affect the decrement?	Decrement should get larger or remain unchanged	Decrement should get smaller
4. How should time-on-task affect mind-wandering frequency?	Frequency should decrease	Frequency should increase

mindless for a time. It is possible, however, that when attention is withdrawn from the primary task, it does not vanish but instead is simply redirected internally. A recent surge in research into the phenomenon of mind wandering provides precedent for this idea, and thus, a more tractable instantiation of the underload account may be the *mind-wandering hypothesis*.

Mind-wandering theorists have argued that when external perceptual input fails to hold the focus of one's attention, the mind tends toward self-generated, task-unrelated thought (TUT)—a phenomenon that is colloquially (and in the scientific literature) referred to as mind wandering (Smallwood & Schooler, 2006). Although most mind-wandering researchers have not directly applied their ideas to the vigilance domain per se (for exceptions, see McVay & Kane, 2012; Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012), it is worthwhile considering how a mind-wandering variant of the underload hypothesis would account for performance decrements over time in vigilance task settings. Specifically, instances of mind wandering directly impair performance in sustained-attention tasks as a result of the fact that (a) the act of mind wandering itself consumes the same attentional resources that are needed for the primary task (Smallwood, 2010; Smallwood & Schooler, 2006); (b) the apparently low demands (understimulation) of a sustained-attention task fosters especially high levels of mind wandering over time; and (c) when the mind wanders, attention becomes "decoupled" from the external environment, as attentional resources are redirected toward internal thoughts (Schooler et al., 2011; Smallwood, Beach, Schooler, & Handy, 2008). Both mindlessness and mind-wandering variants of the underload theory of vigilance performance share the notion that available attentional resources have been withdrawn from the primary task, thus qualitatively distinguishing them from the resource-depletion hypothesis. However, the mind-wandering hypothesis entails greater specificity (compared with the mindlessness hypothesis) because it describes what becomes of attention after it is withdrawn from the task.

Adjudicating between resource-depletion and mind-wandering accounts

We now examine the available evidence from the vigilance domain as it concerns overload and underload theories of performance decrements. Specifically, however, when examining the extant data, the resource-depletion (a variant of the overload theory) and mind-wandering (a variant of the underload theory) hypotheses are what we compare and contrast. We wish to make explicit that although the resource-depletion account as stated here has been extensively examined by vigilance/sustained-attention researchers, the mind-wandering hypothesis we have outlined has received comparatively little attention in the vigilance domain. However, the mind-wandering account is often described as encapsulating the mindlessness hypothesis (e.g., Helton & Warm, 2008), and so researchers who have been directly contrasting depletion and mindlessness accounts have also (explicitly or implicitly) been contrasting depletion and mind-wandering accounts.

In what follows, we discuss the four primary lines of inquiry that have shaped theoretical accounts of vigilance/sustained-attention performance. These investigations center around (a) whether vigilance tasks are effortful, (b) the effects of increasing task demands, (c) the effects of arousal/task engagement, and (d) direct examinations of mind wandering as a function of time-on-task. We have summarized the position of the mind-wandering and depletion hypotheses with regard to these four lines of inquiry in Table 1. As explained later, neither theory in its current form adequately accounts for the full range of data.

Vigilance and subjective workload

To better understand the phenomenology associated with performing a vigilance task, researchers have considered how subjectively effortful such tasks are experienced to be by participants. The depletion hypothesis suggests that the workload experienced during vigils is high and that this high workload drains resources, leading to vigilance decrements (Caggiano & Parasuraman, 2004). In contrast, according to the mind-wandering hypothesis, the experienced workload during vigils should be low (i.e., vigils are understimulating), which ultimately begets a withdrawal of attention from the task (referred to in the mind-wandering literature as *perceptual decoupling*; Schooler et al., 2011; Smallwood et al., 2011).

As a means of determining whether typical sustained-attention tasks are best characterized as being too stressful or too boring, Grier et al. (2003) had participants perform an abbreviated vigilance task as well as the sustained attention to response task (SART; as per Robertson et al., 1997), in which observers must respond to the presentation of single digits but must withhold responses to the digit "3" (in essence this is the opposite of standard vigilance tasks in which most stimuli require no response, and infrequent stimuli do require a response). After performing these tasks, ratings of mental workload and stress were obtained with the National Aeronautics and Space Administration—Task Load Index (NASA–TLX; see Hart, 2006; Hart & Staveland, 1988) and the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999), respectively.[1] Critically, similarly high scores on both subjective ratings of workload and stress were observed in both tasks, suggesting that the observed performance decrements are best characterized by mental overload, not underload, which is taken as evidence in support of the resource-depletion hypothesis (see Warm, Parasuraman, & Matthews, 2008, for a review of this idea).

Although subjective reports of workload and stress are certainly informative, when possible, researchers typically prefer objective dependent measures. Although certain psychological states do not lend themselves particularly well to objective observation, there are well-known physiological markers of stress. In a recent study, participants' heart rate and respiration were monitored while they performed a vigilance task. Both declined over time, in parallel with decrements in performance, which is interpreted as evidence that underarousal may hinder the endogenous control of attention and underlie the vigilance decrement (Pattyn, Neyt, Henderickx, & Soetens, 2008).

