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Task Demand and Workload: Effects on Vigilance Performance and Stress

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The present study was designed to explore the effects of task demand and perceived mental workload on vigilance performance and self-reported stress. Forty participants were assigned at random to one of two task demand conditions: high (n = 20) and low (n = 20). Performance metrics and self-reported workload and stress-states were collected. Overall performance efficiency and the rate of the vigilance decrement were influenced by the task demand of the signal being observed. Statistically significant pre-task to post-task decrease in self-reports of energetic arousal elucidate the vigilance decrement phenomenon ($F_{(1, 38)} = 16.66$, $p < .001$). The significant pre-task to post-task decrease in motivation ($F_{(1, 38)} = 12.63$, $p<.001$), concentration level ($F_{(1, 38)} = 12.30$, $p<.001$), and the self focused attention ($F_{(1, 38)} = 4.55$, $p <.03$) of the participants would also explicate to some extent the overall performance inefficiency. The results support a resource theory perspective in regards to the vigilance decrement.

Keywords: Task demand, Workload, Stress, Vigilance

Participants during vigilance or sustained attention tasks monitor visual displays or auditory streams for prolonged periods of time. Vigilance participants are typically required to execute overt detection responses to infrequently occurring critical signals and to not respond to more frequently occurring neutral signals (Davies & Parasuraman, 1982; Warm, 1984; Warm & Jerison, 1984). Vigilance tasks and the processes that influence their performance are of interest because of the insights they provide into the factors that control attention (Broadbent, 1971; Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Vigilance tasks are also of interests given the vital role that vigilance plays in automated human-machine systems in transportation (Parasuraman & Riley, 1997), process and quality control, medicine, and baggage inspection at airport security checkpoints (Hancock & Hart, 2002; Wickens & Hollands, 2000).

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, Warm, Dember, Jones, LaGrange, & Matthews, 2000). The vigilance decrement is found with experienced as well as naive watch-keepers 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.

Vigilance and task demand

In most vigilance experiments, critical signals for detection occur within a framework of nonsignal events that must be examined for the presence of signals. Detection probability varies inversely with the rate of cascade of background events or the *background event rate* (Davies & Parasuraman, 1982; Matthews, Davies, Westerman, & Stammers, 2000). As Warm and Jerison (1984) have noted, a result of this sort is paradoxical in two ways. It implies that the more one has to look or listen for critical signals in a vigilance study the less the probability that such signals will discovered and that signal detection in vigilance is determined to a considerable degree by what is going on when no signal is presented. The effect of task demand (event rate) was the primary concern of this investigation.

At this time, the most widely accepted explanation of the task demand (event rate) effect is the resource model proposed by Parasuraman and his associates (Davies & Parasuraman, 1982; Parasuraman & Davies, 1977; Parasuraman, Warm, & Dember, 1987). According to that view, the need to make repetitive signal/non-signal discriminations in the performance of a vigilance task consumes the information-processing resources or information-processing entities available to a limited-capacity information processing system which are not replenished over time. Within this model, high task demands are assumed to be more capacity draining that low task demands because of the need at the high task demands to make more frequent and rapid decisions about whether or not a stimulus event constitutes a critical signal for detection. As a result performance efficiency is poorer and the vigilance decrement is steeper in the context of high as compared to low task demands.

Vigilance and workload

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 under stimulating, 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 task demand (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 (high workload) 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) 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 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.

Vigilance and 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). 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, Joyner, Gilliland, Huggins, & Falconer, 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.* Accordingly, the Task Engagement, and Distress dimensions encompass the affective, motivational, and cognitive aspects of stress, while the Worry dimension is primarily cognitive in character (Matthews et al., 2002)

A number of studies with the DSSQ have shown that participation in a vigilance task typically leads to a loss in task engagement accompanied by increased feelings of distress. (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 vital role in reducing worker health, safety, and productivity (Nickerson, 1992; Strauch, 2002).

Accordingly, the present study was designed to pore over the effect of task demands in terms of high and low event rate and perceived mental workload on stress states response and vigilance performance. Another aim of the present study was to test the effects of stress responses induced by the high and low task demands on vigil performance.

Method

Participants:

40 students (28 girls and 12 boys) served as observers in this experiment. All were enrolled in psychology course at Banaras Hindu University and participated to fulfil their course requirement. They ranged in age from 18 to 27 years, with a mean of 21.7 years. All participants had normal or corrected-to-normal vision which was tested in the lab with the help of Snellen vision chart.

