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EFFECTS OF SIGNAL SALIENCE AND CUEING ON CEREBRAL BLOOD FLOW VELOCITY DURING SUSTAINED ATTENTION

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ABSTRACT

Transcranial Doppler sonography, a low-cost noninvasive procedure, which allows continuous monitoring of blood flow in the left and right middle cerebral arteries, was employed while participants performed a 40-min vigil. Two levels of signal salience (high and low) were combined factorially with four conditions in which monitors were forewarned about the imminent arrival of critical signals (100 %, 80%, and 40% reliable cueing and a no-cue control). For both levels of signal salience, the frequency of signal detections remained stable over time in the 100% cue-reliability condition but declined over time in the remaining cue conditions, so that by the end of the vigil, performance efficiency was best in the 100% condition followed in order by the 80%, 40%, and no-cue conditions. These performance effects for cueing were *mirrored* by blood flow measurements taken from the right hemisphere in conjunction with low salience signals. No effects for cueing were observable in blood flow recordings taken from the left hemisphere in conjunction with either high or low salience signals. The results indicate that blood flow and signal detection in vigilance are at least partially related to common mechanisms, such as the expenditure of information processing resources. They are also consistent with past findings indicating that vigilance performance is right lateralized.

TABLE OF CONTENTS

ABSTRACT.....	Page vi
LIST OF TABLES.....	iv
LIST OF FIGURES.....	v
CHAPTER 1	
General Introduction.....	1
Vigilance and Automation.....	1
Historical Origins.....	2
The Activation Hypothesis.....	4
Vigilance and Arousal.....	4
Pharmacological Support.....	5
Electrophysiological Support.....	7
Challenges to the Activation Hypothesis.....	9
Resource Theory and Arousal.....	12
The Habituation Model.....	14
An Inhibition Approach.....	14
Tests of the Habituation Model.....	14
Neuroimaging Techniques and Vigilance.....	16
Brain Systems in Sustained Attention.....	16
Brain Stem.....	17
Frontal Cortex.....	17
The Cingulate Gyrus.....	19
Functional Brain Imaging Limitations.....	20
CHAPTER 2	
The TCD Alternative.....	22
An Introduction to TCD.....	22
The Nature of the Technique.....	22
TCD Applications.....	23
The Mayleben Study.....	25
The Present Study.....	27
Signal Salience.....	27
Cueing.....	28
CHAPTER 3	
Participants.....	31
Design.....	31
Apparatus and Procedure.....	31

Cerebral Blood Flow Measurement.....	36
CHAPTER 4	
Results.....	38
Vigilance Performance.....	38
Detection Probability.....	38
False Alarm Probability.....	40
Cerebral Hemovelocity.....	41
Basic Control Issues.....	41
Hemovelocities During Active Vigilance.....	44
Energetic Arousal.....	48
Standard Scores.....	48
Pre-Post Comparisons.....	49
CHAPTER 5	
Discussion.....	52
REFERENCES.....	60
APPENDIX A: Instruction sets for the vigilance tasks.....	83
APPENDIX B: Detailed summaries of all ANOVA tables.....	89
B1. Analysis of Variance for Correct Detection scores.....	90
B2. Analysis of Variance for False Alarm scores.....	90
B3. Analysis of Variance for Cerebral Hemovelocity in Left and Right Hemispheres.....	91
B4. Analysis of Variance for Cerebral Hemovelocity for Passive Observer group.....	91
B5. Analysis of Variance for Cerebral Hemovelocity during Active Vigilance.....	92
B6. Analysis of Variance for Cerebral Hemovelocity within High Salience.....	92
B7. Analysis of Variance for Cerebral Hemovelocity within Low Salience.....	93
B8. Analysis of Variance for Cerebral Hemovelocity for Left Hemisphere/Low Salience.....	93

B9. Analysis of Variance for Cerebral Hemovelocity for Right Hemisphere/Low Salience.....	93
B10. Analysis of Variance for DSSQ Energetic Arousal scores.....	94
B11. Analysis of Variance for Pre-vigil DSSQ Energetic Arousal scores.....	94
B12. Analysis of Variance for Post-vigil DSSQ Energetic Arousal scores.....	94

LIST OF TABLES

Table	Page
1. Mean percentages of correct detections for the several cueing groups in each period of watch for both the high and low salience conditions. Standard errors are in parenthesis.....	39
2. Mean percentages of false alarms for the several cueing groups in each period of watch for both the high and low salience conditions. Standard errors are in parenthesis.....	41
3. Mean cerebral hemovelocities (in cm/sec) at baseline under all combinations of cueing and signal salience in the left and right MCA's. Standard errors are in parenthesis.....	42
4. Mean hemovelocitv scores in the left and right MCA's for all Combinations of signal salience and cueing during each period of watch. Standard errors are in parenthesis.....	45
5. Mean pre-vigil and post-vigil scores on the Energetic Arousal Scale for All combinations of salience and cueing. Standard errors are in parenthesis.....	39

LIST OF FIGURES

Figure	Page
1. Examples of all possible neutral and critical signals.....	32
2. Percentages of correct detections as a function of periods of watch for the four cueing groups.....	40
3. Passive observers' hemovelocity scores for high and low contrast stimuli as a function of time on task. Data for the left and right cerebral hemisphere are presented separately in each panel.....	44
4. Hemovelocity scores as a function of periods of watch for the four cue-level groups. Data are from the right hemisphere/low salience condition.....	47
5. Mean Energetic Arousal z-scores, collapsed across hemisphere and salience, for the pre-task and post-task scores within each of the cue-level groups.....	50

ABSTRACT

A recent comprehensive review by Parasuraman, Warm, & See (1998) has indicated that brain imaging studies utilizing positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) techniques have led to the identification of several brain systems that are activated during the performance of sustained attention or vigilance tasks. These systems are located in the nucleus locus coeruleus, the brainstem reticular formation, the midbrain tegmentum, the right intralaminar region of the thalamus, the cingulate gyrus and the right frontal lobe. However, as Parasuraman, Warm, and See (1998) have emphasized, an important limitation of these studies is their failure to relate the brain systems they have identified to performance efficiency, perhaps because of the high cost and restrictive environments associated with the PET and fMRI techniques. As a result, the question of the functional role of these brain systems in vigilance remains generally unanswered.

To date, only two experiments have addressed this issue. In one of them, Paus, et al. (1997) reported that the vigilance decrement-- the decline in performance efficiency over time which characterizes vigilance performance (Warm, 1984)-- was accompanied by PET measured declines in blood flow (CBF) in several subcortical structures and in the orbital frontal cortex. In the other study, Mayleben (1999) attempted to circumvent the cost and restrictive environment limitations that accompany PET and fMRI measurements by using transcranial Doppler sonography (TCD)-- a relatively inexpensive and noninvasive procedure which allows continuous monitoring of CBF in the main-stem intracranial arteries. The procedure features good temporal resolution while placing participants under less restrictive conditions than PET or fMRI measurement (Aaslid, 1986). Mayleben confirmed the Paus, et al. (1997) finding that the vigilance decrement is accompanied by a decline in blood flow over time. In addition, he also

found that the absolute level and temporal course of blood flow was tied to the capacity demands of the vigilance tasks that he employed. Specifically, a successive or absolute judgment task which had been shown previously to impose a higher level of information processing than a simultaneous or comparative judgment task (Warm & Dember, 1998) was associated with an elevated level of blood flow in comparison to the simultaneous task and a steeper decline in blood flow over time.

Mayleben (1999) accounted for his results within the framework of a resource utilization model proposed by Parasuraman and his associates in which a limited-capacity information-processing system allocates resources to cope with situations which confront it (Parasuraman & Davies, 1977; Parasuraman, Warm, & Dember, 1987). Within that view, demanding tasks consume more processing resources than their less demanding counterparts and the vigilance decrement reflects the depletion of information processing resources that cannot be replenished in the time available. Mayleben suggested that brain blood flow reflects the availability and/or utilization of information processing assets. Hence, the higher level of blood flow and the greater blood flow decrement over time for the successive as compared to the simultaneous task. The present study is designed to extend this line of investigation by examining two other vigilance parameters that can be linked conceptually to the resource utilization model -- signal salience and cueing. A key finding in vigilance experiments is that the accuracy of signal detection increases as the salience (signal-to-noise ratio) of critical signals increases while the magnitude of the vigilance decrement decreases with signal salience (Warm & Jerison, 1984). Within the Parasuraman resource model, it seems reasonable to assume that more processing resources would need to be dedicated to the detection of low salience as compared to high salience signals.

Accordingly, it was anticipated that as in the case of the Mayleben (1999) experiment, the more demanding condition (low signal salience) would be associated with elevated blood flow levels and a more pronounced blood flow decrement over time in comparison to a less demanding condition (high signal salience). Cueing refers to a situation in which observers are forewarned about the imminent arrival of critical signals for detection. Such forewarning, when perfectly reliable, results in a high level of signal detection and the absence of a vigilance decrement (Hitchcock, Moroney, See, Dember, & Warm, in press). Within the resource model, Hitchcock and his associates have shown that reliable cueing reduces the observing/decision making demand placed upon observers over time. Consequently, it was expected that in the presence of reliable cueing, the temporal decrement in blood flow would be attenuated in comparison to a non-cued control condition and also in comparison to conditions in which cueing was less than perfectly reliable, since in such conditions monitors would not be relieved of the need to attend to the vigilance display continuously.