In addition, individual differences in trait boredom proneness (assessed with the Boredom Proneness Scale; Farmer & Sundberg, 1986) predict performance on the first 10 min of the Mackworth clock task (Kass, Vodanovich, Stanny, & Taylor, 2001). It has been argued that Boredom Proneness Scale scores do not predict performance in the latter part of the task because the task promotes extremely high levels of state boredom, which effectively maximizes the boredom level of all participants and counteracts individual differences in pretask boredom proneness. It seems, therefore, that vigilance tasks may be both described as boring while at the same time experienced as effortful. Taken together, researchers conducting studies of experienced workload during vigils have not been able to settle the debate between overload and underload theories of the vigilance decrement. A further complication is that it is unclear whether the behavioral constructs of stress and boredom are mutually exclusive because boredom is often described as an aversive experience (Eastwood, Frischen, Fenske, & Smilek, 2012). Consequently, researchers have endeavored to directly manipulate task demands and workload in vigilance/sustained-attention tasks in an effort to distinguish between overload and underload theories of performance decrements, and it is to this line of inquiry that we turn next.

Vigilance and task demands

The resource-depletion hypothesis predicts that tasks with higher demands will deplete resources faster and thus yield a more pronounced vigilance decrement than tasks with lower demands (Caggiano & Parasuraman, 2004). In contrast, if task monotony underpins the vigilance decrement (as the mind-wandering hypothesis would suggest), then simpler tasks should precipitate greater (or faster) attentional withdrawal relative to more demanding tasks, resulting in larger vigilance decrements over time.

Overall, the available evidence strongly suggests that more demanding tasks show the worse overall performance and the largest vigilance decrements (Helton & Russell, 2011b, 2013; Helton & Warm, 2008; Smit, Eling, & Coenen, 2004). For example, when participants perform a vigilance task under low-demand (i.e., the standard task performed singly) or high-demand (i.e., the standard task performed in concert with some secondary task) conditions, larger decrements occur in the high-demand conditions (Helton & Russell, 2011b, 2013; Smit et al., 2004). Similarly, a presumably easy vigilance task (because it included highly perceptible stimuli) led to a smaller vigilance decrement than a task that was presumably hard because it included stimuli that were difficult to perceive (Helton & Warm, 2008). Finally, reducing the demands on attention by inserting warning cues (such as a sudden-onset, briefly presented pattern) prior to stimulus onset has also been shown to result in a smaller performance decrement than a condition without such cues (Maclean et al., 2009). It therefore seems clear that increasing the attentional demands of a task increases the magnitude of the vigilance decrement—evidence taken as strong support for the depletion hypothesis.

Let us now consider whether the foregoing findings, although consistent with the resource-depletion hypothesis, are inconsistent with the mind-wandering hypothesis. First, the attentional-resource theory of mind wandering holds that both task-related thought and TUT draw on the same limited pool of executive and attentional resources (Smallwood, 2010; Smallwood & Schooler, 2006). Thus, when the attentional demands of a given task increase, the proportion of total resources available for mind wandering decreases. For instance, when high versus low perceptual load is manipulated in a visual search task, mind-wandering rates are found to be higher in the low-load condition relative to the high-load condition (Forster & Lavie, 2009). In addition, mind-wandering rates are lowest in the most difficult condition in a word reading task (Thomson, Besner, & Smilek, 2013).

As a result, some have argued that if instances of mind wandering underlie the vigilance decrement, then increasing task difficulty should reduce such instances and, consequently, alleviate the decrement. Indeed, some have made this point explicitly: "The majority of the evidence suggests an easier task should increase TUTs, and therefore, if the mindlessness model of vigilance is correct, lead to a steeper vigilance decline" (Helton & Warm, 2008, p. 20). However, when outlining their attentional-resource theory of mind wandering, Smallwood and Schooler (2006) stated that "when mind wandering occurs in *demanding* [emphasis added] tasks, it should be associated with deficits in performance because fewer resources are available to complete the primary task" (p. 947). In other words, performance costs associated with mind wandering are greater in more demanding tasks. Indeed, it has been shown empirically that mind wandering has a greater detrimental impact on reading comprehension of difficult relative to easy texts (Feng, D'Mello, & Graesser, 2013) and on difficult relative to easy encoding tasks when recognition memory is measured (Thomson, Smilek, & Besner, 2014).

In summary, the fact that increases in task difficulty lead to steeper vigilance decrements, although consistent with the resource-depletion hypothesis, is also entirely consistent with a mind-wandering hypothesis. Unfortunately then, with regard to adjudicating between depletion and mind-wandering hypotheses of vigilance decrements, we are no further ahead than when we started.

Vigilance and task engagement

Another approach that has been taken by researchers interested in distinguishing between overload and underload accounts of the vigilance decrement is the manipulation of task engagement. According to the mind-wandering hypothesis, more engaging tasks (as a result of being less monotonous and boring) serve to better "couple" attention to the primary task and will therefore result in fewer attention lapses over time (Barron, Riby, Greer, & Smallwood, 2011). According to the resource-depletion hypothesis, however, manipulations of task engagement should either have no effect on the vigilance decrement or they should increase the decrement to the extent that increases in task engagement are confounded by increases in task demands (Helton & Russell, 2011a, 2012).

