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COMMENTARY

A Critical Examination of the Research and Theoretical Underpinnings Discussed in Thomson, Besner, and Smilek (2016)

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Thomson, Besner, and Smilek (2016) propose that performance decrements associated with sustained attention are not consistently the result of a decline in perceptual sensitivity. Thomson et al. (2016) present empirical evidence using a novel, nontraditional vigilance task to support their assumptions. However, in the present rebuttal, we argue that the authors have not only have misinterpreted previous research in sustained attention, but also have misapplied those interpretations to their study. Thomson et al. have also neglected key elements of the literature in their argument, including research on expectancy theory and individual differences on vigilance performance. Furthermore, Thomson and colleagues implement an experimental paradigm that is not appropriate for evaluating sensitivity and bias changes in vigilance tasks. Finally, their analyses do not capture the manner in which changes in response bias and sensitivity can manifest in signal detection theory. We discuss the theoretical and experimental issues contained in Thomson et al. (2016) and propose suggestions for future vigilance research in this area.

Keywords: sustained attention, vigilance, Signal Detection Theory

Thomson, Besner, and Smilek (2016) challenge the assertion that a decrease in sensitivity is one of the more compelling outcomes associated with the vigilance decrement. The researchers argue that traditional signal detection measures of sensitivity are not free of bias, because most vigilance tasks elicit an extremely low number of false alarms. Thomson et al. (2016) suggest the vigilance decrement may have several causes other than a loss of sensitivity, and they present empirical evidence supporting this assumption. Thomson and colleagues also suggest resource-depletion theories of vigilance (i.e., a decline in sensitivity occurs because of a depletion of cognitive resources at a rate faster than they can be replenished; Parasuraman, Warm, & Dember, 1987) do not adequately explain the decline in performance.

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We contend that Thomson and colleagues did not consider several important aspects of existing theory and research on sustained attention, which ignores several crucial findings based on over 70 years of vigilance research and conflates their findings. Thomson et al. (2016) discuss changes in observers' "task engagement," but their interpretation and operationalization of task engagement differs from traditional definitions adopted by most vigilance researchers (Szalma & Matthews, 2015). Their argument omits important aspects of the vigilance literature, including previous work on expectancy theory, mental workload, and individual differences. Furthermore, their argument regarding the limitations of signal detection theory to vigilance is not consistent with established theory and research. In the present article, we discuss the theoretical, methodological, and procedural problems associated with the arguments described in Thomson et al. (2016). We present the following as a comment on Thomson et al. (2016) and offer several suggestions to improve theory and research on sustained attention, as well as to clarify the theoretical and empirical questions to be addressed in future work in this area.

A Reintroduction to the Problem of Vigilance

Vigilance, or the ability to sustain attention for a prolonged period of time (Davies & Parasuraman, 1982; Jerison, 1970; Parasuraman, 1986; Warm, 1977; Warm & Jerison, 1984), is a phenomenon that has been of interest to both basic and applied researchers for nearly 70 years (Mackworth, 1948). Inattention to a display, or to any source of information in the environment, can result in the detection of fewer critical events. The most pervasive finding in empirical vigilance research is the vigilance decrement function: a decline in detection performance as a function of time on task (Davies & Parasuraman, 1982; Jerison, 1970; Mackworth, 1948; See, Howe, Warm, & Dember, 1995; Warm, 1977). In the decades since Mackworth's seminal work, researchers have proposed multiple theories to explain both vigilance and the performance decrement associated with it (Loeb & Alluisi, 1984; Warm, Finomore, Vidulich, & Funke, 2015).

The Vigilance Taxonomy

Parasuraman and Davies (1977) described a vigilance taxonomy that was reflective of the information processing requirements associated with specific types of vigilance tasks (see also Davies & Parasuraman, 1982; Parasuraman, 1979). This taxonomy identifies four dimensions that have been shown to influence performance in vigilance tasks. These four dimensions include the following: task type (successive or simultaneous); event rate (low or high); sensory modality (auditory or visual); and source complexity (single or multiple). A fifth dimension was proposed by See et al. (1995), which distinguished between cognitive and sensory tasks.

