# Vigilance Requires Hard Mental Work and Is Stressful

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**Objective:** We describe major discoveries and developments in vigilance research. **Background:** Vigilance tasks have typically been viewed as undemanding assignments requiring little mental effort. The vigilance decrement function has also been considered to result from a decline in arousal brought about by understimulation. **Methods:** Recent research in vigilance is reviewed in four areas: studies of task type, perceived mental workload during vigilance, neural measures of resource demand in vigilance, and studies of task-induced stress. **Results:** Experiments comparing successive and simultaneous vigilance tasks support an attentional resource theory of vigilance. Subjective reports also show that the workload of vigilance is high and sensitive to factors that increase processing demands. Neuroimaging studies using transcranial Doppler sonography provide strong, independent evidence for resource changes linked to performance decrement in vigilance tasks. Finally, physiological and subjective reports confirm that vigilance tasks reduce task engagement and increase distress and that these changes rise with increased task difficulty. **Conclusions:** Converging evidence using behavioral, neural, and subjective measures shows that vigilance requires hard mental work and is stressful. **Application:** This research applies to most human-machine systems that require human monitoring, particularly those involving automated subsystems.

## INTRODUCTION

> Eternal vigilance is the price of liberty. *(Wendell Phillips, speech to the Massachusetts Anti-Slavery Society, Boston, 1852)*

This oft-quoted but occasionally misattributed (to Thomas Jefferson) phrase memorably conveys the message that freedom does not come without cost – it requires constant vigilance. What could be a clearer expression of the view that vigilance (and liberty) does not come easily but requires work? Yet until recently, psychologists and human factors researchers typically viewed vigilance tasks – whether performed to safeguard freedom or to prevent accidents – as benign assignments that do not require much of observers: in short, that such tasks are mentally undemanding. Recent discoveries in vigilance research have proven that assertion to be false. In this article, we discuss these developments, providing evidence based on behavioral, neural, and subjective measures that vigilance requires hard mental work and is stressful.

### Background

Vigilance refers to the ability of organisms to maintain their focus of attention and to remain alert to stimuli over prolonged periods of time (Davies & Parasuraman, 1982; Parasuraman, 1986; Warm, 1984a, 1993). The famous neurologist Henry Head first described studies of vigilance in brain-injured patients in the 1920s (Head, 1923, 1926). Subsequently, the neurologist–turned human factors psychologist Norman Mackworth (1948, 1950/1961) began the systematic study of vigilance during World War II. His experiments sought to determine why airborne radar and sonar operators on antisubmarine patrol missed weak

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signals on their displays signifying the presence of enemy submarines in the sea below, particularly toward the end of a watch. To study the problem, Mackworth developed a simulated radar display called the "Clock Test" in which a black pointer made small jumps around the circumference of a blank-faced clock devoid of any scale markings to serve as reference points. Occasional larger jumps were the critical signals for detection in experiments lasting continuously for 2 h. Using this display, Mackworth confirmed field-generated suspicions that vigilance wanes quickly. He found that the accuracy of signal detections declined by about 10% to 15% after only about 30 min and then showed a more gradual decline over the remainder of the watch period.

Mackworth's experiments spawned a considerable body of empirical work by both basic experimental psychologists and human factors researchers (see Arrabito, Abel, & Lam, 2007; Ballard, 1996; Davies & Parasuraman, 1982; Jerison & Pickett, 1963; Jerison, Pickett, & Stenson, 1965; Mackie, 1977; Matthews, Davies, Westerman, & Stammers, 2000; Nachreiner & Hanecke, 1992; Parasuraman, 1984b, 1986; See, Howe, Warm, & Dember, 1995; Warm, 1984b, 1993; Warm & Parasuraman, 1987). The former became involved because vigilance tasks provided a vehicle for examining many of the factors influencing human attention (Broadbent, 1958, 1971; Broadbent & Gregory, 1965; Coren, Ward, & Enns, 2004; Dember & Warm, 1979). The latter turned to vigilance research because of its importance for understanding human performance in a variety of industrial and military systems (Adams, 1987; Craig, 1985; Mackie, 1987; Wiener, 1984, 1987).