Procedure:

Of the 40 participants, 20 were assigned at random to low task demand and 20 in a high task demand conditions. All observers participated in a 30-min vigil divided into three continuous 10-min time-periods. Participants inspected the random presentation of a square of 3.5 cm and a square of 3.0 cm at low and high task demand conditions as target and non-target, respectively. The task was displayed on 15'' SVGA colour monitor via stimulus presentation software Superlab® (Cedrus, 2007, version 4.0) at high (30 events/min.) or low (15 events/min.) event rate. The squares were exposed for 100 ms against a white background. Critical signals (target) for detection was the appearance of the ''bigger square", while making no overt response to neutral signals (non-target) "small square". Observers signified their detection of critical signals by pressing the key on a response pad. Prior to the main vigil, all the participants were given a 3-minute of demo to familiarize themselves with the vigilance task and 10-minute of practice, which serve the purpose of selecting the participants in different experimental conditions. The criteria for the selection of participants before the main session was based upon their practice performance in which they have to score 75% or above on correct detection measure. The high task demand condition, comprised of total 300 events. Out of these events, 60 events were targets and 240 events were non-targets whereas the low task demand condition comprised of total 150 events. Out of these events, 30 events were targets and 120 events were non-targets. Thus, the ratio of target and non-target was 1:4.

The experiment was conducted in a small cubical with an ambient illumination provided by a 40-watt light bulb housed in a covered ceiling fixture located above the observer and angled to reduce glare on the computer monitor. The monitor was mounted on a computer table at eye-level approximately 55 cm from the seated participant. Participants surrendered their wristwatches, and cell phones at the outset of the experimental session and had no knowledge of its duration other than it would not exceed 60 min.

Subjective assessments

Self-report assessments were made using Multidimensional Stress-State Questionnaire (MSSQ) and NASA-TLX. Participants perceived stress states were assessed with Hindi adaptation of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999; Matthews et al., 2002), which is a multidimensional, self-report instrument for assessing transient mood states. Specifically, this version of the MSSQ comprised 10 factor-analytically determined scales. The Multidimensional Stress-State Questionnaire (MSSQ) was administered in two sessions: a pre-vigil questionnaire completed prior to the practice period and a post-vigil questionnaire completed after the vigil.

The shortened adaptation of the NASA-TLX was administered immediately upon completing the main vigilance task (Matthews et al., 2002). The modified NASA-TLX omits the paired comparison procedure of the standard version, an omission that is not deemed critical for valid workload assessment with this instrument (Nygren, 1991). Omission of the paired comparison procedure allowed the NASA-TLX to be embedded conveniently within the DSSQ and avoided the necessity of running separate groups of participants with each scale to control for the possibility of inter-scale interactions. Participants rated their mental demand, physical demand, temporal demand, performance, effort and frustration associated with a task on 10 point scale.

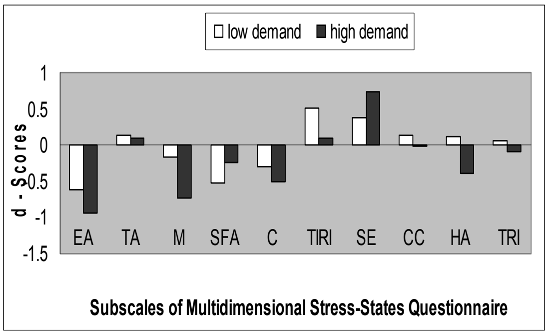
Results

Subjective stress-states (MSSQ):

The MSSQ scores were analysed with ten 2 (Task demand condition: high and low) x 2 (Time: pre- and post-task) mixed repeated measures analyses of variance. There was a statistically significant pre-task to post-task decrease in energetic arousal, $F_{(1, 38)}$ =16.66, p<.001 and increase in task-irrelevant-interference (TIRI), $F_{(1, 38)}$=71.94, p<.03 regardless of task demand conditions. There was also statistically significant pre-task to post-task decrease in motivation ($F_{(1, 38)}$= 12.63, p<.001), concentration level ($F_{(1, 38)}$= 12.30, p<.001), and the self focused attention ($F_{(1, 38)}$=4.55, p<.03) of the participants. Though not statistically significant, there was a trend of elevation in tense arousal state. All other effects and interactions of the MSSQ were statistically insignificant, p > .05.

For comparative purposes, individual normalized change scores were calculated for each scale using the formula, d = (individual post-score-individual pre-score) / (standard deviation of the pre scores for the scale), as has been performed in previous studies (Helton et al., 2000; Szalma, Hancock, Dember, & Warm, 2006). The mean change scores for the ten scales for the two task demand groups are presented in Figure 1. Mean change scores are displayed as departing from a standard score of 0 (i.e., no change). The profile of state change exhibited by the observers indicates that they are less energetically aroused and less motivated at high task demand condition. However, they are more tensed and have more task-irrelevant-interference (TIRI) at the low task demand condition.