In one study, task-irrelevant pictures that were negative in emotional valence were inserted into a vigilance task, and performance was compared with a neutral-picture condition. Critically, performance was worse for the negative-picture condition, even though this condition should have fostered the greatest level of energetic arousal and task engagement, thus minimizing attentional withdrawal according to the underload account (Ossowski, Malinen, & Helton, 2011). Similarly, poorer vigilance performance has been observed in a condition with task-irrelevant negative or neutral pictures relative to a no-picture condition (Helton & Russell, 2011a; also see Helton & Russell, 2012). As a result, experimental findings regarding task engagement with task-irrelevant pictures have been interpreted as evidence in favor of underload theories in general and the resource-depletion hypothesis in particular.

There is some evidence, however, that task-irrelevant auditory stimulation can alleviate the vigilance decrement to some extent (Davies, Lang, & Shackleton, 1973). In addition, manipulations of arousal and engagement in a task-relevant manner can, in some instances, improve performance. Specifically, when participants monitor for a single event in a vigilance task either under standard-single task, complex-single task, or complex-multitask conditions, they are more likely to detect the single event in the complex-single-task condition than in the standard-single-task condition (Molloy & Parasuraman, 1996). Performance is also worse for the complex-multitask condition than in the complex-single-task condition. Taken together, these observations support the idea that performance will suffer if tasks are either too boring (single-task condition) or too demanding (complex-multitask condition). Indeed, this idea is similar to the so-called "inverted-U" hypothesis describing the relationship between arousal and performance in a vigilance task (Wiener, Renwick, Curry, & Faustina, 1984; see also Yerkes & Dodson, 1908).

In a more recent study, participants performed a simulated air traffic control task in which they monitored for rare events (collisions). Participants performed the task under standard conditions (i.e., "simply monitor for potential collisions") or in an "engagement" condition in which participants had to click on incoming aircraft in addition to monitoring for critical events. Crucially, it was found that after some practice, the vigilance decrement is completely abolished in the engagement condition but not in the standard condition (Pop, Stearman, Kazi, & Durso, 2012). This result is interpreted as strong support for the idea that the vigilance decrement stems from prolonged underarousal, not from resource depletion. Indeed, the engagement condition would arguably place the highest demand on attentional resources and should therefore have displayed a greater decrement according to the depletion account.

There is evidence, therefore, that increasing task engagement can indeed alleviate the vigilance decrement, particularly when such engagement is tied to the task-relevant stimulus attributes. These findings are consistent with the mind-wandering hypothesis of the vigilance decrement, because engagement should result in greater attentional-resource allocation to the primary task and, consequently, less resource allocation to mind wandering (thus mitigating attention lapses). However, it should be noted that measures of mind wandering across conditions were not obtained in the studies noted earlier, and so it is still debatable as to whether the effects of task-relevant engagement on performance over time imparts benefits via reductions in mind wandering. Consequently, we now turn to studies in which subjective reports of mind wandering have been obtained.

Vigilance and subjective reports of mind wandering

Assessments of mind wandering in the laboratory have presented a challenge to researchers interested in linking mental state to objective task performance. To quantify mind wandering, researchers are (at present) forced to rely on various types of self-reports, which by definition necessitate introspection on the part of the participant. Consequently, perhaps the most direct way to differentiate between the mind-wandering and depletion hypotheses of vigilance performance is to gather reports of mind wandering during the task and to assess the relation to performance. Direct measures of mind wandering during standard vigilance tasks, however, may prove difficult (i.e., asking participants to report whether they are on- or off-task periodically—the *probe-caught method*; Smallwood, McSpadden, & Schooler, 2007), because these interruptions may qualitatively change the nature of the task itself (in fact it has been suggested that brief breaks or task switches can be effective in diminishing the vigilance decrement; Ariga & Lleras, 2011; but see Helton & Russell, 2012; Ross, Russell, & Helton, in press).

The few researchers that have measured mind wandering in sustained-attention tasks have employed retrospective measures, such as the "thinking content" portion of the DSSQ. For example, when participants complete the DSSQ following a vigilance task in which stimuli are highly perceptible (easy condition) or perceptually degraded (difficult condition), no difference in retrospectively reported instances of TUT are observed across the two groups. However, for both groups, higher instances of reported TUT predict worse overall detection accuracy (Helton & Warm, 2008). This finding is consistent with the observation that reports of attention failures in everyday life predict errors in a modified vigilance task (i.e., SART; Robertson et al., 1997). Thus, there is at least some evidence suggesting that detection accuracy in sustained-attention tasks is tied to attention lapses owing to instances of mind wandering (but see Head & Helton, in press, who found that TUTs from one session to the next did not predict attention lapses from one session to the next). With respect to the vigilance decrement, however, the mind-wandering hypothesis predicts that the decrease in detection accuracy over time is mirrored by a commensurate increase in the frequency of reported mind wandering.