See et al. (1995) emphasize the specific importance of task type and event rate in the taxonomy. Simultaneous tasks require comparative judgments of stimuli by participants, whereas successive tasks require participants to maintain a standard in working memory when making judgments. This working memory component of successive tasks increases task difficulty for participants. Likewise, tasks utilizing high event rates, which also impose higher levels of demand on participants' working memory, are more difficult than tasks utilizing low event rates. Helton and Russell (2011, 2013) have provided additional evidence for the importance of working memory in vigilance. Their results indicate the vigilance decrement results from diminished cognitive resources brought on by the greater demands on observers' working memory. In addition, Helton and Russell (2013) provide further support to Caggiano and Parasuraman's (2004) finding that different types of tasks can drain resources from working memory at different rates during vigilance tasks. This evidence demonstrates a connection between working memory demands and vigilance performance, which helps to support a resource depletion explanation of the vigilance decrement.

Traditional Measurements of the Vigilance Decrement

The decline in sensitivity associated with the vigilance decrement has been examined as a function of the type of information processing (e.g., successive vs. simultaneous displays, cognitive vs. sensory tasks, etc.) and event rate (i.e., rare, moderate, high). Sensitivity is typically measured using either the parametric index d' or the nonparametric index A'. The metric d' is defined as parametric, meaning it is based on assumptions of normality and equal variances of the signal and nonsignal distributions (Green & Swets, 1966; See et al., 1995). It represents the distance between the means of the signal and nonsignal distributions. The metric A', on the other hand, is nonparametric, meaning it does not require these assumptions. It is an area-based measure of sensitivity where lower values indicate a larger area under the receiver operating characteristic (ROC) curve plotting hits against false alarms. It is important that a large number of studies have shown that the vigilance decrement is observed for both measures of sensitivity (See et al., 1995).

The sensitivity decrement can be impacted by signal salience, or the relative strength of the target stimuli compared with their environment or to nontarget events. Evidence for the effect of signal salience on vigilance performance can be found as far back as the 1950s, when Baker (1959) referred to signal intensity as a key component affecting observers' expectancies during vigilance tasks. More recently, Warm and Jerison (1984) discuss the inverse relationship that exists between performance on vigilance tasks and signal salience. See et al. (1995) use the concept of signal salience as a primary explanation of the vigilance decrement, pointing to a large literature that shows a decline in perceptual sensitivity as the reason for performance decrements. Furthermore, later studies have shown increases in self-reported stress levels in low-signal salience vigilance tasks (Helton & Warm, 2008; Helton, Warm, Matthews, Corcoran, & Dember, 2002).

Resource Theory

One of the most widely cited theories currently used to explain the vigilance decrement is resource theory (Hancock & Warm, 1989; Hockey, 1997; Parasuraman et al., 1987). Traditionally, mental resources have been theorized as pools of energy (or cognitive capacity; Moray, 1967) that can be drained and/or replenished as a function of task demands (Hirst & Kalmar, 1987). Resources have been conceptualized as either a general underlying attentional process (Kahneman, 1973), or as specific capacities deployed during certain tasks (i.e., multiple resource theory; Wickens, 1984, 2002). Both versions of resource theory suggest that individuals are limited in their information processing capacity and that these constraints limit the efficiency of performance (Davies & Parasuraman, 1982; Kahneman, 1973; Wickens, 2002). According to this account, resources can be depleted because of either the information processing demands of the task or, as the supply of resources diminishes, attention can no longer be efficiently directed toward the task (Caggiano & Parasuraman, 2004; Dillard et al., 2014; Parasuraman et al., 1987; Warm, Dember, & Hancock, 1996; Warm, Matthews, & Finomore, 2008).

Physiological evidence suggests that mental resources could be related to physical resources necessary for the effective metabolic functioning of the brain, as measured by indices such as brain oxygenation and cerebral blood flow velocity (Helton et al., 2010; Matthews, Warm, Reinerman-Jones, Langheim, Washburn, & Tripp, 2010b; Reinerman-Jones, Matthews, Langheim, & Warm, 2011). Numerous empirical studies have shown that declines in sensitivity (as indicated by poorer vigilance performance) are associated with similar deteriorations in indices of psychophysiological functioning (Warm, Matthews, & Parasuraman, 2009). Metabolic resource depletion therefore serves as a prospective mechanism driving the vigilance performance decrement. Empirical results show an initial increase in cerebral blood flow velocity (Parasuraman & Caggiano, 2005) and blood oxygen saturation levels in cortical tissue (Punwani, Ordidge, Cooper, Amess, & Clemence, 1998; Toronov et al., 2001) resulting from the cognitive demand of engaging with the vigilance task. This increase in metabolic resource uptake is subsequently followed by a characteristic decline. Cerebral blood flow velocity declines as a function of time on task in both the frontal and parietal lobes (Paus et al., 1997).