Figure 1. Standardized pre-post vigil change scores (Z- Scores) as a function of low and high task demand conditions for Energetic Arousal (EA), Tense Arousal (TA), Motivation (M), Self Focused Attention (SFA), Concentration (C) Task Irrelevant Interference (TIRI), Self Esteem (SE), Control & Confidence (CC), Hedonic Arousal (HA) and Task Relevant Interference (TRI).

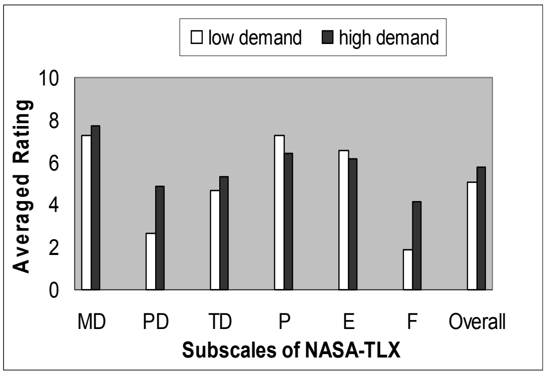


Subjective workload states (NASA-TLX):

Ratings of mental workload on each subscale of NASA-TLX as well as overall averaged workload were presented in Figure 2. It is apparent from Figure 2 that overall mental workload was higher in high task demand condition (M = 5.78; SD = 1.68) than in low task demand condition (M = 5.06; SD =

1.52). The main effect of the task demand for physical demand ($F_{(1, 38)}$ = 6.99, p< .01) and frustration ($F_{(1, 38)}$ = 9.60, p< .004) was significant with demand ratings higher in high task demand than in low task demand conditions. Though, the other components of mental workload fail to achieve the significance level nevertheless there was a trend of increment in workload from low to high task demand conditions in mental demand and temporal demand components of NASA-TLX, while effort and performance components of NASA-TLX showed decrement in workload.

Figure 2. **Workload scores across low and high demand conditions (MD = Mental Demand; PD = Physical Demand; TD = Temporal Demand; P = Performance; E = Effort; F = Frustration).**

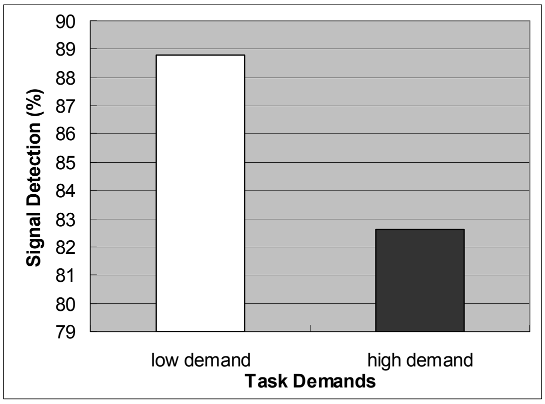


Correct detections performance (Hits):

In the present vigil experiment, correct detections were defined as key presses on a response pad to the occurrence of critical signals (bigger square) on the computer monitor.

The mean percentage of correct detections in all experimental conditions were subjected to 2 (task demand: High and Low) x 3 (10-min Time periods) mixed ANOVA in which the arcsine transformation was used to normalized the data (Kirk, 1995; Maxwell & Delaney, 2004). The analysis revealed that the overall detection rate in low task demand condition (M = 89%; SD = 0.07) was significantly higher than in high task demand condition (M = 83%; SD = 0.16). ANOVA results of hits performance demonstrated that the main effect of time period ($F_{(2, 76)}$ = 4.26; p < .01) was significant (see figure 3). However, their interaction was not found significant, p > .05.

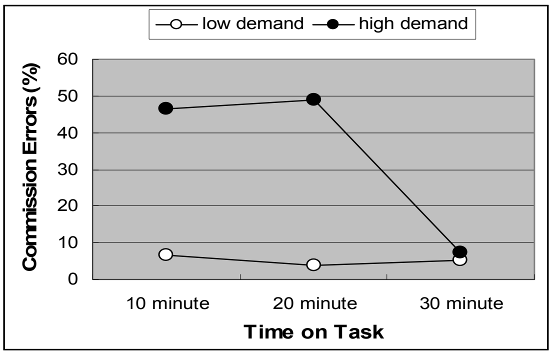
Figure 3. T ask demands as a function of correct detection (p < .01).