To our knowledge, there are only two studies in which subjective reports of mind wandering over time in a standard vigilance task are actually measured (by "standard," we mean that there is a low proportion of trials requiring the observer to respond). In one such study, participants performed a vigilance task in which they monitored line segments for a rare "short" line. In addition, participants indicated whenever they became aware that their thoughts had wandered off-task (the so-called "self-caught" method; see Schooler, Reichle, & Halpern, 2004). Consistent with the mind-wandering hypothesis, self-caught reports of mind wandering increased across the duration of the task, whereas detection accuracy decreased (Cunningham, Scerbo, & Freeman, 2000). Similarly, increases in off-task reports to thought probes across blocks in a standard vigilance task were accompanied by increases in mean reaction times as well as reaction time variability for correct target detections (McVay & Kane, 2012). In addition, a negative relation between mind wandering and performance over time has been observed in other task contexts (i.e., tasks that are not nominally vigilance tasks). For example, it has been shown that declines in performance on the SART (a modified vigilance task) are mirrored by increases in reported TUT across blocks (McVay & Kane, 2009). Likewise, in a simple visual search task, accuracy decreases over time, whereas reports of mind wandering increase (Thomson, Seli, Besner, & Smilek, 2014). Finally, instances of mind wandering also increase over the course of a lecture, whereas memory for the presented material decreases (Risko et al., 2012).

Taken together, there is at least some direct evidence that mind wandering is tied to performance in sustained-attention tasks. Furthermore, in general, instances of mind wandering increase with time-on-task, whereas performance decreases over that same time period. These findings constitute a key piece of evidence in favor of the mind-wandering hypothesis, which holds that instances of mind wandering should increase as attention becomes withdrawn from the primary task (and is consequently redirected internally). In fact, if the notion that mind wandering consumes some proportion of the available attentional resources is accepted, then under a resource-depletion account, instances of mind wandering should decrease as the task proceeds, because the act of mind wandering itself is argued to require the very resources that supposedly become depleted (Smallwood, 2010; Smallwood & Schooler, 2006).

Where the Resource-Depletion and Mind-Wandering Accounts Fail

In this section, we address the explanatory limitations of both the mind-wandering and resource-depletion hypotheses of vigilance performance. In reviewing the data with respect to the vigilance decrement, we argue that there are four general findings that a successful theory of vigilance performance would have to clarify (described earlier and itemized in Table 1). First, there is mounting evidence that, despite how they may appear on the surface, vigilance tasks are quite effortful and can even be stressful (although this does not preclude such tasks from also being perceived as boring). It should be noted, however, that to date, little is known about the phenomenology of such tasks over time, because such measures are typically obtained retrospectively (but see Caggiano & Parasuraman, 2004). Second, as we have argued here, increasing task demands may increase the speed of resource depletion but may also increase the performance costs associated with mind wandering and so cannot be taken as clear evidence for either mind-wandering or depletion accounts. Third, manipulations of task-engagement, in which attention is directed toward task-relevant stimulus attributes, are beneficial in alleviating vigilance decrements, to a point. Fourth, direct measures of mind wandering in sustained-attention tasks indicate that mind wandering increases with time-on-task and predicts worsening performance.

The resource-depletion hypothesis can explain some, but not all, of the forgoing key findings. Specifically, resource depletion can explain the subjectively effortful nature of vigilance tasks. In fact, it is this finding that prompted researchers to propose the depletion hypothesis in the first place, as it is argued that perceived effort (and stress) are the phenomenological outcomes of attempting to maintain task performance in the face of dwindling processing resources. That increasing task demands are correlated with decreasing performance over time is also well accounted for under a depletion theory, as it is argued that the speed of resource depletion is a function of the resource demands of the primary task. What the resource-depletion framework has difficulty explaining is the finding that more engaging tasks (that place higher demands on information-processing resources) can, in some cases, promote better performance or smaller decrements over time. Finally, the resource-depletion account may have some trouble explaining the seemingly tight link between mind wandering and performance over time in vigilance/sustained-attention tasks. Specifically, a resource-depletion account that posits relative independence of mind-wandering-related attention lapses and performance decrements cannot readily account for data suggesting that the two co-occur over time. Furthermore, even if mind wandering was shown to be epiphenomenal to performance over time, the very fact that mind wandering increases at all is problematic for the depletion hypothesis, because, as we have stated previously, mind wandering is argued to consume the very resources that are presumably depleted.

As with the depletion hypothesis, the mind-wandering hypothesis of the vigilance decrement (i.e., a mind-wandering hypothesis that is based on attentional resources; Smallwood, 2010; Smallwood & Schooler, 2006) can explain some, but not all, of the extant data. Specifically, tasks that promote mind wandering (as vigilance tasks are argued to do) should be low in attentional-resource demands and, consequently, should be perceived as easy. As we have discussed, however, there are numerous claims that such tasks are perceived as difficult and even stressful. The mind-wandering account can, however, explain the fact that increasing task difficulty magnifies the vigilance decrement. Specifically, high demand tasks leave only a small proportion of the total attentional resources available for mind wandering, and thus, when mind wandering does occur in more demanding tasks, performance costs are exacerbated. The effects of increasing task-engagement can also be explained via a mind-wandering account. In particular, increasing perceptual coupling to the task-relevant stimuli will increase the amount of attentional resources that are devoted to the task in an exogenous manner, thus minimizing mind wandering and allowing performance to be maintained over time.