Two levels of signal salience (high and low) were combined factorially with four cueing conditions (no cueing, 100%, 80% and 40% reliable cueing to produce eight experimental conditions. Sixteen observers (equated for sex) were assigned at random to each condition. All observers participated in a 40-min vigil during which they monitored a simulated air-traffic control display (presented on VDT) for aircraft appearing on a collision course (the display was updated 30 times/min; critical signal probability = .03 in each of four continuous 10-min periods of watch). The Michelson contrast ratio of the aircraft to their surrounding background was .90 in the high salience condition and .40 in the low salience condition. Observers were forewarned of the arrival of a critical signal by a male voice announcing “look” which indicated that a critical signal would appear within the next five display updates. Observers in the 100% cueing

condition were informed that critical signals would always be forewarned, and never occur at any other time. Those in the 80% and 40% cueing conditions were informed the forewarning is only reliable 80% or 40% of the time and that signals may also occur outside of the “cued widow.” (less than 1% of the time in 80% condition and 1-5% of the time in the 40% condition). TCD-determined hemovelocities in the left and right middle cerebral arteries (MCA’s) were measured during a 5-minute baseline rest period and throughout the sustained attention task. Half the participants (equated for sex) in each combination of signal salience and cueing had measurements taken from the left MCA and half from the right MCA. An important element in a study of this sort is the need to show that time-based declines in blood flow are indeed task-linked. Toward that end, hemovelocity measures collected on 16 observers indicates that blood flow remains stable at a baseline level when observers simply look at the display without an information processing imperative.

The results revealed that while the concordance between these hemovelocity scores and performance was not perfect, they overlapped considerably in terms of the effects of cueing over time. For both measures, similar differences among the cue conditions emerged with time on task. Thus, the results indicate that blood flow and signal detection in vigilance are at least partially related to common mechanisms.

The finding that the co-ordination between bloodflow and signal detection in the cue/time relation was restricted to hemovelocity recordings taken from the right hemisphere with low discriminability (low salience) signals has two important implications for an understanding of brain systems in vigilance. To the extent that low signal salience and non-existent or unreliable cueing increase the observing/decision making demands placed upon observers in vigilance tasks, the results of this study support Mayleben’s (1998) suggestion that the common

mechanism underlying bloodflow and signal detection may be information processing resource utilization, i.e., blood flow may serve as a metabolic index of the expenditure of such resources. The finding that the crucial Cue x Time interaction was restricted to the right hemisphere (and also the finding that blood flow was significantly higher in the right as compared to the left hemisphere) provides converging evidence for the claim, based upon the results of earlier PET, hemovelocity, and psychophysical studies, that vigilance performance is controlled to a considerable extent by the right cerebral hemisphere (Mayleben, 1998; Warm, Richter, Sprague, Porter, & Schumsky, 1980; Parasuraman, et al., 1998).

CHAPTER 1

General Introduction

Vigilance and Automation. Vigilance or sustained attention concerns the ability of observers to detect transient and infrequent signals over prolonged periods of time (Davies & Parasuraman, 1982; Warm, 1977; 1984; 1993). This aspect of human performance is of considerable concern to human factors and ergonomics specialists because of the vital role it plays in automated human-machine systems (Davies & Parasuraman, 1982; Gopher & Kimchi, 1989; Howell, 1993; Parasuraman, 1986; Parasuraman, Warm, & Dember, 1987; Proctor & VanZandt, 1994; Warm, 1984; 1993; Wickens, Gordon, & Liu, 1998). As described by Sheridan (1970; 1987) and by Warm and Dember (1998), the expanded use of automation in our technological society has altered the role of the human operator in many work settings from that of an active, hands-on controller to that of a monitor-executive, who must attend to displays and take action only in the event of imminent problems. Thus, operator vigilance is a vital aspect of system function in a variety of activities, including air-traffic control and cockpit resource management, seaboard navigation, military surveillance, nuclear power plant monitoring, and industrial process and quality control (Satchell, 1993; Warm, 1984; 1993; Wickens, 1992). Vigilance is also a critical element of performance efficiency in many medical settings such as cytological screening and prodromal symptom monitoring, as well as the inspection of anesthesia gauges during surgery (Daly & Wilson, 1993; Gill, 1996; Loeb, 1994; Paget, Lambert, & Sridhar, 1981; Weinger & Englund, 1990).

One of the presumed benefits of automation in the workplace is a reduction in the information-processing load placed on operators. It has been shown, however, that many types of accidents can frequently be attributed to an over-reliance on automated control systems (Molloy & Parasuraman, 1996), a condition which Satchel (1993) has described as the “peripheralization

of operators.” As a result, operators are less likely to track system status over time and to intervene in a beneficial manner. As Parasuraman (1986) has pointed out, even in instances of full automation, the demands of sustained attention cannot be entirely circumvented, since people may ultimately be needed to serve in a “fail-safe” capacity in the event of system malfunction. Hence, knowledge of the factors that control vigilance performance and the mechanisms that underlie it is critical for system integrity and public safety (Nickerson, 1992; Warm & Dember, 1998).

Historical origins. The term “vigilance” was first used in a technical sense by the British neurologist Sir Henry Head (1923), who employed it to refer to a state of maximum physiological or psychological readiness to react (Davies & Parasuraman, 1982; Warm, 1984). However, the systematic study of vigilance did not begin until 20 years later, prompted by an unanticipated and potentially perilous problem encountered by the Royal Air Force in its efforts to seek and destroy enemy submarines during World War II. A major technological innovation at that time was the use of radio detection and ranging (radar) in military surveillance or watch-keeping tasks. However, after only about 30 minutes on watch with this new equipment, airborne radar observers began to miss “blips” on their pulse-position displays indicating the presence of U-boats on the surface of the sea below. As a result, the U-boats were free to prey upon allied ships. In addition to the cost in lives and material, those detection failures were especially distressing because they occurred among individuals who were highly motivated to perform well and because they pointed to a serious deficiency with the human component of a newly developed technology for anti-submarine warfare (Warm, Dember, & Hancock, 1996).

In response to a request from the Royal Air Force to investigate the problem, Norman Mackworth (1948; 1950/61) devised a simulated radar display known as the “Clock Test,” in

which observers were asked to view the movements of a black pointer along the circumference of a blank-faced clock devoid of any scale markings or reference points. Normally, the pointer would move 0.3 inches to a new position once every second. From time to time, it would execute a “double jump” of 0.6 inches -- the critical signal for detection. In Mackworth’s experiments, *as in most that have followed*, observers were tested individually; the task was prolonged and continuous, in Mackworth’s case lasting for two hours; critical signals were clearly perceivable when observers were alerted to them, but were not compelling changes in the observer’s operating environment; the signals appeared in a temporally unpredictable manner with low probability of occurrence (signals occurred approximately 3 to 5 per cent of the time); and the observers had no control over the occurrence of signals.

Using the Clock Test in this way, Mackworth was able to trace the course of vigilance performance over time and to confirm in the laboratory the suspicion generated in the field that the quality of sustained attention is fragile; it wanes rapidly with time on task. He found that the frequency of operators’ detections declined by as much as 10 percent within the first 30 minutes of watch and continued to drop off thereafter, though at a more gradual rate. This decline in efficiency, known as the *vigilance decrement* or the *decrement function*, has been confirmed repeatedly in subsequent investigations and is the most ubiquitous aspect of vigilance performance (Davies & Parasuraman, 1982; See, Howe, Warm, & Dember, 1995; Warm, 1984, 1993). In general, the decrement is often complete within 20 to 35 minutes after the start of the vigil, with at least half of the final loss typically completed within the first 15 minutes (Teichner, 1974). Under especially demanding circumstances, where the signals to be detected are of extremely low salience, the vigilance decrement can even be observed within the first five minutes of the watch (Jerison, 1963; Neuchterline, Parasuraman, & Jiang, 1983; Temple et al., in

press). The decrement occurs in experienced monitors, such as those employed in Mackworth's experiments, as well as in inexperienced monitors, and it is not limited to controlled laboratory settings; it has also been found in actual operational environments (Baker, 1962; Colquhoun, 1967; 1977; Pigeua, Angus, O'Niell, & Mock, 1995; Schmidke, 1976). As Dember and Warm (1979) have noted, the performance decrement seems to result merely from the need to look or listen for relatively infrequent signals over a long period of time.

The Activation Hypothesis

Vigilance and Arousal. One approach to attacking experimentally the mechanisms which underlie vigilance performance, *and the approach featured in this investigation*, is to explore their neurobiological bases (Parasuraman, Warm, & See, 1998). Along this line, examination of the typical vigilance paradigm (see above) has led to the inference that vigilance tasks represent tedious and under-stimulating situations in which the level of workload is exceptionally low. This view has been the foundation for the well-known arousal or activation model of vigilance, which accounts for the decrement function as stemming from a lack of stimulation necessary for alertness. According to the activation model, elements of the central nervous system require a varied perceptual environment in order to maintain a level of general excitation and wakefulness adequate for efficient performance. When stimulus variability falls below a critical level, wakefulness and alertness are reduced. Thus, the activation hypothesis maintains that the repetitious and monotonous aspects of vigilance tasks suppress the nonspecific brain activity needed for continued alertness. This results in a reduced responsiveness to stimulation, which in turn, leads to a decline in the efficiency of signal detection (Aston-Jones, 1988; Craig, 1985; Dember & Warm, 1979; Frankmann & Adams, 1962; Heilman, 1995; Loeb & Alluisi, 1977; 1984; Proctor & Van Zandt, 1994; Welford, 1968).

Early versions of the activation hypothesis (cf. Frankmann & Adams, 1962) considered arousal to be mediated principally by the ascending reticular formation (ARAS), a network of neurons stretching from the diencephalon to the hindbrain (Kolb & Whishaw, 1990). This view was based upon the classic studies of Lindsley (1960) and Moruzzi and Magoun (1949) showing that lesions of the ARAS produced coma and the absence of electroencephalographic (EEG) desynchronization to stimuli, and that behavioral activation could be triggered by electrical stimulation of the ARAS. Over the years, however, the unidimensional nature of the arousal concept has been questioned seriously (Lacey, 1967; Loeb & Alluisi, 1984), and recent work has demonstrated that brain arousal systems are composed of many subsystems that differ considerably in their neurophysiological characteristics (Marroco & Davidson, 1998). At least four main projection systems have been identified as playing functional roles in arousal and attention. These include the cholinergic basal forebrain, the noradrenergic nucleus locus ceruleus (LC), the dopaminergic median forebrain bundle, and the serotonergic dorsal raphe nucleus (Parasuraman, Warm, & See, 1998).

