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Event Rate and Vigilance: A Psychophysiological Investigation of Mental Workload

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Maintaining attention with concentration over prolonged periods of time during vigilance task, which may be monotonous, generally increases reaction time and errors. Such decrement in performance gets intensified during higher event rate condition. The present study was conducted on 40 male undergraduate and postgraduate students to examine the effects of event rate and task duration on behavioural, physiological and subjective measures. Two event rates were manipulated and mental workload was measured prior to and after the 40-minutes successive discrimination vigilance task. Correct responses were higher under low event rate while both event rates showed decrement in accuracy with progress in time block. Heart rate and heart rate variability pattern observed across time period in two event rate conditions were inconsistent with previous researches. Perceived mental workload increased from pre to post task session though the workload was reported as similar under high and low event rate conditions. Maintaining vigilance is a demanding task which resulted in deterioration of performance as well as mounting of perceived mental workload. Findings of present study may be implemented to work settings while designing systems and work environment, which involve vigilance functions and where production, safety and efficiency of operators are major concerns.

Keywords: Vigilance, Event rate, Mental workload, Heart rate, Heart rate variability.

Vigilance is concerned with the ability of observers to detect infrequent signals over prolonged periods of time. Increased automation and advances in technology has shifted the role of operators from active controller to passive observers in which action is only required when problems occur (Sheridan, 1970; 1987; Warm & Dember, 1988). This trend increases the interest among researchers, especially human factors and ergonomic specialists, to study the watch-keeping or vigilant behaviour. Maintaining attention for a prolonged period of time is a basic requirement for a variety of jobs. Nevertheless, it comes with costs on performance in terms of slow reaction time and decrement in detection rates as time on task increases. This quintessential finding of vigilance study is known as decrement function or vigilance decrement in literature.

Several theoretical explanations have been put forth to account for the vigilance decrement. Among them the two most common, though contrary, explanations used in literature are based on arousal theory and resource theory. Explanations based on arousal theory state that vigilance tasks are tedious and under stimulating therefore they impose little workload upon observers and after a certain time of performing the same repetitive task, the supervisory attentional system loses effectiveness and ceases to focus awareness on the vigilance task (Manly, Robertson, Galloway & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). Other studies also found correlation between task-irrelevant mental activities and attentional lapses during a vigilance task (Smallwood et al., 2004). Furthermore, performance decrement in vigilance attention was found to be related with lower event related potential (ERP) responses and lower cortical activation (Dockree, Kelly, Foxe, Reilly & Robertson, 2007). This view is termed by different names such as underload or mindlessness or boredom theory. Pattyn, Neyt,

Henderickx, and Soetens (2008) also provided support to the boredom hypothesis with their physiological and subjective findings related with vigilance.

In contrast to the underload theory, other authors view the decrement as the result of a decrease in attentional capacity over time-on task and difficulty to maintain the effort, due to high mental workload (Grier et al., 2003; Helton et al., 2005; Temple et al., 2000). This view is similar to resource theory which argue that the performance decrement occurs because individual expend resources for maintaining attention at a rate faster than they can be replenished. Within this framework vigilance decrement reflected the depletion of information-processing resources that cannot be replenished in the time available (Warm, Parasuraman & Mattews, 2008). These studies utilized NASA Task Load Index (NASA-TLX, Hart & Steveland, 1988) to measure the workload placed by vigilance task on observers. The workload scores for vigilance are found to be greater than several other types of tasks, such as time estimation, simple tracking and grammatical reasoning (see Helton et al., 2005). These lines of researches are coined as overload or mindlessness or cognitive fatigue hypothesis. The workload of vigilance studies affirm the resource view that the workload imposed by vigilance tasks reflects both the impact of focused mental endeavor and depletion of information processing resources (Johnson & Proctor, 2004). Studies measuring stress states of vigilance also provide additional support to overload hypothesis (Helton, Dember, Warm, & Matthews, 2000; Szalma et al., 2004; Temple et al., 2000). In these studies task induced stress was measured via task engagement, distress and worry scales of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999) which assessed affective, motivational and cognitive aspects of stress states. A number of studies with the DSSQ have shown that maintaining alertness during vigilance task typically leads to a loss of task engagement accompanied by feelings of distress (Szalma et al., 2004; Warm et al., 2008). Furthermore, task engagement is found to be a predictor of performance on high-workload vigilance tasks and this engagement is an indicator of attentional resource availability (Reinerman et al., 2006).