Finally, according to a mind-wandering hypothesis, increases in mind wandering over time-on-task are argued to result in the attention lapses that produce the vigilance decrement. However, the particular mechanism that results in increased mind wandering over time is unspecified. In fact, if one were to posit a reason as to why mind wandering increases over time-on-task, on the basis of the attentional-resource account of mind wandering, one might conclude that increases in reported mind wandering over time-on-task may at least partially owe to the fact that as experience with a task accrues, the resources required to adequately perform that task diminish. As a result, there is a greater proportion of available resources that can be devoted to mind wandering (Smallwood et al., 2004; Teasdale et al., 1995). Specifically, it has been stated that "practice on the SART is associated with a higher frequency of verbal reports reflecting task disengagement" (Smallwood et al., 2004, p. 675). The problem with this explanation, however, is that increases in mind wandering should therefore be mirrored by improvements in performance (because the task has become easier) or, at the very least, no change in performance (because less attention is required to maintain a given level of performance).[2] This conceptualization is at odds with the idea that in vigilance tasks, performance decreases over time. Nonetheless, the fact that a mind-wandering hypothesis of the vigilance decrement does not explicitly qualify the mechanism of increased mind wandering over time is problematic and is a shortcoming of the mind-wandering hypothesis.

It is clear then that neither a mind-wandering (on the basis of an attentional-resource view) nor a resource-depletion hypothesis of the vigilance decrement can account for the full range of findings that we have outlined here. We next describe a theoretical framework that combines aspects of both resource-depletion and mind-wandering theories to explain the full range of behavior in vigilance/sustained-attention tasks.

A Resource-Control Theory of Mind Wandering

Our resource-control theory of mind wandering is not only derived from resource-depletion theories but is also derived from two different theories of mind wandering: the attentional-resource account of mind wandering (Smallwood & Schooler, 2006) and the control-failure account of mind wandering (McVay & Kane, 2010, 2012). We believe that these two accounts of mind wandering are complimentary ideas that, when combined, hold greater explanatory power with respect to mind wandering in general and sustained-attention/vigilance performance in particular.

The central tenets of our resource-control theory are as follows:

1. The amount of attentional resources available to an individual (for both on- and off-task thought) is effectively fixed and does not change over time.
2. Mind wandering consumes attentional resources that would otherwise be available for the primary task.
3. Self-generated thought is the default state of the individual, such that there is a continuous bias for attentional resources to be absorbed by mind wandering.
4. Executive control is required to sustain active goal maintenance and to prevent task-irrelevant thoughts from consuming attentional resources needed for the primary task.
5. Executive control is reduced as time-on-task increases.
6. Many tasks require less than the full complement of attentional resources, and so mind wandering can, in some instances, occur without incurring performance costs.

Control-failure account of mind wandering

Our resource-control theory draws on aspects of both the attentional-resource account of mind wandering as well as the resource-depletion account of sustained attention. Another key component of our resource-control theory is the role of executive control. Failures of executive control have been posited as an explanation for mind wandering as a result of the fact that some recent findings are inconsistent with, or are not readily explained by, attentional-resource accounts. For example, random thought-sampling in everyday life shows that individuals with high working memory capacity (WMC) are better able to maintain task-relevant thoughts, particularly in more demanding/effortful task contexts (Kane et al., 2007). A follow-up study demonstrated that individuals with higher WMC (which is presumably an index of executive control) reported fewer instances of mind wandering during the SART (McVay & Kane, 2009). These findings have led some to conclude that mind wandering is not resource dependent per se but instead reflects failures in executive control (see also McVay & Kane, 2012). Put differently, when one attempts to perform a given task, he or she must exert control (i.e., active goal maintenance) to prevent the focus of attention from shifting toward internal thought. As a result, those individuals with a greater capacity for executive control are better able to maintain the focus of attention on the primary task. Although other researchers have debated the claim that mind wandering primarily reflects failures in executive control (e.g., Smallwood, 2010; Watkins, 2010), it is our view that attentional-resource and control-failure theories of mind wandering are neither incompatible nor mutually exclusive.

Differentiating resource-control from other theories of sustained attention

We assume that mind wandering consumes attentional/executive resources (Smallwood, 2010; Smallwood & Schooler, 2006) but that mind wandering impairs