## Vigilance in Human-Machine Systems

Interest in vigilance research among human factors practitioners has waxed and waned over the years but has increased recently because of the prevalence of automation in human-machine systems (Parasuraman & Riley, 1997). As Sheridan noted (1970, 1980), advancements in automation technology have shifted the roles of workers from active controllers to that of system supervisors who serve in a fail-safe capacity in which they need only react when problems arise. Consequently, vigilance has become a crucial component of human performance in many work environments where automated systems are common. These include military surveillance, air traffic control, cockpit monitoring, seaboard navigation, industrial process/quality control, long-distance driving, and agricultural inspection tasks (Dorrian, Roach, Fletcher, & Dawson, 2007; Hartley, Arnold, Kobryn, & Macleod, 1989; R. F. Johnson & Merullo, 2000; McBride, Merullo, Johnson, Banderet, & Robinson, 2007; Proctor & Van Zandt, 1994; Satchell, 1993). Vigilance is also a critical component of performance efficiency in medical settings such as cytological screening, electrocardiogram monitoring, and the inspection of anesthesia gauges during surgery (Daly & Wilson, 1993; Gill, 1996; Weinger & Englund, 1990) and, given the current emphasis on homeland security, in airport baggage inspection (Hancock & Hart, 2002) and detection of illicit radioactive materials at border crossings and ports (Sanquist, Doctor, & Parasuraman, in press).

Several studies have shown that accidents ranging in scale from major to minor are often the result of vigilance failures on the part of human operators in semiautomated systems (Molloy & Parasuraman, 1996). Hawley (2006), for example, described the role of vigilance and situation awareness in fratricide incidents in the Iraq war involving the highly automated Patriot missile system (see also Hawley, Mares, & Giammanco, 2005). One solution would be to design automated systems that eliminate the need for the human component. However, this is often not feasible because human judgment is required in the event of system failure (Parasuraman, 1987) and because some functions are difficult or impossible to automate. Hence, understanding the factors that influence vigilance performance is a critical human factors concern for system reliability and for public safety (Nickerson, 1992).

## The Vigilance Decrement

The quintessential finding in vigilance research is that detection performance declines over time, a result known as the *vigilance decrement.* Most of the decrement typically appears within the first 15 min of watch (Teichner, 1974), but when task demand conditions are high, it can appear as rapidly as in the first 5 min (Helton, Dember, Warm, & Matthews, 2000; Helton et al., 2007; Jerison, 1963; Nuechterlein, Parasuraman, & Jiang, 1983; Rose, Murphy, Byard, & Zikzad, 2002; Temple et al., 2000). The vigilance decrement is found with experienced as well as naive watchkeepers and, counter to the claim that it may simply be an artificial laboratory phenomenon (Mackie, 1984), occurs in operational as well as laboratory settings (Baker, 1962; Colquhoun, 1967, 1977; Pigeau, Agnes, O'Neil, & Mack, 1995; Schmidtke, 1976).

Traditionally, the vigilance decrement was thought to be caused by a decline in arousal brought about by the understimulating nature of vigilance tasks (Frankmann & Adams, 1962; Heilman, 1995; Loeb & Alluisi, 1984; Welford, 1968). According to that view, the repetitious and monotonous aspects of vigilance tasks suppress activity in brain systems, such as the brainstem reticular formation and the diffuse thalamic projection system, necessary to maintain continued alertness. As a result, the efficiency with which signals are detected is reduced. More recent research using divergent methodologies has challenged that view. The studies provide powerful converging evidence showing that vigilance assignments impose substantial demands on the information-processing resources of observers and are highly stressful. This more recent view has emerged from studies examining (a) task type, (b) perceived mental workload, (c) neural measures of resource demand in vigilance, and (d) task-induced stress. We discuss these converging sources of evidence in turn.

## VIGILANCE AND RESOURCE DEMAND

### Task Type

A major feature of vigilance tasks is their diversity. Such tasks can be presented in different sensory modalities and use different psychophysical dimensions to define critical signals. The assortment of tasks (see Hancock, 1984; J. F. Mackworth, 1970) initially led to a serious problem – low intraobserver correlations across tasks (ranging from .10 to .40; see Davies & Parasuraman, 1982; Warm & Jerison, 1984), implying that vigilance is not a unitary process (Buckner & McGrath, 1963). Instead, vigilance was viewed as task specific and controlled by different processes in different tasks. If true, such a situation would render the prediction and control of vigilance extremely difficult (Warm & Dember, 1998).