The perceived mental workload of vigilance tasks also varies directly with event rate (Tiwari, Singh, & Singh, 2009; Warm, Dember, & Hancock, 1996; Yadav, Singh, & Tiwari 2015) and higher event rate tasks are considered as highly demanding. Event rate is the rate of presentation of stimulus. Greater vigilance decrement has been reported with high event rate as compared to low event rate tasks and the quality of vigilance performance has been found to be inversely related to the rate of presentation of background events (Galinsky, Rosa, Warm, & Dember, 1993; Tiwari et al., 2009). In the present study, behavioural measures and subjective report regarding workload has also been validated by two physiological measures i.e. heart rate (HR) and heart rate variability (HRV). Heart rate measure is used to describe the frequency of the cardiac cycle and calculated as the number of contractions (heart beats) of the heart in one minute and expressed as 'beats per minute' (bpm). Studies related with heart rate and vigilance has been inconsistent. Few stated that the heart rate is negatively correlated with vigilance performance (McIntire et al., 2011; Dussault, Jouanin, Philippe & Guezennec, 2005) while other argued that it is positively correlated with vigilance performance (Jeroski, Miller, Langhals, & Tripp, 2014). Nevertheless, it was found to be related to the time on task i.e. heart rate was found to decrease with increase in time on task (Griew, Davies & Treacher, 1963; Jeroski et al., 2014; Stroh, 1969; Thackray, Jones, & Touchstone, 1974)

Heart rate variability is another component associated with heart rate which is the variation of beat to beat intervals. Heart rate variability has been found to increase during a vigilance task (Kibler, 1968; Jeroski et al., 2014; O'Hanlon, 1970; O'Hanlon, 1971; Thackray et al., 1974). Furthermore, HRV was found to be negatively correlated with detection rate (O'Hanlon, 1970; Jeroski et al., 2014) and positively correlated with response time (Thackray et al., 1974) and error score (Griew et al., 1963). In addition, HRV was found to be inversely correlated with mental workload (De Ward, 1996; Rowe, Sibert & Irwin, 1998). Thus, monitoring heart rate data during a

vigilance task might therefore, help to identify the amount of mental effort taken and whether the vigilance decrement is due to low mental effort or high task demand.

Thus, present study was designed to study the mental workload associated with vigilance task in two task demand conditions varied by two event rates. Three assumptions were tested in this study: First, participants would perform better under low event rate condition than in high event condition on behavioural measures; Second, physiological and behavioural measures would be different across time periods during vigilance task and third, perceived mental workload would be different in pre and post task sessions across event rate conditions.

Method

Participants

Forty male students from Banaras Hindu University participated in this study. The participants were randomly assigned in two event rate conditions, in such a way that 20 candidates were allocated in each event rate condition. The participant's age varied from 19 to 28 years with a mean age of 23.4 years (SD = ± 2.78). All participants had either normal or corrected to normal (20/20) vision.

Experimental Design

A 2 (event rate: high & low) × 4 (time block: Four 10-min. blocks) mixed factorial design was used for behavioral and physiological measures in which event rate was treated as a between subject variable and time block as a within subject variable. Reaction time and accuracy were taken as behavioural measures whereas, heart rate and heart rate variability (HRV) were taken as physiological measures.