Pharmacological Support. Several pharmacological studies conducted with animal and human observers have contributed to the view that the cholinergic system plays an important role in attention and arousal processes (Robbins & Everett, 1995; Sarter, 1994; Warburton, 1977). For example, Sarter and colleagues demonstrated that administration of the benzodiazepine agonist chlordiazepoxide (CDP; an agent with sedative properties) impaired performance in rats during a long-duration vigilance task (McGaughy & Sarter, 1995; Moore, Dudchenko, Bruno, & Sarter, 1992). Moreover, when infused directly into the basal forebrain, CDP blocks the cortical release of acetylcholine (Moore, Sarter, & Bruno, 1993). This finding led McGaughy and Sarter

(1995) to conclude that the impairment of vigilance performance is closely tied to GABAergic modulation of cortical acetylcholine release.

Neurophysiological studies in animals have also suggested an influential role of the noradrenergic system in cortical arousal (Aston-Jones, Rajkowski, Kubiak, & Alexinsky, 1994). Activation of LC cells in awake monkeys and rats results in a widespread release of norepinephrine to cortical targets, and LC cellular activity is also elevated during periods of behavioral alertness (Aston-Jones, Chiang, & Alexinsky, 1991). Further, as noted by Parasuraman, Warm, and See (1998), LC discharge is associated with electroencephalographic (EEG) desynchronization and reduction in EEG amplitude, both of which are correlated with increased behavioral arousal. In a study designed to assess the role of noradrenaline in human sustained attention, Smith and Nutt (1996) reported that the drug clonidine, an α -2 adrenoreceptor agonist, which reduces the release of norepinephrine, increased the number of very long reaction times in a vigilance task and that this effect could be reversed by idazoxan, a drug that acts to increase levels of noradrenaline. Findings such as these help support the role of noradrenaline in human sustained attention.

In addition to studies focusing upon specific neurotransmitters, the results of a wide range of investigations showing that stimulants such as amphetamine and caffeine improve vigilance performance, while depressants such as alcohol, chlorpromazine, hyoscine, and scopolamine impair performance, are consistent with the activation hypothesis (Davies & Parasuraman, 1982; Loeb & Alluisi, 1984; Rohrbaugh, Stapleton, Parasuraman, Frowein, Eckardt, & Linnoila, 1987; Temple et al., in press; Wesnes & Reville, 1984).

Electrophysiological Support. In addition to the pharmacological investigations described above, further support for the activation hypothesis comes from studies which have made use of

global brain wave patterns in the electroencephalogram (EEG) and event-related brain potentials (ERPs). Electroencephalography is a widely accepted method for recording central nervous system (CNS) activity (Kolb & Whishaw, 1990). While providing a continuous account of changes in global brain wave patterns, the EEG technique is also sensitive to transitions between various states of arousal (Lindsley, 1951). Generally, as individuals move from a state of wakefulness toward deepening stages of sleep, their brain waves decrease in frequency and increase in amplitude (Carlson, 1991). During normal-waking alert behavior, EEG beta waves (13-24 Hz) tend to dominate, while relaxed wakefulness is characterized by alpha (8-12 Hz) activity. Theta wave (4-7 HZ) activity begins to appear during light sleep (dozing), while deep sleep is associated with delta waves (1-3 HZ).

Electrocortical studies of vigilance have revealed a close link between performance efficiency and EEG activity, in which brain waves shift to lower frequency bands as the overall level of performance declines over the course of the vigil (Daniel, 1967; Davies & Krkovic, 1965; Eason, Beardshall, & Jaffee, 1965; Fernandez-Guardiola, Ayala & Kornhauser, 1968; Gale, 1977; Gale, Haslum & Lukcas, 1972; O'Hanlon & Beatty, 1977; Wilkinson, Morelock, & Williams, 1966). For example, O'Hanlon and Beatty (1977) observed a reduction in the presence of the EEG beta waves and an increase in the abundance of EEG theta activity while performance efficiency declined during a two-hour simulated radar task. This shift from high frequency EEG beta activity to the lower but still-waking frequencies during the vigil was correlated significantly with the decline in performance. Similar results were reported by Horvath, Frantik, Kopriva, and Meissner (1975), who observed that an increase in theta activity coincided with the onset of the performance decrement. They also noticed that observers consistently failed to detect critical signals when theta wave activity was present during

performance of a sustained attention task. In addition, Beatty, Greenberg, Deibler, and O'Hanlon (1974) reported that suppression of theta activity by operant methods enhances monitoring efficiency.

More recent studies carried out by Makeig and associates (Makeig & Inlow, 1993; Makeig & Jung, 1995) further substantiate the relation between EEG activity and vigilance performance. Utilizing a quantitative analysis of EEG signals employing fast Fourier transform methods termed power spectrum analysis (Basar, 1980), these investigators described the micro-structural changes in EEG recordings during vigilance. They found that the EEG power spectra were associated closely with performance error (i.e., the percentage of undetected critical signals) during both auditory and visual vigilance tasks. In these studies, increases in error rate were accompanied by increased power in the delta and theta wave bands (lower EEG frequencies), and there was a shift from higher to lower EEG frequency bands that paralleled the decline in performance over time.

Unlike the more global brain wave patterns just described, event related potentials (ERPs) are relatively small changes within the EEG waveform that are contingent upon the occurrence of some external or internal event (Luck & Girelli, 1998; Nunez, 1990). Different components within ERPs are defined by their positive or negative polarity (peaks or troughs) and their latency of occurrence. The measurement of ERPs permits the separation of evoked responses to external stimulation or internal cognitive events from the background of continuous spontaneous electrical activity of the brain in the EEG record (Luck & Girelli, 1998). In one of the first ERP studies of vigilance, Haider, Spong, and Lindsley (1964) found that the principal negative ERP component (N1) decreased in amplitude over time during a visual vigilance task and that this component was smaller for missed signals than for correct detections. These

findings were interpreted as indications of a reduction in cortical arousal with time on task. Similar findings were reported by Wilkinson, Morlock, and Williams (1966) using an auditory task. These investigators showed that the amplitude of the P200 component declined over the course of the vigil in a manner that paralleled the decline in performance efficiency. Wilkinson and his colleagues also postulated a causal relation between lowered electrocortical arousal and the decrement function.

Challenges to the Activation Hypothesis. Although early ERP studies supported the activation hypothesis, later experiments, which focused upon other components, such as the N200 and the P300, have challenged the activation view. These components were of interest because they have been linked to specific aspects of human information processing (Israel, Wickens, Chesney, & Donchin, 1980; Wickens, 1984). Consequently, as Parasuraman, Warm, & See (1998) have indicated, changes in these components during vigilance would point to local modifications in information-processing activity rather than a general decline in arousal.

In a comprehensive study, Davies and Parasuraman (1977) analyzed changes in four ERP components (N100, P200, N200 and P300) to signals and non-signals for all possible responses to stimulus events during a visual vigilance task (hits, misses, correct rejections and false alarms). While all four components declined in amplitude with time on task, only the longer latency (late appearing) ERP's, the N200 and the P300 waves were related to performance. The amplitude of these waves was greater for detected than for missed signals. Based upon their results, Davies and Parasuraman reasoned that rather than reflecting gross changes in arousal level, the later ERP components reflect voluntary changes in decision processes associated with signal detection over time. Other studies have also found that only late ERP components show amplitude and latency changes over time that parallel the vigilance decrement, a result which

runs counter to the notion of a general decline in arousal or alertness (Koelega, Verbaten, VanLeeuwen, Kenemans, Kemner, & Sjouw, 1992; Polich, 1987; Rohrbaugh, Stapleton, Parasuraman, Zubovic, Froein, Varner, Adinoff, Lane, & Linnoila, 1987). Moreover, even the findings described above relating EEG changes to performance cannot be considered as evidence for a direct association between arousal and the vigilance decrement. As noted in a careful review by Parasuraman (1984), a reduction in arousal over time can also occur under task conditions in which no decrement occurs, when observers perform other prolonged tasks, or when no task is performed for a comparable period of time.

Further challenges to the activation hypothesis come from experiments aimed at testing the arousal notion solely at the behavioral level. If, as described by the activation position, detection failures in vigilance result from declines in arousal brought about by lack of stimulation, increasing the amount of stimulation in a vigilance task should enhance performance efficiency. Consistent with that expectation, added sensory input in the form of mild exercise, low-frequency vibration, occasional whiffs of hedonically positive odors (Clementine, Muguet, Peppermint, Vanilla Bean), music, and variety audio stimulation (a sound track containing a mixture of audio excerpts from television programs, mechanical noises, and traffic sounds) has been found to increase the rate of signal detections (Davenport, 1974; Dember, Warm, & Parasuraman, 1995; Jones, Ruhl, Warm, & Dember, 1999; McGrath, 1963; Poulton, 1978; Zuercher, 1965). On the other hand, the sound track described above and a similar form of auxiliary stimulation using a sound track containing excerpts of baseball and news broadcasts, instrumental and vocal music, and dramatic presentations have also been found to degrade performance (Jones, 1971; McGrath, 1963), and the decrement has been found to be greater under extremely stimulating than under less stimulating conditions (Alluisi & Hall, 1963;

Broadbent & Gregory, 1963; Grubb, Warm, Dember, & Berch 1997; Miller, Warm, Dember, & Schumsky, 1998). Thus, tests of predictions about performance efficiency based upon the activation hypothesis have produced inconsistent results. As Dember and Warm (1979) have noted, such inconsistencies might be handled by arguing that detection efficiency is adversely affected by too little or too much arousal, i.e., by appealing to the Yerkes-Dodson law (Yerkes & Dodson, 1908), in which the relation between arousal and performance takes an inverted-U shaped function. Such an approach, however, will render the activation hypothesis incapable of being tested in a rigorous experimental manner, since the point at which some experimental manipulation will fall on the curve cannot be specified prior to the experiment.