Parasuraman and Davies (1977; see also Parasuraman, 1976, 1979) proposed that the apparent diversity of findings in vigilance research might be accommodated by using *attentional resource theory* (see Fisk & Scerbo, 1987; Fisk & Schneider, 1981; Kahneman, 1973; Wickens, 1984) as a framework. Within the resource model, the vigilance decrement reflects the depletion of information-processing resources or information-processing assets that cannot be replenished in the time available. Parasuraman (1979) proposed that vigilance tasks could be categorized by whether target detection required successive or simultaneous discrimination and that these tasks imposed differential demands on attentional resources. The former are absolute judgment tasks in which observers need to compare current input with a standard retained in working memory to separate critical signals from nonsignal stimulus events. Simultaneous tasks are comparative judgment tasks in which all the information needed to distinguish signals from nonsignals is present in the stimuli themselves, and there is little involvement of recent memory for the signal feature. Because of the memory imperative, successive tasks are more capacity demanding than their simultaneous counterparts (see also Caggiano & Parasuraman, 2004).

To examine the view that there is a general process factor in vigilance, researchers have conducted several experiments in which performances were compared across different tasks within and across the successive/simultaneous categories (Parasuraman, 1976). The results showed that *within-category* correlations were substantial, ranging from .60 to .80, whereas *cross-category* correlations remained at the low levels seen in earlier research. Subsequent studies on training for vigilance using knowledge of results paradigms have shown strong evidence for transfer of training across tasks within the simultaneous/successive categories but not across categories (Becker, Warm, Dember, & Howe, 1994; Szalma, Miller, Hitchcock, Dember, & Warm, 1999). These findings indicate that vigilance is not task specific. Rather, it is *task type specific,* with the simultaneous/successive distinction representing one important task category.

In a number of experiments, researchers have examined the contention that successive tasks are more demanding of attentional resources than simultaneous tasks. In these experiments, several factors known to increase information-processing demand were compared for their relative effects on simultaneous and successive tasks (Parasuraman, Warm, & Dember, 1987; Warm & Dember, 1998). The factors included (a) increases in the rate of appearance of stimuli that need to be scanned for the presence of critical signals or increased event rate, (b) event asynchrony or irregularities in the time when events occurred, (c) spatial uncertainty in the location or appearance of critical signals, and (d) multitasking. Each of these challenges impaired performance on successive tasks to a greater degree than on simultaneous tasks, a result that might be expected if successive tasks are more resource demanding than their simultaneous counterparts.

## The Workload of Vigilance

The attentional resource approach to understanding vigilance led to a natural link to a major area of research and practice in human factors – mental workload or the degree of information-processing capacity that is expended during task performance (Eggemeier, 1988; O'Donnell & Eggemeier, 1986). Beginning with the work of Wickens (1984), theories of mental workload often refer to the resource concept, with converging evidence being sought using behavioral, neural, or subjective measures. Among the latter, the NASA-Task Load Index (NASA-TLX) has been one of the most widely used instruments (Wickens & Hollands, 2000). The NASA-TLX is a multidimensional scale that provides an overall or global measure of workload and also identifies specific components of workload. The components are defined along three dimensions imposed on the observer by the task – mental, physical, and temporal demand – and three dimensions related to the interaction of the observer and the task – performance, effort, and frustration (Hart & Staveland, 1988).

Using the NASA-TLX, Warm, Dember, and Hancock (1996) conducted a series of studies showing that rather than being understimulating, vigilance tasks are resource demanding and associated with high workload. More specifically, they reported that the vigilance decrement is accompanied by a linear increase in overall workload over time. Furthermore, overall workload is closely tied to the psychophysical demand of the vigilance task, increasing as (a) critical signals become less salient, (b) the spatial uncertainty of signal location rises, and (c) the event rate is increased. In all of these studies, the global workload scores fell within the upper end of the NASA-TLX scale, and there was a consistent workload signature among the subscales in which mental demand and frustration were the primary components of the workload associated with the vigilance tasks.