Tools and Apparatus

Sensory Vigilance Task

The successive discrimination sensory vigilance task was used in which discrimination was made between squares of two sizes. The target was 3.30 cm2 and the non-target was 3.00 cm2. The experiment was designed with Superlab Software (Cedrus, 2007, Version 4) and stimuli were displayed at the centre of 15'' colour monitor of Pentium IV computer. Participants were instructed to detect target (big square) over non-target (smaller square) and to respond immediately by pressing a designated key. Two experimental task conditions namely high event rate (HER) and low event rate (LER) conditions comprising of 40 events/minute and 24 events/minute respectively were employed. One event comprised of fixation (500 ms), presentation of target/non-target (100 ms) and a blank screen (900 or 1900 ms) for response. The probability of target/non-target was kept 20:80.

NASA-Task Load Index Scale (NASA-TLX)

Computerized version of the NASA-TLX was administered immediately before and after the vigilance task. The standard version of the NASA-TLX was used, which comprised of two parts; in the first part the participants were asked to rate six sub-scales on a 100-point rating scale while the second part utilized pair-comparison procedure in which participants had to choose any one of the sub-scale presented in pairs.

NASA-TLX (Hart & Staveland, 1988) is a multidimensional psychometric test that provides a reliable index of global workload and also identifies the relative contributions of six sources of workload. Three of those sources reflect the demands related to task placed upon operators, namely mental demand, physical demand, and temporal demand, whereas the remaining three sources characterize the interaction between operators and task i.e. performance, effort, and frustration. The NASA-TLX workload scale has high test-retest reliability (r = 0.83), which has been recommended as one of the most effective measures of perceived workload (Wickens & Hollands, 2000).

PhysioPac

PhysioPac (developed by Medicaid Systems, Chandigarh) was used for measuring and recording the heart rate during vigilance task session. It is a window based computerized polygraph. The PhysioPac is a highly sensitive oscilloscope capable of simultaneously recording signals in different modes from many sources. Heart rate variability was derived from heart rate data.

Procedure

All the participants signed an informed consent form prior to participation. They were

also asked to fill a biographical questionnaire regarding their age, gender, education, handedness, familiarity with computer, medical problem (if any), and use of medicine (if any). In the sequence, participants were tested for visual acuity on Snellen chart. Participants who had either normal or corrected to normal (6/6) vision were selected for the experiment.

Prior to the vigilance task session, the electrodes for physiological recording were placed at the right places. All the participants were given 3-minutes demonstration of the task to familiarize with the vigilance task, followed by 10-minutes practice session. At the end of the 10- minutes practice session, feedback was provided to each participant about accuracy and latency performances. Only those participants, who scored hit rates of 60 % or above were selected for the final 40-minutes experimental session. Physiological recordings were taken during practice as well as in the final task session. NASA-TLX was administered individually prior to the onset and after completion of the vigilance task for the assessment of mental workload.

The experiment was conducted in a cubicle of 6 x 8 x 10 feet (L x W x H) with an ambient illumination provided by a 40-watt light bulb housed in a covered ceiling fixture located above the participant and angled to reduce glare on the computer monitor. The monitor was mounted on a computer table at an eye-level of approximately 55 cm from the participant.

Results

Behavioural Measures

Participants in low event rate condition (M = 309.55 ms, SD = 105.37) were slower in detecting targets as compared to high event rate condition (M = 254.27 ms, SD = 63.38), however, the AVOVA revealed that the main effect of event rate was only marginally significant, $F_{(1, 38)} = 3.142$, $p = .08$, $\eta_p^2 = .076$. The main effect of the time block was also found to be marginally significant, $F_{(3, 114)} = 2.397$, $p = .07$, $\eta_p = .076$. Figure 1 shows that for low event rate, maximum decrement was observed during time block III while for the high event rate, highest decrement was registered during time block II. The interaction between event rate and time block was not found to be significant (p =.319).