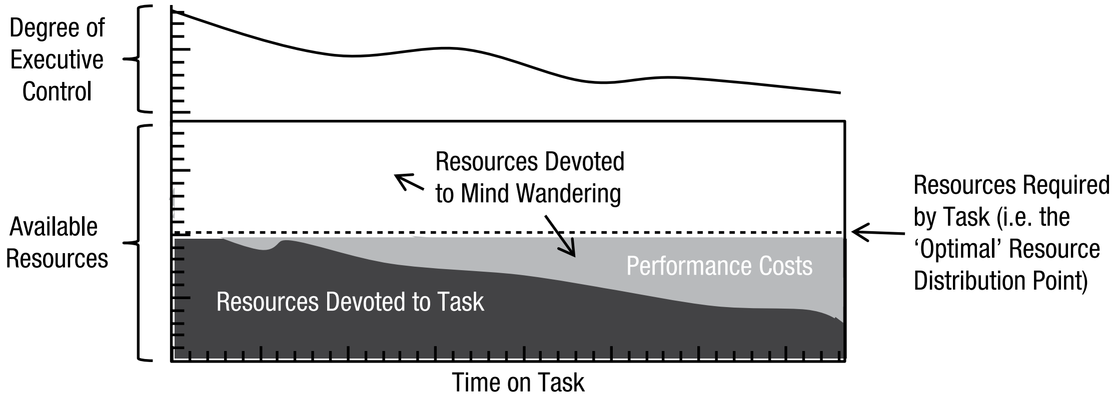

Fig. 1. Depicts the resource-control account of sustained attention in which the total amount of attentional resources available to the observer remains constant (depicted on the *y*-axis), and the amount of resources needed for the primary task remains constant (the dotted line). However, executive control wanes over time-on-task (the declining line along the top of the figure), resulting in a disproportionate amount of resources being devoted to mind wandering (the combination of the white and light gray portions) and not enough resources being devoted to the primary task (the decreasing dark gray portion), resulting in performance costs (the light gray portion beneath the dotted line). It is important to note from the figure that it is not a failure in executive control per se that causes mind wandering (because mind wandering occurs early in the task when one is exerting a high degree of control) but a failure in executive control that leads to performance costs that are due to mind wandering.

behavior because of failures of executive control (McVay & Kane, 2009, 2010, 2012). This resource-control theory of mind wandering, we argue, provides more explanatory power with regard to the extant data in the vigilance and mind-wandering literatures. Attentional-resource and control-failure accounts of mind wandering have recently been described as perhaps reflecting different aspects of mind wandering. Specifically, in outlining his *process-occurrence framework*, Smallwood (2013) argued that although the two accounts have been construed as contradictory explanations for the same phenomenon, it may well be the case that the control-failure hypothesis describes how an instance of mind wandering is initiated, whereas the attentional-resource hypothesis is a description of how an instance of mind wandering is maintained (but see Franklin, Mrazek, Broadway, & Schooler, 2013, for a critique of this idea). Before applying our resource-control theory to the extant data, we first wish to point out the ways in which our account is distinct from the process-occurrence framework suggested by Smallwood (2013).

First, according to our resource-control account, it is not strictly failures of executive control that cause mind wandering in the first place. Instead, failures of control result in a misappropriation of attentional resources, such that instances of mind wandering exceed the available "free" resources and consume resources needed for the primary task. In fact, we argue that there are situations in which one will mind wander (as in an easy task) and yet still be exerting a high degree of executive control (because we assume that individuals possess the goals of pursuing both task-related thought and TUT; see Thomson, Besner, & Smilek, 2013, for a further discussion of this idea). Second, whereas the process-occurrence framework outlined by Smallwood (2013) describes a relation between executive control and attentional resources in general, our resource-control theory was specifically devised to explain the nature of attention over time. Specifically, in our account, the relation between executive control and attentional resources interacts with time-on-task. We therefore take the view that our resource-control account dovetails with Smallwood's process-occurrence framework but that our instantiation of the relation between executive control and attentional-resource allocation is borne out of necessity when one attempts to apply a theory of mind wandering to vigilance performance.

An illustration of the relation among mind wandering, executive control, and task demands as a function of time-on-task, under our resource-control account, is shown in Figure 1. As can be seen, the amount of available resources remains fixed over time (depicted on the *y*-axis), as does the amount of resources required by the primary task (depicted by the dotted line). The solid line (at the top of the figure) depicting the degree of executive control is decreasing over time. As a result, there is a commensurate increase in resource allocation to mind wandering (the light gray and white portions combined) and a decrease in resource allocation to the task itself (depicted by the dark gray portion of the graph), resulting in increasing performance costs (depicted by the light gray portion of the graph). In Table 2, we outline the way that time-on-task theoretically affects the primary components of our resource-control model. For comparison

Table 2. How Time-on-Task Affects the Component Processes of the Mind-Wandering, Resource-Depletion, and Resource-Control Theories

	Theory		
Component	Resource-depletion	Mind-wandering	Resource-control
Total available resources	Decreases	Unchanged	Unchanged
Resources required by task	Unchanged	Not specified	Unchanged
Executive control	Not specified	Not specified	Decreases
Resources devoted to task	Decreases	Decreases	Decreases
Resources devoted to mind wandering	Decreases	Increases	Increases
Mind-wandering rate	Not specified	Increases	Increases

purposes, we also outline the way in which time-on-task is argued to affect these components with respect to the mind-wandering and resource-depletion accounts (when applicable).

Perhaps the key feature of our model is that we depict a decrease in task-related processing over time because of the reduction in executive control. One could argue, however, that a reduction in control should not necessarily result in a strict decrease in either task-related thought or TUT but rather would simply result in greater variability of resource distribution. There is reason to believe, however, that TUT is the default tendency of individuals and that without the exertion of executive control over thought processes, attentional resources will tend toward TUT. It has been shown, for example, that patterns of brain activation in the so-called "default" network tend to be very similar both when the brain is "at rest" and during instances of self-reported mind wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason et al., 2007; Smallwood et al., 2013). For this reason, we posit that when executive control wanes over time, resource distribution favors TUT. This point is made explicit by McVay and Kane (2010), who described executive control in the following way: "we propose that mind wandering reflects a failure of the executive-control system to adequately combat interfering thoughts that are generated and maintained *automatically* [emphasis added]" (p. 189). This contention fits well with the notion that in the absence of, or even in spite of, intention, the mind will tend toward TUT. We now briefly turn our attention to potential explanations of why executive control falters over time, before outlining the theoretical and empirical predictions of our resource-control account of the wandering mind, with emphasis on sustained-attention/vigilance tasks.