It is important to note at this point that there is debate in the literature about the way in which attentional capacity should be viewed. Following Kahneman's (1973) lead, some investigators have adopted a unitary resource model, whereas others, following Wickens's (1984) lead, have preferred to view attentional capacity in terms of a multiple pool of resources or a multiple-resource model. All of the studies described earlier employed a unitary resource model. More recent studies have begun to employ a multiple-resource approach to understanding vigilance performance. Thus, in a multitasking situation, Caggiano and Parasuraman (2004) have reported that performance efficiency in a successive-type vigilance task involving spatial working memory declined significantly over time when the concurrent task also involved spatial working memory but not when the spatial working memory component was absent in the concurrent task. In addition, experiments using a new workload scale, the Multiple Resource Questionnaire (Boles, Bursk, Phillips, & Perdelwitz, 2007), have supplemented the NASA-TLX studies in demonstrating that vigilance tasks are highly mentally demanding in respect to multiple components of workload (Finomore et al., 2006; Warm, Matthews, & Finomore, 2008).

The workload of vigilance studies led A. Johnson and Proctor (2004) to affirm that the finding of high information-processing demand in vigilance tasks challenges arousal theory and supports the attentional resource view that the workload imposed by vigilance tasks reflects the impact of focused mental effort and a drain on information-processing resources. The workload findings also led Grier et al. (2003) and Helton et al. (2005) to make a similar argument against a recent view suggested by Robertson and his colleagues (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997) that the repetitive and tedious nature of vigilance tasks leads observers to withdraw attentional effort over time and approach their assignment in a thoughtless, routinized manner.

## Neural Measures of Resource Demand in Vigilance

Although many human factors investigators have used attentional resource theory, the resource concept has also been criticized (e.g., Navon, 1984). One criticism is that resources are typically *inferred* from performance measures rather than measured directly; consequently, explaining performance changes (such as vigilance or dual-task decrements) in terms of resources represents circular reasoning. The criticism could be countered if resources were assessed *independently* of performance, using, for example, neuroimaging measures while observers perform a vigilance task. We describe several studies that have used this approach.

Neuroimaging studies employing positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have shown that increased cerebral blood flow in regions of the prefrontal cortex can be used to quantify attentional resources and mental workload (Parasuraman & Caggiano, 2005). Several vigilance studies using PET and fMRI have also found that changes in cerebral blood flow and glucose metabolism are involved in the performance of vigilance tasks and that vigilance tasks activate a variety of brain regions (Parasuraman, Warm, & See, 1998). However, as Parasuraman et al. (1998) pointed out, with a few exceptions (Coull, Frackowiak, & Frith, 1998; Paus et al., 1997), neuroimaging studies have neglected to link the brain systems they have identified to performance efficiency, perhaps because of the high cost of using PET and fMRI during the prolonged running times involved in vigilance experiments. Furthermore, PET and fMRI must be conducted in highly restrictive environments that prevent any observer movement. Observers, however, rarely remain motionless during the performance of a vigilance task. Instead, they fidget, with the amount of motor activity increasing with time on task (Galinsky, Rosa, Warm, & Dember, 1993).

Recent studies using a less expensive and less restrictive imaging system, known as transcranial Doppler sonography (TCD), have provided strong independent evidence for resource changes linked to performance decrement in vigilance tasks. TCD employs ultrasound signals to monitor cerebral blood flow velocity or hemovelocity in the main stem intracranial arteries – the middle, anterior, and posterior arteries. TCD measures the difference in frequency between outgoing and reflected energy as it strikes moving erythrocytes (see Tripp & Warm, 2007). When a particular area of the brain becomes active, as in the performance of mental tasks, by-products of this activity, such as carbon dioxide ($CO_2$), increase. The increase in $CO_2$ leads to a dilation of blood vessels serving that area, which in turn results in increased blood flow to that region (Aaslid, 1986). Consequently, TCD offers the possibility of measuring changes in metabolic activity during task performance (Duschek & Schandry, 2003; Tripp & Warm, 2007).

In studies by Warm and colleagues, blood flow velocity was measured in the medial cerebral artery, which carries about 80% of the blood flow within each cerebral hemisphere (Toole, 1984). As described in recent reviews (Warm et al., 2008; Warm & Parasuraman, 2007), these studies provide dramatic support for a resource model of vigilance. They show that the vigilance decrement is paralleled by a temporal decline in blood flow velocity but only when observers actively engage with the vigilance task. When observers were asked to view the vigilance display passively without a work imperative for an amount of time equal to that in the active conditions – what might be considered the case of maximum understimulation – blood flow velocity remained stable throughout the course of the session.