The overall correct responses were higher in low event rate (M = 84.35%, SD = 10.57) than in high event rate condition (M = 66.06%, SD = 66.05) which resulted in a significant main effect of event rate, $F_{(1, 38)} = 18.244$, $p < .001$, $\eta_p^2 = .514$. The main effect of the time block was also significant, $F_{(3, 114)} = 3.243$, p = .025, $\eta_p^2 = .079$, suggesting that four time blocks differently affected accuracy performance. Both the event rates showed that accuracy decreased (by 8.38%) as the time period increased from time block I to time block III. However, as the time block increased from third to fourth there was a slight improvement in accuracy performance. However, there was a larger decrement in the high event rate (5.59 %) as compared to the low event rate (2.09 %) condition, though, the interaction between event rate and time block was not significant. Thus, behavioural measures showed speed-accuracy tradeoff i.e. the reaction time performance is better in one condition (HER) and accuracy performance is better in another (LER).

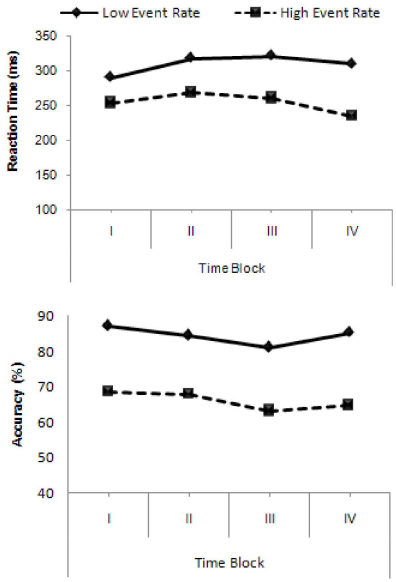

Figure 1. Reaction time and accuracy performance as a function of event rate and time block.

Physiological Measures

The ANOVA results for heart rate revealed that the main effect of event rate was not significant, $F_{(1, 38)} = 0.233$, $p = .632$, suggesting

that the HR pattern was found similar across two event rate conditions with slightly higher HR in low (*M* = 78.04, *SD* = 3.56) than high (*M* = 77.47, *SD* = 4.29) event rate condition. The interaction between event rate and time block was found to be significant, $F_{(3, 114)} = 2.756$, $p = .046$, $\eta_p^2 = .068$. Heart rate pattern was found to be different across two event rate conditions as both event rate conditions showed an increase in heart rate from the first to the second time block. However, from the second to fourth time block there was increase in HR only for low event rate while for high event rate heart rate decreased (see Figure 2).

Heart rate variability was relatively higher in low (*M* = 1.79, *SD* = 0.86) than high (*M* = 1.39, *SD* = 0.72) event rate condition. The main effects of event rate, $F_{(1, 38)} = 8.770$, $p = .005$, $\eta_p^2 = .188$, and time block, $F_{(3, 114)} = 2.794$, $p = .044$, $\eta_p^2 = .068$, were significant indicating that HRV decreased with time block though the decrement was larger in high (39.71 %) than low (16.22 %) event rate condition. In time block III both HER and LER showed fairly similar value of HRV. Separate t-test also suggested that in block I (t (38) = 1.34, $p = .188$) and block III (t (38) = .211, $p = .834$) both event rate did not differ significantly. Furthermore, the interaction of event rate and time block was not significant.

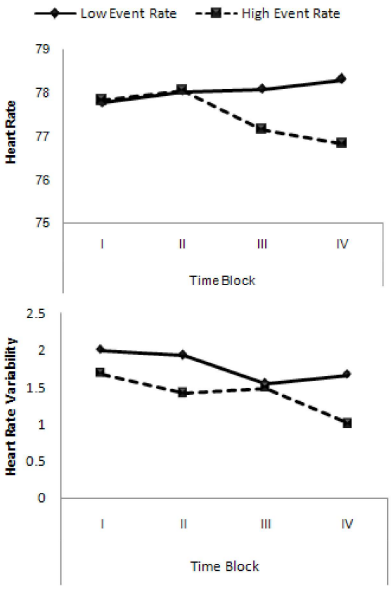

Figure 2. Heart rate and heart rate variability as a function of event rate and time block

Subjective Measures

Perceived measures i.e. mental workload was recorded for each participant through administering NASA-TLX at pre and post vigilance task session. The data on NASA-TLX measure was submitted to 2 (event rate) x 2 (session) x 6 (scale) ANOVA with session and scale as within-subject factor, and event rate as between-subject factor.