The deceleration of cerebral blood flow velocity (which signifies metabolic resource depletion) is sensitive to the magnitude of information-processing demands imposed by the task at hand. For example, successive vigilance tasks are judged to be more demanding than their simultaneous counterparts given that they entail a greater demand on limited working memory resources. While both successive and simultaneous vigilance tasks result in significant decreases in cerebral blood flow velocity over time, the decline is greater in successive versus simultaneous tasks (Mayleben et al., 1998; Schnittger, Johannes, Arnavaz, & Munte, 1997). Empirical results concerning blood oxygen saturation levels as measured by transcranial cerebral oximetry exhibit the same tendency: Blood oxygenation levels decline as a function of time on task (Helton et al., 2007). Such a decline in metabolic resources (as seen in several different physiological measures) is associated with the vigilance performance decrement.

In addition to depleting physiological resources, vigilance tasks are also associated with high levels of perceived workload and stress (Smit, Eling, & Coenen, 2004; Warm, Parasuraman, & Matthews, 2008). With regard to mental workload, Thomson and colleagues summarize the findings of Smit and colleagues by stating "central to this theoretical account, is the notion that observers are willfully engaged in effortful processing throughout the course of a vigil" (p. 79). In their study, Smit and colleagues (2004) examined the vigilance decrement in high- and low-task demand vigilance tasks, however Smit et al. (2004) never stated that the vigilance decrement is associated with a *willingness to engage* in the task (more on this momentarily). Rather, Smit, et al. (2004) argue that *task demand*, not *engagement*, arises as a function of the monotony (i.e., repetitive stimuli with rare signal appearance) associated with vigilance. Indeed, Smit et al. (2004) go so far as to state "we suggest that both the overall level of performance and the decrement in performance can be explained by the resource view on performance, at least as far as highly demanding tasks are concerned in which the decrement is caused by a drop in sensitivity" (p. 41). We believe Thomson et al. (2016) have equated a decline in task engagement as measured by the Dundee Stress State Questionnaire (DSSQ; Grier et al., 2003; Matthews et al., 2002) with a decline in willful, *behavioral* disengagement in attention. In a later section, we discuss why equating these two concepts may be problematic.

The Thomson et al. (2016) Interpretation of Vigilance and Sensitivity

Thomson and colleagues argue that the vigilance decrement may result from a number of causes other than a decline in sensitivity. For example, the authors state, "from the results of our empirical demonstration, we submit that the observed decreases in sensitivity metrics observed in many standard vigilance tasks may actually reflect shifts in response bias" (p. 79). The authors propose that the sensitivity decrement is an artifact because of a "floor effect" associated with false alarm rates. Citing studies in which signal detection measures were not computed, including Helton and Russell (2011, 2012), Thomson and colleagues detail how extremely low false alarm rates introduce statistical bias in sensitivity estimates. Their article cites the meta-analysis conducted by See et al. (1995) that examined 42 studies spanning 12 years, which found a substantial (i.e., large effect sizes) and consistent sensitivity decrement across studies. The results of that meta-analysis robustly demonstrate that sensitivity does in fact decline as a function of the task in some contexts.

In addition, the meta-analysis by See et al. (1995) presents a series of variables that may moderate the relationship between sensitivity declines and the vigilance decrement. Several such variables, including signal amplitude (or salience), would primarily affect participants' ability to distinguish signals from nonsignals, but theoretically would not affect other measures of performance, including response bias. In their resulting regression analysis, signal salience did not emerge as a significant predictor of declines in sensitivity, but the authors "recommend that researchers study them further before attempting to incorporate them into the taxonomy." Indeed, these same authors provide such support for the effect of signal salience on sensitivity. See, Warm, Dember, and Howe (1997) provide evidence in their Figure 1b of ROC plots for z-scores of proportions of hits and false alarms. This evidence is critical to supporting the effect of sensitivity on the vigilance decrement, because the ROC plots align with predictions based in signal detection theory for a variable considered to be independent of participants' response criterion.