Commission error performance (False alarms):

Mean percentage of overall commission errors showed that participants committed more errors in high task demand condition (M = 34.28%; SD = 0.29) than in low task demand condition (M = 5.40%; SD = 0.07). A 2 (Task demand: High and Low) x 3 (Periods of watch) mixed ANOVA based upon an arcsine transformation of the percentages commission errors showed that commission errors were significantly greater when signals appeared on a temporally high demanding condition (M = 34.28%; SD = 0.29) as compared with low demanding condition (M = 5.40%; SD = 0.07). The ANOVA results of commission errors data showed significant main effect of time periods ($F_{(2, 76)}$ = 15.58; p < .001) and significant interaction effect between time periods and task demand ($F_{(2, 76)}$ = 16.25; p < .001). The task demand x periods interaction is shown in see figure 4. It is evident that while the false alarms rates in the two task demands were apart initially, the rate of gain in false alarms over time was reduced to match the low vigil condition.

Figure 4. Task demand as a function of commission errors and time periods (p< .001).



Reaction time performance

Mean reaction times of responses were calculated for each participants by period of watch in milli-second (ms). The analysis revealed that the overall reaction times were slower for high task demand condition (M = 372.22 ms; SD = 121.55) than for low task demand condition (M = 395.48 ms; SD = 277.33) which suggested that participants took more time in detecting signal under low demand than high demand condition. Moreover, the ANOVA results of reaction time performance did not achieve a significant level (p > .05).

Discussion

The effects of task demand on performance efficiency in this study matched those of previous research with long-duration vigil and with the abbreviated vigil (Gluckman, Warm, Dember, & Rosa, 1993; Krulewitz, Warm, & Wohl, 1975; Helton, Shaw, Warm, Matthews, & Hancock, 2008). As in these earlier investigations (Matthews et al., 2000; Temple et al. 2000; Warm, 1993), detection probability was poorer in the context of high as compared to low task demand and the vigilance decrement was steeper.

The participants reported feeling less energetic after the vigil than prior to its start. Decreasing energetic arousal indicates mental fatigue or resource depletion. The general elevation of tense arousal is consistent with a substantial number of experiments demonstrating that observers find long-duration vigilance tasks to be stressful (Hancock & Warm, 1989; Szalma et al., 2004; Warm, 1993). The post-task decrease in motivation, self-focused attention, and concentration. The differential mood change reported in this study are consistent with the view that stress arises when task demands tax an observer's information processing resources (Lazarus & Folkman, 1984; Matthews, 2001) and that high task demands are more capacity demanding than low task demand (Davies & Parasuraman, 1982; Parasuraman & Davies, 1977; Parasuraman, Warm, & Dember, 1987; Singh & Tiwari, 2005).

It is noteworthy, that the negative mood changes in the two task demand conditions were accompanied by some positive changes, for instance, a decrease in task irrelevant interference (TIRI) in the high task demand condition and an increase in self-esteem in the high task demand condition. The former (TIRI results) suggests that observers in the high task demand condition were more task-oriented than their low task demand colleagues. The post-test increase in self esteem has been found previously in vigilance tasks and most likely reflects the observer's satisfaction in completing a difficult assignment (Warm et al., 2008).

The findings of this study provide evidence in support of a resource theory interpretation of the vigilance decrement. First, the most obvious finding is that a high task demands exacerbate signal detection performance: the task demand effect (I. L. Singh, Tiwari, & A. L. Singh, 2007a; 2007b). This finding is easy to predict from resource theory, as an objectively more difficult task should deplete more resources than an easier task. Moreover, the overall statistically significant decline in energetic arousal in both conditions is also supportive to the resource theory of the vigilance decrement, as this decline indicates the tasks are mentally challenging. Secondly, the overall workload is closely tied to the psychophysical demand of the vigilance task, increasing as the task demand (event rate) is increased. A visual inspection of Figure 2 showed that there was a trend of overall workload scores be higher in high demand condition than its counterpart, and there was a consistent workload signature among the subscales in which mental demand, physical demand, temporal demand and frustration were the primary components of the workload associated with the vigilance tasks.

The relationship between subjective states and performance is an area where resource theory could benefit from further research, although Matthews et al. (2002) have made an initial venture. Recent advances in brain imaging technology coupled with a wide variety of performance measures and reports of conscious states will also further clarify the role of resource allocation in vigilance and signal detection tasks (see Mason et al., 2007; Weissman, Roberts, Visscher, & Woldorff, 2006).

As noted in beginning of the paper, vigilant behavior plays a key role in the operational environment. Therefore, it is important to consider the practical implications of the present study. Basically, it involves a caution to avoid high task demands in display design. Moreover, in view of the broad problem of job related stress that is a critical concern within the human factors community (Sauter, Murphy, & Hurrell, 1990), the present results also indicate that high task demands invoke greater stress reactions than their low task demand analogs.

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