The main effect of the session was found to be significant, $F_{(1, 38)} = 78.802$, $p < .001$, $\eta_p^2 = .677$, it suggests that all the six sub-scales showed an increase in workload after completion

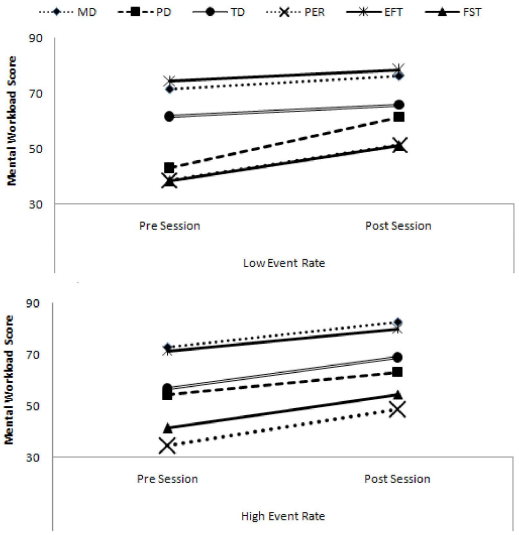

Figure 3. Mental workload as a function of event rate, task session, and subscale.

Note. MD = Mental demand, PD = Physical demand, TD = Temporal demand, PER = Performance, EFT = Effort, FST = Frustration.

of the 40-minutes vigilance task. The main effect of the subscale, $F_{(5, 310)} = 35.67$, $p < .001$, $\eta_p^2 = .365$, was also found to be significant indicating that the six subscales contributed differently towards the perceived mental workload. Figure 3 indicates that among the six subscales effort (LER: *M* = 76.38, *SD* = 14.73; HER: *M* = 75.5, *SD* = 19.51) and mental demand (LER: *M* = 73.88,

SD = 15.75; HER: *M* = 77.63, *SD*: 19.26) were rated as high contributors to mental workload followed by temporal demand (LER: *M* = 63.63, *SD* = 24.64; HER: *M* = 62.75, *SD* = 16.90) and physical demand (LER: *M* = 52.13, *SD* = 23.11; HER: *M* = 58.63, *SD* = 23.55). However, scores on frustration and performance scales fell below the middle range of the scale. The main effect of event rate ($F_{(1, 38)}$ = .158, *p* = .694) and other interaction effects (p >.05) were not found to be significant.

Discussion

The purpose of the study was to elucidate the effects of the background event rate and time block on performance efficiency, physiological indices and dimensions of perceived mental workload accompanying vigilance performance. Successful vigilance requires maintenance of alertness on long monotonous task, though with increase in time, performance efficiency usually drops. There are two paradigms that explain this decrement during vigilance; the first argues that the vigilance decrement arises from the subjects' inattention or mindlessness or out of boredom, while the latter states that decrement occurs due to the high demand placed and higher information processing resources needed by the vigilance task.