In addition to performance itself, one might also test the implications of the activation hypothesis by measuring the perceived mental workload of vigilance tasks. On the basis of that model, it might be anticipated that such tasks would be associated with an exceptionally low level of workload. Quite the opposite is the case, however. Recent studies using the NASA Task Load Index (TLX, a well regarded instrument for the measurement of mental workload, Hart & Staveland, 1988; Nygren, 1991) have shown that the cost of mental operations in vigilance is substantial. In these studies, vigilance-based overall workload scores have consistently fallen at the upper end of the TLX scale, and the values were higher than those obtained in a wide range of other tasks such as memory search, choice reaction time, mental arithmetic, and grammatical reasoning. In addition, Mental Demand, Temporal Demand, and Frustration have been found consistently to be the principal determinants of workload (Deaton & Parasuraman, 1993; Dittmar, Warm, Dember, & Ricks, 1993; Hitchcock, Dember, Warm, Moroney, & See, 1999; Matthews 1997; Sawin & Scerbo, 1995; Scerbo, Greenwald, & Sawin, 1993; Temple, et al., in

press; Warm, Dember, & Hancock, 1996). A result of this sort is inconsistent with the view that vigilance tasks are understimulating.

Resource Theory and Arousal. It is evident that the classic arousal or activation model has generated a considerable amount of research on the neurobiological basis of vigilance performance. Pharmacological studies, studies using global EEG brain wave patterns (alpha and theta activity), and studies making use of auxiliary stimulation have provided data which implicate arousal as a factor in vigilance. However, data from studies involving late-appearing ERP components (N200, P300), as well as from those focusing on auxiliary stimulation, high levels of task demand, and the workload of sustained attention challenge the ability of arousal theory to adequately account for vigilant behavior. Therefore, despite intensive study, the precise role played by arousal is obscure at present. In this regard, it might be best to echo Parasuraman, Warm, and See's (1998) conclusion that arousal influences the overall level of vigilance but is not a causal factor in the vigilance decrement. Along this line, it would also appear that any account of the mechanism by which arousal influences performance cannot be anchored in the assumption that vigilance tasks produce a lack of stimulation necessary for alertness.

In order to clarify the picture, more recent studies have adopted a different approach to the role of arousal in vigilance which links arousal to attentional resource theory, a position which is widely used to characterize attention and information-processing (Gopher & Kimchi, 1989; Kahneman, 1973; Navon, 1984; Navon & Gopher, 1979; Norman, 1975; Pashler, 1998; Proctor & Van Zandt, 1994; Sanders, 1998; Wickens, 1984; 1987; 1992; Wickens, Gordon, & Liu, 1998). Resources have been conceptualized as reservoirs of energy that can be dedicated to information-processing tasks (Hirst & Kalmar, 1987). A unitary-resource approach views resources as being allocated to information processing in general, while a multiple-resource

approach considers them as task-specific (Kahneman, 1973; Sanders, 1998; Wickens, 1984). Parasuraman and his associates (Davies & Parasuraman, 1982; Parasuraman, 1979; Parasuraman & Davies, 1977; Parasuraman, Warm, & Dember, 1987; Warm & Dember, 1998) have adopted a unitary approach, proposing that because of the need to make continuous signal/noise discriminations under conditions of great uncertainty and little opportunity for situational control, vigilance tasks consume processing resources which are not replenished in the time available. As a result, performance declines with time on task. Within the resource theory approach, arousal can be viewed as the agent that is responsible for the production of resources (Humphreys & Revelle, 1984; Kahneman, 1973; Parasuraman, Warm, & See, 1998; Warm, Dember, & Hancock, 1996).

Support for a view of this sort comes from studies by Matthews and Davies and their associates (Matthews & Davies, 1998) featuring a self-report measure of arousal known as *energetic arousal* (alertness-sluggishness) that correlates with psychophysiological measures of autonomic activity under performance testing conditions (Thayer, 1978). The Matthews and Davies experiments have demonstrated that when confronted with psychophysical challenges that were designed to increase their information-processing load, observers in vigilance tasks who were high on energetic arousal fared better than those who were low on this measure. The hypothesis that energetic arousal is associated with attentional resource availability differs from traditional arousal theory in that facilitative effects of energy increase with attentional demands of the task, contrary to the Yerkes-Dodson Law. Consequently, energetic arousal may provide a meaningful bridge between the arousal and information-processing approaches toward an understanding of vigilance performance. As described in chapter 3, this bridge will be explored further in the present study.

The Habituation Model.

An inhibition approach. An alternative neurobiological approach to the psychology of vigilance is the habituation model proposed by Jane Mackworth (1968; 1969). Habituation refers to the waning of neural responsiveness due to repeated stimulation (Groves & Thompson, 1970). It is an active process of inhibition that is differentiated from fatigue by the phenomenon of dishabituation, the sudden reappearance of responsiveness following qualitative or quantitative changes in the pattern of stimulation (Sharpless & Jasper, 1956). Generally, the accumulation of habituation is considered to be a positive function of the frequency of stimulus presentation.

According to Mackworth, the repetitive stimulation of the continuous background events of the vigilance task serves to habituate the “alpha block,” an arousal response in which the alpha rhythm in the electrical activity of the brain is replaced by an activated desynchronized pattern of activity as a result of incoming stimulation. With the development of habituation, the observer’s ability to separate signals from noise is degraded, attending to the task becomes increasingly more difficult, and the observer’s performance suffers a decline over time. Moreover, the rate of habituation is usually a negatively accelerated function of the number of stimulus presentations per unit time, and the vigilance decrement often displays a similar time course. Additionally, it should be noted that many ERP components habituate over time (Näätänen, 1992; Parasuraman, Warm, & See, 1998).

Tests of the habituation model. Support for the habituation position comes from studies of individual differences which indicate that observers who demonstrate rapid habituation of the galvanic skin response, a measure whose strength over time parallels the vigilance decrement (Davies & Krovic, 1965; Milosevic, 1975), show a greater decrement than those who are slow to habituate (Crider & Augenbraun, 1975; Siddle, 1972). On the other hand, extensive reviews by

Gale (1977) and Parasuraman, Warm, & See (1998) indicate that for almost every neurophysiological study supporting the model, there is one that contradicts it, as exemplified in a study by Polich (1989), in which neural habituation was shown to be unrelated to performance efficiency.

In addition to neurophysiologically oriented studies, psychophysical tests have also failed to support the habituation model. In one such test, Krulewitz, Warm, and Wohl (1975) performed an experiment in which they suddenly increased or decreased the rate of cascade of background events in which critical signals were embedded-- the event rate-- during a vigil. According to the habituation view, any change in stimulus conditions produces dishabituation, which should result in improved performance. Shifts in event rate represent drastic changes in stimulation. Therefore, the habituation model leads to the expectation that such shifts should enhance the quality of sustained attention regardless of the direction of the shift. Contrary to expectation, observers who experienced a slow-to-fast shift (6 events/min to 21 events/min) performed more poorly than non-shifted controls at the fast event rate. Moreover, while the performance of observers who experienced a fast-to-slow shift (21 events/min to 6 events/min) eventually exceeded that of non-shifted controls at the slow event rate, it did so only after the shifted group had experienced the new event rate for 20 minutes. Such a result does not coincide with the expected time course of dishabituation, which is considerably more rapid than 20 minutes (Thompson & Spencer, 1966). Other performance tests of the model have focused upon Mackworth's (1968) point that the development of habituation can be arrested when the habituating stimulus occurs in an irregular manner. Accordingly, one might expect that the quality of sustained attention would be enhanced if the stimuli to be inspected for the possibility that they are critical signals occur irregularly or asynchronously in time instead of at regular intervals as is normally the case in vigilance

experiments (e.g., once every second as in the Clock Test described above). Contrary to predictions from the model, asynchronous event schedules have been found to suppress rather than augment signal detection in vigilance tasks (Richter, Senter, & Warm, 1981; Scerbo, Warm, Doettling, Parasuraman, & Fisk, 1987; Scerbo, Warm, & Fisk, 1987). Taken collectively, the weight of neurophysiological and psychophysical evidence suggests that the quality of vigilance performance cannot be accounted for in terms of the habituation of cortical responses to incoming stimuli.

Neuroimaging Techniques and Vigilance

Brain systems in sustained attention. As indicated above, early efforts to understand the neurophysiological foundations of vigilance performance based upon simple global systems such as arousal and habituation have not been successful. Consequently, more recent investigators have adopted the view that, like most perceptual and cognitive processes, vigilance may be mediated by multiple distinct brain systems rather than by a single overarching system (Posner & Raichle, 1993). In the search for such systems, neurophysiological studies have shifted from an emphasis on pharmacological and electrophysical approaches to the use of sophisticated brain-imaging techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI).

PET is an imaging technique that allows for the assessment of brain physiology and biochemistry, including cerebral blood flow, cerebral glucose metabolism, and blood-brain barrier permeability (Hoffman, Hanson, & Coleman, 1993). It is founded on the principle that blood supply and glucose metabolism are largely coupled within a given brain region (Corbetta, 1998; Sokoloff, 1977). As neuronal activity increases, there is an associated increase in blood flow, which delivers the oxygen and glucose required for CNS metabolic activity. In order to

create functional images of this activity, participants are typically infused intravenously with a radioactive glucose-based tracer that is metabolized by the brain. The resulting regional radioactivity is subsequently recorded by a special detector. The PET technique measures metabolic activity in various parts of the brain through changes in the concentration of the radioactive tracers, under the assumption that the most active brain regions at any given time will use the most glucose. Hence, the most radioactive concentrations will be in these active regions.

Functional MRI is non-invasive, compared to PET, since it does not require the use of ionizing radiation or the injection of tracer elements in order to study brain functions. Instead, fMRI uses radio frequency electromagnetic waves to detect changes in the magnetic property of oxygenated versus deoxygenated hemoglobin in order to determine changes in regional cerebral blood flow associated with neural activity (Haxby, Courtney, & Clark, 1998; Kolb & Wishaw, 1990). The sensitivity of PET and fMRI for localizing changes in brain function has enabled investigators to identify several brain regions that may be involved in vigilance (Seidman et al., 1998). These regions include the brain stem, the frontal lobe, and the cingulate gyrus.

Brain stem. Evidence supporting the role of the brain stem in vigilance comes from Kinomura, Larsson, Gulyas, and Roland (1996), who reported a PET study in which participants reacted to a short-duration signal detection task involving visual or somatosensory stimuli. Compared to an eyes-closed condition, performance on either task was associated with activation of the midbrain tegmentum and the right intralaminar region of the thalamus. These findings led Kinomura and associates to conclude that the brain stem and thalamic regions were involved in the control of vigilance.