The degree of blood flow decline in these studies was directly related to task demands, particularly in the right cerebral hemisphere. The finding of lateralized effects is important. It coincides with the results of the PET and fMRI studies, which also pointed to a right hemispheric system in the control of vigilance (Parasuraman et al., 1998), and it rules out the possibility that the hemovelocity effects were confounded by gross changes in systemic vascular activity, such as changes in heart rate variability, blood pressure, and cardiac output, because these changes are not likely to be lateralized.

The TCD studies are part of the emerging *neuroergonomics* approach (Parasuraman & Rizzo, 2007). One goal of this approach is to use knowledge of brain function to enhance human-system performance. See Parasuraman and Wilson (2008 [this issue]) for a review of the contributions of neuroergonomics. In that regard, the finding that TCD-measured temporal declines in hemovelocity parallel the vigilance decrement suggests that TCD may offer a convenient tool to "monitor the monitor" and help to decide when observer vigilance has reached a point where task aiding is necessary or observers need to be rested or removed.

### Stress

Thus far, we have described converging evidence from behavioral, subjective, and neural measures for the view that vigilance tasks are mentally demanding. The final source of evidence we consider comes from an examination of task-induced stress. If a given cognitive activity requires extensive application of resources and that activity has to be carried out for long, unbroken periods of time, then it is likely that the activity should induce stress (Hancock & Warm, 1989). This has been confirmed in studies using both physiological and self-report measures.

The stress response of an observer during a vigilance session can be assessed by measuring levels of circulating catecholamines (Lundberg, 2005; Parasuraman, 1984a). Several studies have reported that epinephrine and norepinephrine levels are elevated during vigilance (Frankenhaeuser, Nordheden, Myrsten, & Post, 1971; Frankenhaeuser & Patkai, 1964; Lundberg & Frankenhaeuser, 1979). O'Hanlon (1965) also found elevated norepinephrine levels in experienced observers who were simply waiting to perform a vigilance task a second time, as if the mere anticipation of performing the task induced a stress reaction.

Several studies using self-report measures have shown that observers rate themselves significantly less attentive and more sleepy, bored, strained, irritated, and fatigued after a vigil than before its start (see Warm et al., 2008). These studies measured only *unidimensional* aspects of stress states. To develop a more systematic multidimensional framework for understanding transient states of mood, arousal, and fatigue, Matthews and colleagues (Matthews et al., 1999; Matthews et al., 2002) developed the Dundee Stress State Questionnaire (DSSQ) to assess ways in which stress may be experienced as disturbances in affect, motivation, and cognition. The DSSQ features three factor analytically derived dimensions known as *task engagement, distress,* and *worry.*

Task engagement contrasts enthusiasm and interest with fatigue and apathy, distress encompasses negative moods and lack of confidence, and worry reflects negative self-referent cognitions. A number of studies with the DSSQ have shown that participation in a vigilance task typically leads to a loss of task engagement accompanied by feelings of distress and that these changes increase with increments in task difficulty (see Szalma et al., 2004; Warm et al., 2008). Furthermore, task engagement is reliably predictive of performance on high-workload vigilance tasks, consistent with the hypothesis that engagement is a marker for attentional resource availability (Reinerman et al., 2006). The stress induced by vigilance tasks is more than just an academic concern because stress plays a role in reducing worker health, safety, and productivity (Nickerson, 1992; Strauch, 2002).

## CONCLUSIONS

As described earlier, vigilance tasks have traditionally been considered to be understimulating and mentally undemanding. Research has proven that conventional wisdom wrong. Rather than being simple work assignments as originally believed, vigilance tasks are exacting, capacity-draining assignments that are resource demanding, as revealed by both behavioral and neural measures. They are also associated with a considerable level of subjective workload and stress. These aspects need to be considered in the design of work environments involving vigilance functions and in the evaluation of those who carry out such functions. In addition to moderating the workload of sustained attention assignments, it may also be critical to design tasks to afford engagement, autonomy, and challenge (Hancock, 1997).

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