Results on the behavioural performance indicated that overall accuracy was better under low event rate condition. This finding is consistent with the first hypothesis of the present study and is similar with previous researches as well (Galinsky et al., 1993; Parasuraman & Giambra, 1991; Tiwari et al., 2009; Yadav et al., 2015). These studies confirmed that the quality of vigilance performance is inversely related to the rate of presentation of stimulus events. Nevertheless, the reaction time performance showed different trend as reaction times for correct responses were faster in high event rate condition. This finding was similar to Siraj (2007) who reported reverse effect of event rate on performance. However, better performance in terms of reaction time under high cognitive demand condition was due to observer's perception of time available to detect the signal, as time to respond was least in high (900 ms) than low (1900 ms) event rate condition. The participants became familiar and adjusted their response timing according to the time available for detection of the target as the experiment progressed.

The main effect of time on task was clearly visible on both behavioural and physiological measures. Accuracy rate decreased with time during vigilance task while for reaction time, maximum decrement was observed during time block II to III. These findings are consistent with previous researches which showed decrement function (Helton et al., 2000; Helton et al., 2007; Nuechterlein, Parasuraman, & Jiang, 1983; Temple et al., 2000). Heart rate showed different patterns across event rates. Heart rate decreased under high event rate and increased under low event rate condition even though previous researches showed a decline in heart rate (Griew et al., 1963; Jeroski et al., 2014; Stroh, 1969; Thackray et al., 1974) during vigilance task. Thus, the heart rate trend found in high event rate showed a pattern, which was consistent to previous findings. Heart rate variability decreased with time while previous findings (Kibler, 1968; Jeroski et al., 2014; O'Hanlon, 1970; O'Hanlon, 1971; Thackray et al., 1974) showed an increment in HRV with time on task. Thus, the findings not just affirm the second hypothesis but also provide a background for further researches to study time on task effect on different behavioural and physiological measures.

Further, on each subscale workload score increased from pre to post task sessions irrespective of the event rate conditions signifying that the participants felt greater workload after completion of the vigil task. However, increment in workload was similar in both high and low event rate conditions. Mental demand and Effort were emerged as prime contributors in perceived workload suggesting that 40-minutes vigilance task imposed greater mental demand and participants exerted greater effort to accomplish the task requirement. Previous researchers found that the global workload scores in vigilance typically fall in the middle to upper range of the scale, with mental demand and frustration scales reflecting the principal workload components (see Szalma et al., 2004). Moreover, Dember et al. (1993) demonstrated that the decline

in performance efficiency, typical of vigilance tasks, is accompanied by a linear rise in global workload over the course of vigil task. In the present study successive discrimination task was used which is an absolute judgment task that requires observers to compare current stimulus with a standard stimulus/response pattern retained in working memory to separate critical signals from non-signal events. Because of the memory imperative, successive tasks are more capacity demanding (Warm et al., 2008). Therefore, findings of the present study for perceived workload has been found compatible to the earlier studies as well as third hypothesis of the present study.

Conclusion

It may be concluded from the findings of this study that correct responses were comparatively higher in low event rate condition. It placed relatively lesser demand on the participants, which resulted in higher accuracy. Maintaining vigilance for 40-minutes seems to be an effortful task, which resulted in deterioration of performance as well as mounting of perceived mental workload. Nonetheless, the perceived workload was similar across two event rate conditions. Findings on physiological measures were inconsistent with previous researches. Parasuraman and Davies (1977) defined rates of 24 events per minute or greater as high, and rates under 24 as low. In the present study 24 event/minute was considered as low event rate and 40 event/minute as high event rate. Thus, wide range of event rates might be helpful to examine the workload associated with concentrated attention during vigilance task, and hence, would be beneficial to find evidences for overload or underload view of vigilance decrement.

The present study has many implications as increasing automation in technology and potential risks involved with it have aggravated researchers to investigate the vigilance phenomenon in various perspectives. It is notably imperative to pay cautious consideration on demand factors while designing systems and work surroundings which involve maintenance of attention for longer duration. Findings of this study proposed that by constructing relatively low demanding work conditions and systems, organization can obtain optimal performance from their employees. These findings may be implemented to work settings which involve vigilance functions such as industrial settings, medical settings and baggage inspection at airports and railway stations etc.

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