Why executive control fades over time

We have hypothesized that vigilance decrements stem from the reduction of executive control processes that distribute attentional resources among competing external and internal thoughts and goals. A key element of this theory, as it applies to the vigilance decrement, is the reduction of control over time. There are a number of potential reasons why such controlled processing can only be maintained at a high level for limited time periods. It has recently been argued that the information-processing resources that are required to perform a given task may also be the resources required to exert executive control. Specifically, it has been stated that "in terms of time on task, if sustaining attention depletes resources required for executive control . . . then as time on task increases, the likelihood of a failure in executive control should also increase" (Risko et al., 2012, p. 235). Put differently, executive control may dwindle precisely because information-processing resources have become depleted over time on task. We wish to make it clear that the central tenet of our resource-control theory is that information-processing resources do not become depleted but, instead, that failures of executive control result in an insufficient allocation of those resources to the primary task. Consequently, we must posit alternative explanations as to why executive control fades over time in our model.

It is possible that in the course of a sustained-attention task, individuals learn to reduce the degree of executive control being exerted. For example, vigilance tasks, by their very nature, are characterized by low signal frequency. The low frequency of "critical" trials is "learned" by the monitor as the watch period progresses. As the monitor learns that only a small proportion of trials require that he or she implement a course of action (whereas the vast majority of trials do not require the monitor to do anything), he or she may adjust the level of executive control (or attentional focus) to be more consistent with the most commonly occurring trial type. Indeed, probability-based modulations in performance have been shown to exist in standard performance tasks, such as Stroop (Logan & Zbrodoff, 1979) and even simple search (Thomson, D'Ascenzo, & Milliken, 2013), and a role for learning has been suggested for the deployment of efficient cognitive control (Verguts & Notebaert, 2009).

In other words, executive control processes may be reduced over time simply because the observer learns to engage in less effortful processing. Further, we posit that the reason vigilance tasks are rated as stressful and mentally taxing is because the monitor must attempt to override this learned behavior. Overcoming this conflict requires increasing effort as the task progresses, possibly leading to something akin to so-called "ego depletion" (see Baumeister, 2002; Baumeister, Bratslavsky, Muraven, & Tice, 1998). This idea fits with data showing that subjective mental workload increases during a vigilance task as task performance decreases (Caggiano & Parasuraman, 2004).

Recently, a theoretical model has been proposed that is intended to explain the relation between subjective effort and performance outcomes (Kurzban, Duckworth, Kable, & Myers, 2013). A central tenet of this model is that the use of an executive control system over time comes with a "cost" that is experienced as effort. Consequently, the extent to which one maintains executive control is determined by a function describing this mental cost, weighed against the potential gains to the agent. In the context of vigilance-like tasks, executive control processes may decline over time because of the fact that the "gains" associated with maintaining controlled processing over time may be subjectively minimal (because this effort yields no benefits on the vast majority of trials). In fact, it may make perfect sense to describe waning executive control over time in such tasks as "adaptive" (see Hancock, 2013, for a similar argument) and to view mind wandering as the behavioral outcome of this adaptive process. Put differently, it is simply the case that motivation wanes over time in response to the monotonous and unrewarding nature of vigilance tasks. As a result, the mind tends to wander with increasing frequency. It is even possible that early in the task mind wandering occurs despite the intention to focus on the task (i.e., it is spontaneous in nature) but that later in the task, when motivation falters, mind wandering occurs because of a lack of intention to focus on the task (i.e., it is intentional or deliberate in nature). Indeed, these two qualitative forms of mind wandering can be dissociated in the laboratory (Carriere, Seli, & Smilek, 2013) and may inform future work on the changing phenomenology of mind wandering over time-on-task.

Revisited: The four key lines of evidence

We have argued that there are four key lines of evidence that neither a mind-wandering variant of the underload hypothesis (on the basis of attentional resources) nor a resource-depletion variant of the overload hypothesis can fully explain. We now outline how our resource-control theory of vigilance (and indeed of sustained attention in general) can account for these key findings.

1. *Vigilance tasks are subjectively effortful*: Given that observers actively attempt to pursue the nominal task goals (i.e., they attempt to maintain a high level of performance), decreases in executive control will result in the feeling that greater effort (or work) is required to maintain the correct allocation of attentional resources to the task and to prevent resources from being absorbed by mind wandering.
2. *Vigilance decrements are larger in more difficult tasks*: Manipulations of task difficulty increase the demands on resource-distribution processes because a greater proportion of the available attentional resources must be devoted to the task. As a result, reductions in executive control will have a larger impact on performance over time.
3. *Task engagement can alleviate the vigilance decrement*: Manipulations of task engagement alleviate the demands on endogenous executive control, allowing efficient resource distribution to be maintained over longer periods of time.
4. *Mind wandering increases with time-on-task and is negatively related to performance*: Because there is an inherent bias toward self-generated TUT, reductions in executive control result in a greater proportion of attentional resources being devoted to mind wandering over time at the expense of the primary task, creating a tight link between mind wandering and performance over time.