Frontal cortex. The frontal lobes of the human brain comprise all the tissue anterior to the central sulcus and are believed to be responsible for a variety of “executive level” cognitive

functions (Kolb and Whishaw, 1990). Several brain-imaging studies have pointed to the activation of this area when observers are engaged in a vigilance task. For example, Cohen and associates (Cohen, Semple, Gross, Holcomb, Dowling, & Nordahl, 1988) used PET to examine changes in the prefrontal cortex while participants completed an auditory vigilance task. They found that when observers were engaged in the task, glucose metabolism in the right prefrontal cortex, but not the left, was 5% to 7% higher than resting baseline. A second experiment confirmed the earlier finding that vigilance was right lateralized and localized the increased cerebral activity during task performance to the middle prefrontal gyrus (Cohen, Semple, Gross, King, & Nordahl, 1992).

Additional evidence for the activation of frontal lobe structures during sustained attention comes from a study by Pardo, Fox, and Raichle (1991), who measured cerebral blood flow while subjects completed a somatosensory vigilance task and a visual vigilance task. In the former, participants focused their attention upon either their left or right great toe in order to detect and keep a running count of the number of brief pauses in a series of suprathreshold touches to the toe. In the latter, the same group of observers was required to detect and count decreases in the intensity of a dim, central-fixation mark. In both modalities, right prefrontal and superior parietal activation was observed during task performance, regardless of the laterality of the sensory input. The finding that vigilance task performance is associated with greater right versus left frontal lobe activation has been confirmed in other studies using the PET-measured blood flow and glucose metabolism (Berman & Weinberger, 1990; Buchsbaum, et al., 1990; Deutsch, Papanicolaou, Bourbon, & Eisenberg, 1987; Lewin, et al., 1996; Rivich & Gur, 1985).

The laterality effects, noted in the brain imaging studies, support the results of earlier psychophysical experiments that point to hemispheric specialization in vigilance. These studies

took advantage of the fact that the auditory system is crossed and that contralateral connections from the ear to the cortex are stronger and more efficient than ipsilateral connections (Casseday & Diamond, 1977; Doebling, 1972; Hellige, 1993; Murphy & Venables, 1970; Robinson & Solomon, 1974; Rosenzweig, 1951). Using this approach, Warm, Schumsky, and Hawley (1976) reported that response times to signal detections decreased as observers' temporal uncertainty as to when critical signals would appear decreased and that this effect was markedly stronger for stimuli delivered to the left ear/right hemisphere than for those presented to the right ear/left hemisphere. In a second study, also using auditory stimuli, Warm, Richter, Sprague, Porter, and Schumsky (1980) found that the vigilance decrement, specified as a rise in response time to signal detections over the course of the vigil, was limited to left ear/right hemisphere presentations. Converging psychophysical evidence for right hemisphere dominance in vigilance comes from a study by Davis (1988) in which observers were required to respond to secondary acoustic probes delivered to the right ear/ left hemisphere or the left ear/right hemisphere while they were engaged in a visual vigilance task. The study was based upon the expectation that if vigilance is lateralized, the hemisphere that is processing the vigilance task would have fewer resources available for probe detection than the contralateral hemisphere, and therefore, that probe detections would be slower in the ipsilateral hemisphere. Consistent with that expectation, Davis found that response times were greater for left ear/right hemisphere probes than for right ear/left hemisphere probes.

The cingulate gyrus. The anterior portion of the cingulate gyrus, an area located just above the corpus collosum, has also been implicated in vigilance using the PET technique. Unlike the brain stem and prefrontal cortex, this area has been associated with reduced activation while observers are engaged in a vigilance task (Cohen et al., 1988; 1992; Posner & Petersen,

1990). Posner and Petersen (1990) have postulated that the anterior cingulate gyrus may be involved in active target detection and in executive control functions, and that reduced activation of the anterior cingulate gyrus might be necessary to optimize performance in vigilance and other tasks in which targets occur infrequently.

Functional brain imaging limitations. Recent brain-imaging studies clearly suggest that, rather than a single structure/system, a network of brain regions is involved in vigilance. It is noteworthy, however, that while PET and fMRI have been successful in identifying brain regions that are active during vigilance, these technologies have generally not been used to relate the structures/systems that they have identified to the vigilance decrement or to the overall level of vigilance performance and they have not explored the way in which system activity is modified by task demands. Except for a recent study by Paus et al. (1997), in which the vigilance decrement was accompanied by PET-measured declines in blood flow in several subcortical structures and in the orbital frontal cortex, the question of the *functional* role of the metabolic changes in brain systems identified in the imaging studies remains largely unanswered. According to Parasuraman, Warm, and See (1998), the limited information available on the relation between brain mechanisms and performance efficiency, particularly as mediated by differential task demands, is a major shortcoming of the brain imaging approach to an understanding of the neurobiology of vigilance. Without such information, models of the neural mechanisms that underlie vigilance are merely speculative.

Several factors probably contribute to this drawback. First, the cost to purchase, run, and maintain PET and fMRI scanners is extremely high, and it could be financially prohibitive to tie up the necessary equipment for the prolonged running times characteristic of vigilance research. Moreover, most PET studies of vigilance have utilized 18-fluorodeoxyglucose (FDG), a radio-

tracer element with a decay time of nearly 2 hours which is too long to allow frequent sampling during prolonged vigilance tasks. Functional MRI measurement also provides challenges for studying vigilance performance. This technique requires that people remain almost motionless throughout the scanning procedure in order not to compromise the quality of the obtained brain images (Corbetta, 1998). However, Galinsky, Rosa, Warm, and Dember (1993) have shown that observers become quite restless and tend to “fidget” during the performance of a vigilance task, with the amount of motor activity increasing with time on task. Moreover, MRI acquisition is accompanied by loud noise, and noise is one of several environmental variables that have a negative impact on vigilance performance (Becker, Warm, Dember, & Hancock, 1995; Hancock, 1984). Accordingly, the conditions required for effective use of the fMRI technique may not provide a suitable environment for correlating changes in brain physiology with vigilance performance over a prolonged period of time. What is needed is an imaging technique that will avoid these shortcomings in order to help bridge the gap in our understanding of performance and brain systems in vigilance. One such technique is transcranial Doppler neurosonology (TCD). It is this technique that provides the basic methodological platform for the present investigation of neuroimaging and vigilance performance.

CHAPTER 2

The TCD Alternative

An Introduction to TCD

The nature of the technique. Transcranial Doppler neurosonology is a noninvasive neuroimaging technique that employs ultrasound signals to monitor cerebral blood flow velocity (hemovelocity) in the mainstem intracranial arteries (the middle, anterior, and posterior arteries; Aaslid, 1986; Aaslid, Markwalder, & Nornes, 1982; Caplan, 1990). These arteries are readily isonated through a cranial “transtemporal window” and exhibit discernable measurement characteristics that facilitate their identification (Aaslid, 1986). The TCD technique uses a small, low-frequency (2 MHz) probe positioned on the scalp in order to gauge arterial blood flow. The probe is placed just above the zygomatic arch along the temporal bone, a part of the skull that is functionally transparent to ultrasound. The low weight and small size of the TCD probe permits real-time measurement of cerebral blood flow while not limiting, or becoming hampered by, body motion. Therefore, TCD enables inexpensive, continuous, and prolonged monitoring of cerebral blood flow activity concurrent with task performance.

Blood flow velocities, measured in centimeters/second, are typically highest in the middle cerebral artery (MCA). Velocities in the anterior cerebral artery (ACA) are slightly lower than those in the MCA, but in turn are higher than the posterior cerebral artery (PCA), which exhibits the slowest flow rate of the three major cerebral arteries (Sorteberg, Langmoen, Lindegaard, & Nornes, 1990). The MCA carries about 80% of the blood flow within each cerebral hemisphere (Toole, 1984). When a particular area of the brain becomes metabolically active, as in the performance of mental tasks, by-products of this activity such as carbon dioxide (CO₂) increase. This increase in CO₂ leads to a dilation of blood vessels serving that area, which,

in turn, results in an increase in blood flow to the region (Aaslid, 1986; Hellige, 1993; Risberg, 1986). Consequently, TCD offers the possibility of measuring changes in metabolic resources during task performance.

The use of TCD in brain imaging/performance applications is limited, in part, by its low spatial resolution. TCD can only supply gross hemispheric data; it does not provide information about changes in blood flow activity in specific brain loci, as is the case with PET and fMRI. Nevertheless, TCD offers good temporal resolution, and, compared to PET and fMRI, it can track rapid changes in brain blood flow dynamics that can be followed in real time under less restrictive and invasive conditions. Accordingly, the TCD technique is suitable to study changes in cerebral blood flow velocity that may occur during task performance.

TCD Applications. The primary medical application of TCD technology has been neurological diagnosis and screening for the presence of intracranial cerebral vascular dysfunction (Bishop, Powell, Rutt, & Browse (1986). Recently, however, it has begun to be used to assess the influence of cognitively demanding tasks on cerebral hemovelocity. In experiments of this sort, blood flow is typically sampled in the middle cerebral artery (MCA) while individuals are task engaged. The corresponding velocity values are then compared to a pre-task resting baseline. Several studies have demonstrated that the blood flow velocity in the MCA can be influenced by a variety of tasks such as reading aloud, listening to music, associating words, remembering a set of letters, making ethical decisions, and solving mathematical problems (Markus & Boland, 1992; Njemanze, 1991; O'Dell, Roberts, & McKinney, 1992; Schmelzeis, Roberts, and McKinney 1994). In general, these cognitive activities briefly accelerate blood flow velocity over resting baseline. Additionally, TCD-measured changes in cerebral hemovelocity have also been shown to covary with the information-processing demand of the tasks involved.