With respect to the putative floor effect, it is not necessarily low false-alarm rates that cause problems for the application of signal detection theory. Thomson et al. (2016) argue this point, stating "false

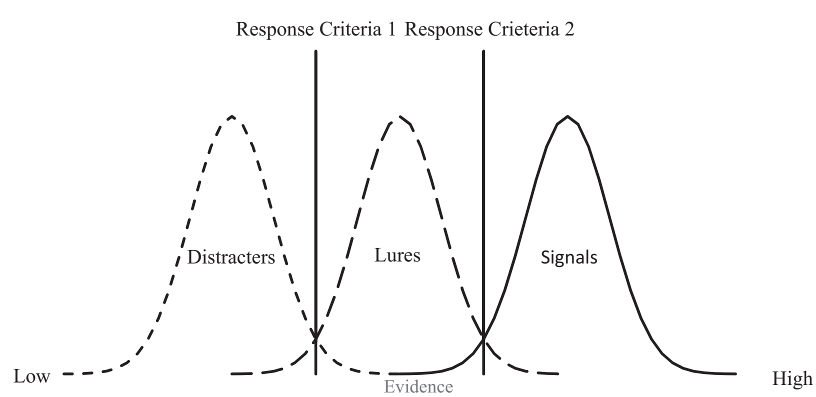

Figure 1. Representation of the three separate distributions theorized by Thomson et al. (2016).

alarm rates must be high enough that declines in hit rate could, theoretically, be accompanied by a *commensurate* decrease in false alarms" (p. 74). However, sensitivity can decline with either a *decrease or increase* in false alarms. Biased estimates indeed are more likely to occur when the frequency of zero false alarms is high, but this is a problem for the Signal Detection Theory (SDT) model itself. That is, a large number of zero false alarms rates may distort parametric measures of response bias as well as sensitivity. Therefore, one cannot unequivocally reject a sensitivity effect because of low false alarm rates, as both measures are derived from the same underlying statistical model.

The Expectancy Theory Interpretation of Sensitivity and Bias

Thomson and his colleagues argue that the vigilance decrement may be caused by other factors, including response bias, rather than a decline in sensitivity. An issue with the Thomson et al. (2016) case for response bias as a potential driver of the vigilance decrement, however, is the authors have largely ignored expectancy theory (Deese, 1955; Frankmann & Adams, 1962), an early vigilance theory which posits that expectancies regarding signal frequencies are determined by previous experiences associated with the task (Deese, 1955). Simply put, individuals develop expectations regarding the likelihood signal appearance based on their experience with the task up to the point of reflection. Baker (1959) expanded upon this notion by outlining factors that may influence expectancies including: signal magnitude, knowledge of results, and, perhaps most importantly, signal rate.

Thomson et al. (2016) did not discuss expectancy theory, and they seem to have misinterpreted Craig's (1978) work on probability matching. Unsatisfied with the lack of predictive validity in measures of response bias, Craig (1978) utilized expectancy theory to demonstrate how individuals adapt to tasks in real time. Crucially, Craig (1978) argued that these changes in response criteria arise because of familiarization with the task and probability matching. Probability matching is the idea that observers actively seek to match their response frequency to their subjective estimate of signal likelihood (Craig, 1987; Vickers, 1979). Craig (1978) described this phenomenon of probability matching as an unfortunate byproduct of poor training, which cannot be characterized as typical in vigilance tasks.

Issues With the Thomson et al. (2016) Operationalization of "Willful Engagement"

Individual difference variables have been shown to have critical effects on vigilance performance. Many studies have examined personality differences that may correlate with vigilance performance, such as boredom proneness (Sawin & Scerbo, 1995; Scerbo, 1998; Thackray, Bailey, & Touchstone, 1977), and traits related to the "Big Five" (e.g., extraversion, neuroticism, conscientiousness, agreeableness, and openness-to-experience; Costa & McCrae, 1992; Laurie-Rose, Murphy, Byard, & Nikzad, 2002; Matthews, 2001; Matthews, Deary, & Whiteman, 2003; Shaw et al., 2010).