Although our resource-control theory was primarily intended to address recent empirical developments concerning the mechanistic underpinnings of sustained-attention/vigilance performance over time, such a theory can also account for historical data. For example, it has long been known that performance feedback is effective in mitigating, to some extent, the vigilance decrement (J. F. Mackworth, 1964; Sipowicz, Ware, & Baker, 1962). It is unclear how a mind-wandering account could, on its own, explain this. For example, being aware that you just made an error would perhaps refocus attention to the task at hand, but only for a brief period of time, which is unlikely to affect the probability of mind wandering many trials later. In addition, it is hard to imagine how feedback could affect the rate of resource depletion. In fact, if anything, the added processing of the feedback information momentarily increases the task demands (even if only briefly), which should increase the speed of resource depletion and magnify the performance decrement. According to the resource-control theory proposed here, however, it is executive control processes that wane over time and result in inefficient distribution of attentional resources leading to off-task thoughts, which, in turn, hinder performance. As a result, performance feedback can lead to more efficient resource distribution (because one knows whether enough resources are being devoted to the task at hand), which would reduce the amount of effort required to "titrate" resource distribution between on- and off-task thought (Thomson, Besner, & Smilek, 2013). We therefore contend that our resource-control theory can account not only for current findings in the sustained-attention, vigilance, and mind-wandering literatures but can also accommodate classic empirical findings. What is needed, however, are direct tests of the resource-control theory. This should be a primary focus of future work.

Future Directions

The resource-control theory of mind-wandering-related attention lapses in sustained-attention/vigilance settings accounts for increases in stress, perceived workload, and mind wandering as a function of time-on-task. It also describes a process whereby executive control and, consequently, task performance decrease as a function of time-on-task. It has been shown that subjective workload and stress do seem to increase as a function of time-on-task (Caggiano & Parasuraman, 2004; see also Scerbo, 2001) and that mind wandering also increases over time (Cunningham et al., 2000; McVay & Kane, 2012; Thomson, Seli, et al., 2014). The resource-control theory offered here also makes the clear prediction, however, that whenever experimental manipulations can be shown to increase the magnitude of the vigilance decrement (either through manipulations of task demands or some other means) that there should be a consequent increase in mind wandering over that same time span. To our knowledge, this relation has not yet been directly tested. More generally, there remains very little direct examination of mind wandering over time in the context of vigilance tasks, despite the large number of studies devoted to explaining the decrement. This line of investigation would seem to be a necessary future endeavor.

In addition, it has long been known that there exist large individual differences in vigilance performance over time (see Hancock, 2013, for a review) and also that there are large individual differences in measures of executive control (Kane & Engle, 2002). It has been found, for example, that executive control ability, indexed by WMC, predicts individual differences in both overall performance and mind-wandering propensity in a modified vigilance task (i.e., only the rare critical trials require no action). It is noteworthy, however, that WMC does not predict performance or mind-wandering rates in a standard vigilance task (i.e., only the rare critical trials require some action; McVay & Kane, 2012). Crucially, the relations among executive control, performance, and mind wandering have not been examined at the individual difference level as a function of time-on-task. If individual differences in the propensity to engage in mind wandering are symptomatic of executive control abilities, then trait-level mind wandering may predict individual differences in the magnitude of the vigilance decrement. Finally, as a general empirical strategy, manipulations that alleviate the endogenous demands on executive control (according to our resource-control theory) should alleviate vigilance decrements. In fact, we contend that many prior manipulations that have alleviated the vigilance decrement have done so via their effects on executive control (i.e., bottom-up ["endogenous"] support—Maclean et al., 2009; performance feedback—J. F. Mackworth, 1964; Sipowicz et al., 1962).

Conclusions

In conclusion, we have proposed a novel account of how and why performance wanes over time in vigilance/sustained-attention tasks. We arrived at this resource-control model of sustained attention by examining the extant data in the vigilance and mind-wandering literatures. To make sense of seemingly conflicting findings with respect to whether vigilance decrements derive from mind wandering or resource depletion, we have combined aspects of attentional-resource (e.g., Smallwood, 2010; Smallwood & Schooler, 2006) and control-failure (e.g., McVay & Kane, 2010) theories of mind wandering. In doing so, we provide a parsimonious account of the vigilance decrement in particular and of attention lapses in general. We have developed a theory that can help to explain mundane attention lapses in everyday life, such as missing your exit after a long and uneventful drive on the highway, but also more serious attention lapses, as when a train engineer fails to notice a rare, but important, red signal. In our future work, we have the goal to empirically test the predictions and suppositions of our resource-control theory so that we may determine the limits of its explanatory power.

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Notes

1. The NASA–TLX requires individuals to make ratings on a 100-point scale on numerous factors, including the following: overall workload, task difficulty, time pressure, performance, mental effort, physical effort, frustration level, stress level, fatigue, and activity type (i.e., skill-based, knowledge-based). Ratings are made after completion of the task, and a global workload score is obtained. The DSSQ consists of several subscales (e.g., Arousal, Concentration, Task-Related and Unrelated Cognitive Interference, Pleasant/Unpleasant Mood). Within each scale, the observer rates the relevance of a number of statements with respect to his or her experience in the just-completed task. Overall scores for "worry," "engagement," and "distress" are then obtained.
2. It could be that as the task becomes easier, participants overestimate how much mind wandering they can do, and so mind wandering increases, but performance decreases. This however, would not explain why the tasks are rated as difficult and stressful and so is unlikely in our opinion.

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