In a series of studies, Droste, Harders, and Rastogi (1989a; 1989b) used TCD to record blood flow velocities in the left and right MCAs during the performance of six 90-sec tasks: reading aloud, dot/distance estimation, noun finding, spatial perception, multiplication, and face recognition. Relative to baseline, all tasks were shown to increase MCA blood flow velocity bilaterally by 1.6% to 10.6%. The largest increase was observed when participants were required to read abstract four-syllable nouns aloud while the smallest velocity changes were observed while participants completed simple multiplication tasks. These investigators also measured MCA blood flow velocities during silent and spoken performances of three cognitive tasks: reading abstract nouns, finding nouns beginning with a certain letter from a list of nouns, and multiplication. Blood flow velocities during each task increased bilaterally over baseline; however, the spoken performances associated with the reading task produced significantly faster velocities than did silent performance of the task.

As in the case of PET and fMRI, TCD measures have also been successful in identifying cerebral laterality differences in task performance. In one experiment, Harders, Laborde, Drost, & Restogi (1989) used the left and right MCA's to measure hemovelocity changes in both hemispheres while participants performed tasks involving spatial imaging and face recognition. As in the studies described above, the performance of these tasks increased blood flow velocity over a resting baseline. However, the increase was lateralized -- it was found in the right but not the left MCA. In a related study in which participants were required to sort mahjong tiles into Chinese characters, circles, or lines, Kelley, Chang, Suzuki, Levin, and Reyes-Iglesias (1993) reported that that task-related changes in blood flow were maximal in the right MCA. The results of both of these experiments are consistent with other findings suggesting that the right hemisphere may be specialized for face recognition and spatial cognition (Benton, 1982; Hellige,

1993). Converging evidence for the validity of the TCD approach in measuring lateralized cognitive processing comes from a study by Meiners and Dabbs (1977), who found that decreases in temperature at the tympanic membrane, which reflect increases in brain blood flow (Minard & Copman, 1963; Serota & Gerard, 1938), were greater in the left ear during verbal tasks and in the right ear during spatial tasks.

Taken collectively, these investigations demonstrate that the TCD technique is a sensitive measure of changes in cerebral hemovelocity brought about by a variety of mental tasks and that such TCD-measured changes appear to be linked to the degree of cognitive demand required for performing those tasks. Accordingly, the relatively inexpensive and noninvasive TCD technique may be ideally suited as a tool for meeting the need identified by Parasuraman, Warm, and See (1998) to relate brain imaging in vigilance to performance efficiency.

The Mayleben Study. The initial effort to use TCD in this way was reported recently by Mayleben (1999), who performed his experiment within the context of the resource model of vigilance offered by Parasuraman and his associates described in Chapter 1 (Davies & Parasuraman, 1982; Parasuraman, 1979; Parasuraman, Warm, & Dember, 1987). Recall that within this model, the vigilance decrement is assumed to result from the depletion of information-processing resources that are not replenished in the time available. Mayleben suggested that cerebral blood flow might represent a metabolic index of resource usage. Therefore, he hypothesized that the vigilance decrement should be accompanied by a decline in cerebral hemovelocity. Along this line, he also hypothesized that the absolute level of blood flow should vary directly with task demands. To explore these possibilities, Mayleben asked observers to perform either a successive- or a simultaneous-type vigilance task during a 30-min vigil. Successive tasks are absolute judgment tasks in which signals and nonsignals are differentiated

by comparing current input against a standard held in *working memory*. In contrast, simultaneous tasks are comparative judgment tasks in which all of the information needed to distinguish signals from nonsignals is present in the stimuli themselves, and recent memory for the signal feature is not required (Parasuraman & Davies, 1977). Due to the *memory imperative*, successive-tasks are considered to be more capacity demanding than their simultaneous counterparts (Parasuraman & Davies, 1977). Support for this view comes from a wide variety of studies showing that simultaneous tasks are more resistant than successive to the negative impact of psychophysical challenges which degrade vigilance performance by draining processing resources (Warm & Dember, 1998) and by studies showing that performance on a highly demanding visual search task is a better predictor of subsequent vigilance performance on a successive than on a simultaneous vigilance task (Matthews, Davies, & Holley, 1993).

As expected, Mayleben and colleagues reported that the temporal decline in performance efficiency, as reflected in a decline in signal detections, was accompanied by a parallel decline in cerebral hemovelocity; moreover, the absolute level of blood flow was significantly higher for observers who performed the successive task than for those who performed the simultaneous task. In addition, Mayleben also found that the blood flow effects were lateralized -- hemovelocity was greater in the right as compared to the left cerebral hemisphere, *principally* in the performance of the memory-based successive task. A result of this sort is consistent with earlier PET-imaging and psychophysical studies showing a right-brain superiority in vigilance (Berman & Weinberger, 1990; Buchsbaum, et al., 1990; Davis, 1988; Deutsch, Papanicolaou, Bourbon, & Eisenberg, 1987; Lewin, et al., 1996; Pardo, Fox, and Raichle, 1991; Reivich & Gur, 1985; Warm, Richter, Sprague, Porter, & Schumsky, 1980; Warm, Schumsky, and Hawley, 1976) and with recent studies by Tulving and his associates (Nyberg, McIntosh, Cabeza, Habib,

Houle, & Tulving, 1996; Tulving, Kapur, Craik, Moscovitch, & Houle, 1994) indicating that memory retrieval is primarily a right-brain function.

The Present Study

Signal salience. The present study was designed to extend the line of research initiated by Mayleben (1998) into the linkage between TCD-measured hemovelocity, task demands, and vigilance performance. Toward that end, the study made use of two other vigilance parameters that could be tied conceptually to a resource-utilization model -- signal salience and cueing.

A common finding in studies of target detection under alerted conditions (in which targets are preceded by a warning) is that the frequency of detections is positively related to the salience of the target as defined by its amplitude (Dember & Warm, 1979). This factor is also important under conditions of sustained attention. Using a detection probability measure, several investigations have demonstrated that the overall quality of sustained attention can be enhanced and the vigilance decrement attenuated by increasing the amplitude of critical signals relative to their background, in other words, by increasing the signal-to-noise ratio (Adams, 1956; Corcoran, Mullin, Rainey, & Frith, 1977; Guralnick, 1972; Loeb & Binford, 1963; Parasuraman & Mouloua, 1987; Thurmond, Binford, & Loeb, 1970; Tickner, Poulton, Copeman, & Simmonds, 1972; Wiener, 1964). One might imagine that monitors would need to inspect their displays more carefully in order to seek out and detect signals having a low as compared to a high signal-to-noise ratio and, therefore, that a low signal salience condition would be more capacity draining than one where the signals are more easily discernable. Support for this idea comes from studies by Becker et al. (1995) and Gluckman, Warm, Dember, Thiemann, and Hancock (1988; see also Warm, Dember, & Hancock, 1996), which demonstrated that the workload of sustained attention is greater for signals of low as compared to high salience.

Given that brain blood flow may reflect the utilization of metabolic resources in information processing and the differential capacity demands imposed by high and low salience signals, one goal for the present study was to examine the relation between signal salience, hemovelocity, and vigilance performance. It was anticipated that low amplitude signals would be associated, at least initially, with elevated blood flow levels in comparison to high amplitude signals and that low amplitude signals would be accompanied by a more pronounced blood flow decrement over time than high amplitude signals. Given the brain imaging (PET and blood flow) and psychophysical findings on cerebral lateralization in vigilance described previously, it was also anticipated that the salience-hemovelocity effects would be right-lateralized.

Cueing. In addition to increasing the signal-to-noise ratio, signal detection in vigilance can also be improved by providing observers with consistent and reliable cues as to the imminent arrival of critical signals. As several experiments have shown, the principal consequence of such forewarning is the elimination of the vigilance decrement (Aiken & Lau, 1967; Annett, 1966; Annett & Clarkson, 1964; Annett & Patterson, 1966; 1967; Weiner & Attwood, 1968). A recent illustration of this effect comes from a study by Hitchcock, Dember, Warm, Moroney, and See (1999) using a simulated air-traffic control display in which critical signals for detection were planes traveling on a collision course. Detection probability scores for cued and non-cued observers were identical early in the watch. The scores for cued observers remained stable as time on watch progressed, while they declined considerably over time for non-cued observers, so that by the end of the watch, there was a large disparity in the frequency of signal detections favoring the cued group. Hitchcock and his associates linked cueing effects to resource theory by arguing that cued monitors would need to observe the display *only* after having been prompted about the arrival of a signal and, therefore, could husband their information-processing resources

over time. In contrast, since non-cued observers were never certain as to when a critical signal might appear, they would have to process information on their displays continuously across the watch, thereby, consuming more of their resources over time than cued observers. Accordingly, given the potential coupling of blood flow to information processing resources, a second goal for the present study was to examine the relation between cueing and hemovelocity in vigilance performance, particularly with regard to the vigilance decrement.

It is important to emphasize that a cardinal feature of all of the studies on the role of cueing in vigilance was the use of a completely veridical cueing regimen; that is, signals always followed cues and cues were never misleading. Such consistency and reliability is not, however, always characteristic of current operational systems, such as aviation predictive displays, which provide operators with cues to the possibility of impending problems. Imperfect reliability is inherent in these cueing systems (Ellis, McGreevey, & Hitchcock, 1987; Merwin, O'Brien, & Wickens, 1997). Consequently, to more fully understand the implications of cueing in vigilance performance and associated changes in brain blood flow, the present study made use of three conditions of cue reliability (100%, 80%, and 40% reliable) in addition to a non-cue condition. All of the cueing conditions contained the same number of cues and the same number of critical signals. They varied, however, in the extent to which the cues accurately forecasted the arrival of critical signals (all signals, 80%, or 40%, respectively), the percentage of cues that were incorrect predictors of a signal (none, 20%, and 60%, respectively), and consequently, the number of critical signals occurring without forewarning (none, 20%, and 60%, respectively). Observers were informed of the level of reliability of the cueing that they would receive. It was assumed that varying the reliability of the cue would vary the extent to which observers would need to devote processing resources to their displays in order to detect signals over the course of the

vigil. Consequently, it was anticipated that the ability of the cue conditions to attenuate temporal declines in both signal detections and hemovelocitv would vary directly with the level of cue reliability. As in the case of the salience-hemovelocitv relation, it was anticipated that cueing-hemovelocitv relations in this study would also be right-lateralized.