Thomson et al. (2016) discuss one individual difference variable: engagement. Engagement can have multiple definitions, especially in regards to the vigilance literature. Engagement can refer to a physical engagement with the task (e.g., pressing a button to submit a response) or a psychological or motivational state of engagement to perform the task (like the experience of flow; Csikszentmihayli, 1990; or the allocation of effort; Hockey, 1997). The *willfulness* of the individual is extremely difficult to measure and the lack of operationalization of the concept in Thomson et al. (2016) leaves much open to interpretation. The article failed to include a review of the substantial literature specific to task engagement.

Task engagement can be conceptualized as a readiness for intensive attention and task-directed effortful control of attention (Matthews, Warm, Reinerman, Langheim, & Saxby, 2010a). The DSSQ defines task engagement as a secondary factor comprised of four primary scales: energy, success motivation, intrinsic motivation, and concentration (Matthews et al., 2002). The DSSQ contrasts task engagement as a cognitive and motivational factor that relates to how observers' interest in the task varies with fatigue and apathy, and Matthews et al. (2002) noted that task engagement reflects a core relational appraisal theme of commitment of effort. Task engagement has been linked to resource depletion models of vigilance and has been shown to be related to perceptual sensitivity in vigilance tasks (Matthews et al., 2010b). The literature on engagement and vigilance generally indicates that pretask and posttask measures of engagement significantly predict performance (Helton, Matthews, & Warm, 2009; Szalma & Matthews, 2015), but the measurement of "willingness to engage" with the task have not been measured in vigilance per se.

We agree with Thomson et al. (2016) that the assumption that all participants are "willfully engaged" (Thomson et al., 2016, p. 79) is untenable. It is most likely the case that individuals vary in their subjective levels of engagement as measured by instruments such as the DSSQ, and that these levels of engagement depend on task demands and the social and physical context in which they are performed (Helton et al., 2009). It is also unlikely that adding a degree of behavioral engagement to vigilance tasks will alleviate the decrement. For instance, studies examining sustained attention have shown that continuous "engagement" in a task does not improve vigilance performance, nor does it alleviate the stress and decline in task engagement as measured by the DSSQ (e.g., Grier et al., 2003). However, in many vigilance studies, performance levels are high during the first period on watch (e.g., 80%–90% detections with less than 10% false alarms), so some degree of "willful" behavioral engagement must exist at the beginning of the watch.

Challenges to the Thomson et al. (2016) Vigilance Task

One important aspect of any vigilance task is time on watch. Generally, vigilance tasks tend to take 30 min to several hours to complete (Davies & Parasuraman, 1982). In the protocol used by Thomson et al. (2016), participants were asked to monitor a sequential presentation of single words consisting of several animals, and they were expected to respond only to words representing four-legged animals. There have been demonstrations that the decrement can be observed in shorter tasks if the demands are sufficiently high. Nuechterlein, Parasuraman, and Jiang (1983) found a decline in perceptual sensitivity within the first 5 min of a 10-min vigil. Furthermore, Temple and colleagues (2000) reported a vigilance performance decrement, high workload, and high subjective stress after a 12-min vigil.

Most research indicating sensitivity or bias effects have employed sensory tasks. The available literature base is not as extensive for cognitive tasks, and there is evidence that such tasks affect performance in ways quite distinct from sensory tasks (See et al., 1995). In addition, given the working memory component associated with cognitive tasks (Caggiano & Parasuraman, 2004), utilizing such high event rates in vigilance raise serious questions regarding the equivalency of the tasks to those that require sensory discriminations. Hence, it is not clear that the pattern of results observed are because of the limitations of sensitivity measures and not the unique characteristics of the task employed by Thomson et al. (2016).

Issues With Online Experimentation

Thomson et al. (2016) utilized a 12-min task to support their case that a sensitivity decline should be examined more carefully. This task was completed remotely online and in a place of the participant's choosing. Participants could complete the experiment anywhere, anytime, and with anyone. A review of the literature shows only one published experiment measuring performance on a vigilance task that was completed online (Ralph, Thomson, Seli, Carriere, & Smilek, 2015). In Ralph et al. (2015), as well as the present Thomson et al. (2016) task, there is no description of evidence regarding the psychophysical equivalency of their task with replication in a traditional vigilance setting. The lack of control and integration of individual difference measures in Thomson et al. (2016) makes it difficult to formulate conclusions about the observed decrement.