CHAPTER 3

Method

Participants

One hundred and twenty-eight students, 64 men and 64 women, from the University of Cincinnati served as observers in order to fulfill a course requirement. They ranged in age from 17 to 32 years, with a mean age of 20.4 years. All had normal or corrected-to-normal vision and were free of known hearing impairments. They were all right-handed, based upon the concordance of their self-reports with the hand used to sign an informed consent form.

Design

Eight male and eight female observers were selected at random to serve in one of eight experimental groups defined by the factorial combination of two levels of signal salience (low, high) and four levels of cueing (100% reliable, 80% reliable, 40% reliable, and a no-cue control). Due to the unilateral imaging capability of the TCD, half of the participants in each of the groups, again equated for sex, had TCD recordings taken from the left cerebral hemisphere, while the other half had recordings taken from the right cerebral hemisphere.

Apparatus and Procedure

All observers participated in a 40-minute vigil during which they monitored the simulated air-traffic control display shown in Figure 1, which had been employed in the Hitchcock et al. (1999) cueing study. The display consisted of a "city" (a solid red circle 10.5mm in diameter; luminance = 23.7 cd/m^2 , as measured by a Spectra-Model UBD 1° Spot Meter) banded by a thin white border (.75mm thick x 12mm in diameter) and ringed by three circular white (luminance = 79.2 cd/m^2) "outer markers" (.75mm thick; 28mm, 53mm, and 83mm in diameter, respectively).

There were two "jet aircraft" represented by two 1mm x 25mm lines, all of which were presented on a light gray background (luminance = 29.6 cd/m²) using a

Figure 1. Examples of all possible neutral and critical signals.

MacIntosh LC visual display terminal (VDT). In the low salience condition, the Michaelson contrast ratio $[(\text{maximum luminance} - \text{minimum luminance})/(\text{maximum luminance} + \text{minimum luminance}) \times 100]$ (Coren, Ward, & Enns, 1999) of the aircraft to their background was 2.1% (light gray targets on a light gray background). In the high salience condition, the contrast ratio was 98.6% (black targets on a light gray background). The aircraft were equidistant from the city (each reached the innermost marker), approaching it from opposite headings, either from northwest to southeast or northeast to southwest. Within each of the two headings, one of the aircraft was always vectored toward the center of the city. The flight path of the other aircraft was parallel to, but displaced to the left or the right of its companion, so that it would pass on a tangent to the innermost marker. The eight permutations of flight headings were presented randomly throughout the vigil and constituted neutral (safe) situations requiring no overt responses from observers. Critical signals for detection (emergency events) were cases in which the two aircraft, in either the northwest/southeast or the northeast/southwest headings (see Figure 1), were aligned on a *collision path* over the center of the city. In all conditions, the display was updated 30 times/minute with a dwell time of 300 msec. Ten critical signals occurred at random intervals within each of four continuous 10-minute periods of watch in all conditions (signal probability per period = .033).

Observers in the 100%, 80%, and 40% reliable cueing groups were instructed that a critical signal (emergency event) would occur within *one* of the *five* display updates immediately following the prompt. The cue consisted of the word "Look" provided through a digitized male voice. Cued participants in the 100% reliable group were informed that the prompt was perfectly reliable and that emergency events would appear *only* during these cued intervals (i.e., the next five display updates). Participants serving in the 80% cued condition were instructed that the

cues were 80% reliable, that 20% of the warnings would be misleading and that 20% of the signals to be detected would occur without any warning at all. Those in the 40% cued condition were told that 40% of the verbal warnings were accurate and that the percentages of misleading cues and non-forewarned signals were both 60%. The structure of the cued conditions allowed for the delivery of the same number of prompts in each cueing situation while enabling differences in reliability. The no-cue control observers received acknowledgment after each response in the form of the word "Logged" spoken in the same male voice. Response acknowledgment controlled for accessory auditory stimulation but provided no forewarning or evaluative information. All of the verbalizations were presented binaurally at an intensity of 60 dB(A) measured at the monitor's ear. Stimulus presentations and verbalizations were orchestrated by a MacIntosh LC personal computer with a built-in speaker. Programming was achieved by means of SuperLab (v1.5) and Microsoft Excel (v3.0) software. Participants indicated their detection of critical signals by pressing the spacebar on the computer's keyboard. Responses occurring within 1500 msec after the appearance of critical signals were recorded automatically by the computer as correct detections. All other responses (spacebar presses) were recorded as false alarms. The 1500 msec cutoff insured that responses to any particular event could not overlap the appearance of the next event. Previous research using this display indicated that if monitors were going to respond to a critical signal, they would do so within this 1500 msec window (Hitchcock et al., 1999). Complete instructions to participants in all conditions are presented in Appendix A.

Participants were tested individually in a 2.85 meter x 4.35 meter x 2.42 meter high interior laboratory room, which also contained the Transcranial Doppler unit. To minimize distractions, a curtain was used to conceal the unit and related equipment; the amplitude of the

unit's auxiliary auditory display was reduced so that it was inaudible to observers. Participants were seated in front of the VDT, which was placed at eye level at a viewing distance of 70 cm. Ambient illumination in the chamber was 0.22 cd/m^2 and was provided by a single 11-watt incandescent bulb housed in a portable light fixture and positioned above and behind the seated observer in order to minimize glare on the display.

Upon reporting for the experiment, observers received a verbal briefing by the experimenter about what they would encounter during the session and then completed an informed-consent form. All monitors received two 5-minute practice trials that duplicated the vigilance task they would later experience, except that verbal cues and response acknowledgment were not presented during practice. In order to be retained in the study, participants had to detect at least 70% of all critical signals during practice, with no more than 10% false alarms. Four participants placed in low salience conditions failed to meet that criterion and were replaced. Observers surrendered their timepieces, cellular telephones, and pagers upon entering the laboratory and were unaware of the length of the vigil other than it would not exceed 120 minutes.

As noted in Chapter 1, Matthews and Davies (1998) have shown that a self-report measure of arousal known as energetic arousal, which correlates with measures of autonomic activity during performance testing, may be linked to the availability of information-processing resources. Consequently, the present study made use of the Energetic Arousal scale of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999) to ensure that observers in all conditions were equated on that measure at the outset of the study and to determine the degree to which changes in a metabolic index of resource utilization, cerebral blood flow velocity (hemovelocity), are paralleled by changes in self-reports of energetic arousal. Toward these ends,

observers completed a pre-test form of the DSSQ immediately after consenting to participate in the study and a post-test version of the DSSQ immediately after completing the vigil.

Cerebral blood flow measurement.

HemoveLOCITY measures were obtained from the mainstem middle cerebral artery (MCA) in the left and right cerebral hemispheres. Recordings were made by means a transcranial Doppler unit model TC2-64B (TCD unit; Nicolet/EME, Madison, WI, USA). To enable recording of hemoveLOCITIES, observers wore a 2-MHz ultrasound transducer embedded in a plastic bracket which was secured around the head by an adjustable Velcro strap and located dorsal and immediately proximal to the zygomatic arch along the temporal bone. A small amount of Aquasonic-100 brand ultrasound transmission gel (Parker Laboratories, NJ, USA) was placed between the TCD transducer and the observer's skin to enhance the bloodflow signal. The mainstem MCA, which was monitored at depths of 50-55mm (distance between the transducer face and sample volume), typically has a hemoveLOCITY range of 50-65 cm/sec. The TCD unit permitted depth adjustment in 5mm increments as needed for isolating the MCA. Time-averaged bloodflow velocities were displayed by the unit every four seconds. These values were channeled into a video cassette recorder for subsequent hand-recording.

Observers were acclimated to the TCD procedure immediately after completing the pre-test version of the DSSQ. At this time, baseline hemoveLOCITY measures were obtained from the appropriate MCA (left or right) during a 5-minute period in which observers were seated in front of the blank VDT and asked to refrain from speaking and to minimize body movement while they breathed regularly and maintained relaxed wakefulness. All observers reported remaining awake during this phase. HemoveLOCITY during the final 60 seconds of the baseline period provided the baseline index, typical of research using the TCD technique (Aaslid, 1986).

Observers wore the transducer during the subsequent practice and testing phases, however, recordings were secured only during the testing phase.

As noted by Parasuraman (1984), any effort to examine task-induced changes in a physiological measure over time must ensure that observed changes are indeed task-linked and not simply the result of sitting in the testing room for a prolonged period. Accordingly, hemovelocities were collected from either the left or right MCA in an additional group of eight male and eight female participants (mean age = 19.9 years) from the University of Cincinnati who served as a passive observing control group. All members of this group were right handed, had normal or corrected-to-normal vision, and were free of known hearing impairments. The passive observers were exposed to the vigilance display but were not provided with a definition of critical and neutral signals or given any information about pressing the computer spacebar. They were told simply to gaze at the display until the session ended. Half of the observers in this group, also equated for sex, were exposed to low-salience and half to high-salience stimuli. In addition, half of the observers within each of these subdivisions had TCD recordings taken from the left and right hemispheres, respectively. Accessory auditory stimulation was not present in the passive-viewing control condition, and observers in this condition did not complete the DSSQ. As in the case of the active observers, however, hemovelocity measures were secured from the passive observers during a 5-min baseline period (immediately after consenting to participate in the study) and during the continuous 40-min “testing” session.

CHAPTER 4

Results

Vigilance Performance

Detection Probability. Performance efficiency was assessed in terms of the percentages of correct detections and false alarms in all experimental conditions. Preliminary examination of the detection probability scores averaged across all conditions indicated that they were similar when blood flow recordings were obtained from the left (82.1%) and right (82.9%) MCA's, $t(126) < 1$, $p > .05$. Given this similarity, and the lack of any theoretical or practical importance of recording site for performance, the data were collapsed across recording sites in order to examine the effects of signal salience, cueing, and periods of watch on detection probability.