Previous research has demonstrated that tasks involving high levels of cognitive mental workload may not be suitable for online experimentation (Noyes, Garland, & Robbins, 2004). Therefore, it may be inappropriate to administer a vigil online, as they are typically characterized as cognitive demanding because of the high levels of global mental workload normally found by the NASA Task Load Index (NASA-TLX; Warm, Dember, & Hancock, 1996). Furthermore, research has found online participants to be less accurate in their responses as a function of the task being administered online (Dandurand, Shultz, & Onishi, 2008), an important consideration when using signal detection analyses. Until issues such as these can be resolved, we believe that caution is warranted in using such studies as a basis for a new theoretical mechanism of sustained attention, as the validity of an online vigilance paradigm has yet to be established and replicated.

Analytical Flaws Within Thomson et al. (2016)

The experimental paradigm implemented by Thomson and his colleagues was intended to provide an illustration of the issues they raised regarding low false alarm rates. Their study utilized a task in which participants must distinguish words representing four-legged animals from other common nouns. To test whether sensitivity would decrease when false alarms are above 0%, they introduced a set of "lure" stimuli to more-closely resemble critical signals. The lure stimuli consisted of 50 nouns representing non-four-legged animals. The authors appeared to have succeeded in making their lure condition more difficult than their standard condition, as shown by their analyses for hits, false alarms, sensitivity, and response bias. The authors reported that when observers' false alarms for lures only were analyzed, response bias became more conservative, but there was not a decline in sensitivity. However, there are problems with several of the authors' analytical techniques.

By examining lure false alarm only, the authors have created three, rather than two, stimulus categories, which transforms the underlying decision space implied by signal detection theory. A representation of this decision space is shown in Figure 1. Their experimental paradigm creates three response distributions: one for distracter items, one for lure items, and one for signals. This creates two possible response criteria: one to distinguish between the distracter and lure distributions (labeled "Response Criterion 1" in Figure 1) and another to distinguish between the lure and signal distributions (labeled "Response Criterion 2" in Figure 1). Moreover, there are three possible measures of sensitivity: one for the distracter and lure distributions; one for the lure and signal distributions; and one for the distracter and the signal distributions, as described in Macmillan and Creelman (2005).

The additional analyses for "corrected" sensitivity and response bias also did not conform to the decision space underlying their experimental design. Thomson et al. (2016) essentially utilized a design with three underlying response distributions (distracter nouns, lure nouns, and target nouns), yet chose to examine the differences between the lure and target nouns. Although the authors seek to compare an equivalent number of targets and related false alarms, their design still exposes observers to a relatively large number of neutral trials. According to resource depletion models, this large number of neutral trials would deplete observer resources required to discriminate signals from lures. The authors' overall analyses showed typical vigilance effects for sensitivity and response bias. However, their subsequent examination of lure false alarms only, while informative of the types of errors participants made, do not unequivocally support the argument that the vigilance decrement is driven by factors other than changes in sensitivity.

Conclusions

Thomson and colleagues sought to examine the traditional view that the vigilance decrement is brought on primarily by a loss of perceptual sensitivity. Although they cite research in which sensitivity measurement was problematic, they do not discuss a larger body of research showing a relationship between vigilance performance and sensitivity. While their critique of the susceptibility of sensitivity measures to low false alarm rates does correctly indicate a limitation of signal detection theory, it is an issue that can compromise the reliability of other metrics, such as response bias, as well.

There were also problems with their methodology, analyses, and interpretation of their results of their illustrative empirical study. Collecting vigilance data online does not align with previous work in the field. Although it may be perfectly reasonable to do so, the validity of such a paradigm should be evaluated prior to using it to illustrate problems with interpreting the decrement function in terms of sensitivity. We also take issue the novel analytical techniques they employ, which involve splitting their nonsignal distribution for further analysis. Although this is an interesting experimental paradigm for investigating sustained attention, the stimulus structure they employed comprises three stimulus categories rather than two, which changes the corresponding decision space for computing sensitivity and bias.

Thomson and colleagues are not necessarily wrong in their assertion that criterion shifts and other factors occur in vigilance and that these may contribute to the decrement in performance. However, the empirically well-established rise in conservatism: (a) is accompanied by a commensurate decline in sensitivity; and (b) may be due to expectancy mechanism, task disengagement, or both. Given the issues we have raised, we believe it may be premature to reject the validity of changes in sensitivity as a description of the performance decrement observed in studies of sustained attention.

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