Mean percentages of correct detections (and standard errors) for the eight combinations of signal salience and cueing are presented for each period of watch in Table 1. It is evident in the table that high salience signals ($M=86\%$) were detected more frequently than low salience signals ($M=78\%$), that detection probability varied directly with the level of cue reliability, (M 's for the 100%, 80%, 40% and no-cue condition = 92%, 86%, 80%, and 71%, respectively) and that performance efficiency declined over time (see tabled means). These impressions were supported by an analysis of variance (ANOVA) of an arcsin transformation of the detection scores, which revealed significant main effects for signal salience, $F(1,120) = 9.08$, $p < .05$, cueing, $F(3,120) = 11.14$, $p < .001$, and periods of watch $F(3,338) = 29.49$, $p < .001$. In addition, the analysis also revealed that the effects of cueing depended upon time on task, $F_{\text{Cue} \times \text{Periods}}(8,338) = 6.03$, $p < .001$.

Table 1.

Mean percentages of correct detections for the several cueing groups in each period of watch for both the high and low salience conditions. Standard errors are in parenthesis.

<i>Salience</i>	<i>Cue group</i>	<i>Periods (10 minutes)</i>				<i>M</i>
		1	2	3	4	
<i>High</i>	<i>100 %</i>	95.0 (1.83)	91.9 (1.64)	92.5 (1.94)	95.6 (2.23)	93.8 (1.91)
	<i>80%</i>	95.0 (2.04)	89.4 (3.35)	90.6 (3.47)	87.5 (3.82)	90.6 (3.17)
	<i>40%</i>	92.5 (3.10)	89.4 (3.81)	85.0 (5.16)	74.4 (5.47)	85.3 (4.39)
	<i>No-cue</i>	90.0 (2.74)	79.4 (4.69)	71.2 (5.76)	63.1 (6.44)	75.9 (4.91)
<i>Low</i>	<i>100 %</i>	90.6 (2.49)	93.1 (2.37)	84.4 (3.65)	93.1 (1.98)	90.3 (2.62)
	<i>80%</i>	86.3 (3.86)	85.6 (3.29)	81.9 (4.67)	76.3 (5.07)	82.5 (4.22)
	<i>40%</i>	88.8 (2.56)	80.0 (3.76)	68.1 (5.86)	66.9 (5.89)	75.9 (4.52)
	<i>No-cue</i>	77.5 (5.52)	71.9 (6.27)	58.8 (7.52)	55.0 (8.61)	65.8 (6.99)
	<i>M</i>	89.5 (3.02)	85.1 (3.65)	79.1 (4.75)	76.5 (4.94)	

All other sources of variance in the analysis were not significant ($p > .05$). In this and subsequent analyses involving repeated measures, Box's epsilon was employed when appropriate to correct for violations of the sphericity assumption (Maxwell & Delaney, 1990).¹

The Cue x Periods interaction is shown in Figure 2. Detection scores for the four cueing groups are plotted as a function of periods of watch. It can be seen in the figure that while the detection scores for the several cueing conditions were similar to each other during the early portion of the vigil, they diverged by the end of the session. More specifically, performance efficiency remained stable over time in the 100% cueing condition but declined over time in the remaining conditions, so that by the end of the

¹ Detailed summaries of all ANOVA tables appear in Appendix B.

Figure 2. Percentages of correct detections as a function of periods of watch for the four cueing groups.

vigil performance efficiency was clearly best in the 100% group followed in order by the 80%, 40%, and no-cue groups.

False Alarm Probability. As was the case with the detection scores, a preliminary examination of the false alarm scores indicated that the frequencies of false alarms were similar when hemovelocity recordings were obtained from the left and right MCA recording sites. Across all experimental conditions, mean percentages of false alarms for the left and right cerebral artery groups were 1.90% and 1.98%, respectively, $t(126) < 1$. Accordingly, the false alarm data were also collapsed across recording sites for further analysis.

Mean percentages of false alarms (and standard errors) for the eight combinations of signal salience and cueing are presented for each period of watch in Table 2. It is evident in the table that false alarms were generally rare in this study (overall mean = 1.94%). Nevertheless, two effects are notable in the data — false alarms were consistently lower when cueing was

completely reliable (100% group) than when it was not, and false alarms varied over time, increasing from the first to the third periods and then declining in the final period. The effects of cueing and time were statistically significant, as revealed by an ANOVA conducted on an arcsin transformation of the false alarm scores, $F_{\text{cueing}}(3,120) = 18.39$, $p < .001$; $F_{\text{periods}}(2,292) = 2.90$, $p < .05$. All other sources of variance in the analysis were not significant ($p > .05$).

Table 2.

Mean percentages of false alarms for the several cueing groups in each period of watch for both the high and low salience conditions. Standard errors are in parenthesis.

<i>Salience</i>	<i>Cue group</i>	<i>Periods (10 minutes)</i>				<i>M</i>
		1	2	3	4	
<i>High</i>	<i>100 %</i>	0.13 (.005)	0.19 (.581)	0.22 (.109)	0.01 (.003)	0.14 (.174)
	<i>80%</i>	1.4 (.415)	1.5 (.581)	1.6 (.468)	1.2 (.330)	1.42 (.457)
	<i>40%</i>	1.9 (.396)	2.6 (.704)	4.2 (1.18)	2.7 (.908)	2.85 (.797)
	<i>No-cue</i>	2.6 (.505)	2.6 (.669)	3.3 (1.17)	2.1 (.515)	2.65 (.715)
<i>Low</i>	<i>100 %</i>	0.54 (.175)	0.39 (.133)	0.32 (.112)	0.37 (.107)	0.40 (.132)
	<i>80%</i>	2.8 (.536)	3.4 (.690)	3.3 (.725)	2.7 (.660)	3.05 (.653)
	<i>40%</i>	3.7 (.796)	3.1 (.652)	2.8 (.711)	2.7 (.547)	3.10 (.676)
	<i>No-cue</i>	2.3 (.495)	1.9 (.475)	1.9 (.529)	1.5 (.394)	1.90 (.473)
<i>M</i>		1.92 (.416)	1.96 (.561)	2.20 (.625)	1.67 (.433)	

Cerebral Hemovelocity

Basic Control Issues. To take into account the wide range of hemovelocity values present in the population (Adams, Nichols, & Hess, 1992), the hemovelocity scores for all participants in the experiment (passive and active) were expressed as a proportion of their resting baseline. For each participant, the scores expressed in this way were averaged within each 10-min period of the study to permit an assessment of blood flow changes over time. As indicated earlier, the baseline measure was derived from the last 60 seconds of a 5-minute resting period.

Given the possibility of wide variations in baseline, it was necessary to ensure that any hemovelocity effects associated with the between groups factors in this study – cueing, salience, and cerebral hemisphere – were not sampling artifacts of the initial resting baseline. Toward that end, comparisons were made of the baseline values used to calculate hemovelocity scores for the *active monitoring participants* during the vigil. Mean baseline values in cm/sec for these participants in all combinations of cueing and salience in the left and right cerebral hemispheres are presented in Table 3. One can see in the table that the mean baseline velocities were similar in all conditions.

Table 3.

Mean cerebral hemovelocities (in cm/sec) at baseline under all combinations of cueing and signal salience in the left and right MCA's. Standard errors are in parenthesis.

Cue group	<i>Left MCA</i>		<i>Right MCA</i>		<i>M</i>
	High	Low	High	Low	
100 %	56.79 (2.91)	60.36 (4.94)	60.58 (3.71)	56.46 (3.14)	58.55 (3.67)
80%	54.92 (2.39)	58.49 (2.41)	60.38 (4.44)	60.81 (2.45)	58.65 (2.92)
40%	56.04 (3.63)	57.52 (2.48)	54.22 (4.09)	59.07 (3.79)	56.71 (3.50)
No-cue	54.98 (2.91)	59.85 (4.64)	55.37 (4.11)	52.06 (2.78)	55.56 (4.64)
<i>M</i>	55.68 (2.96)	59.05 (3.62)	57.64 (4.06)	57.10 (3.04)	

An ANOVA of the data of Table 3 revealed no significant main effects or interactions ($p > .05$ for all sources of variance), indicating that baseline values in the between groups conditions were essentially identical.

Prior to examining the effects of the experimental variables on cerebral blood flow, it was also necessary, as noted earlier, to establish that any temporal changes in blood flow in the two cerebral hemispheres were indeed task-dependent, and not simply the result of participants'

sitting in the testing room for a prolonged period of time. Moreover, since high and low levels of signal salience were determined by varying the contrast of the targets with respect to their background, it was also important to ensure that any changes in blood flow associated with the salience factor were due to the need to process the stimuli and not just the result of differential luminance levels in the monitored display.

To address the task-dependency issues, data from the *passive observing participants* were employed to evaluate the effects of target contrast on blood flow in the left and right MCA's over a time span (40 min) equivalent to that of the main watch. Mean hemovelocity scores in the passive observing group for the high contrast (high salience) and low contrast (low salience) target-definition conditions are plotted as a function of time on task in Figure 3. Data for the two cerebral hemispheres are shown separately in each panel.

Figure 3. Passive observers' hemovelocity scores for high and low contrast stimuli as a function of time on task. Data for the left and right cerebral hemispheres are presented separately in each panel.

It is evident in the figure that hemovelocity scores in the passive group were similar for the two recording sites (hemispheres) and for the two contrast conditions, and that the scores generally remained stable over the 40-min session. A 2 (hemisphere) X 2 (contrast) x 4 (periods of watch) ANOVA revealed no significant main effects or interactions ($p > .05$ in all cases). Clearly, when observers merely gazed at the display for 40 minutes with no information-processing imperative, variations in display contrast and time on task had no impact upon blood flow in either cerebral hemisphere.

Hemovelocities During Active Vigilance. Mean hemovelocity scores during the active vigil for the left and right cerebral hemispheres under all combinations of signal salience and cueing during each period of watch are displayed in Table 4.

Table 4.

Mean hemovelocitv scores in the left and right MCA's for all combinations of signal salience and cueing during each period of watch. Standard errors are in parenthesis.

<i>Hemisphere</i>	<i>Salience</i>	<i>Cue Group</i>	<i>Periods (10 minutes)</i>				<i>M</i>
			1	2	3	4	
<i>Left</i>	<i>High</i>	<i>100 %</i>	0.96 (.001)	0.94 (.001)	0.94 (.002)	0.96 (.002)	0.95 (.001)
		<i>80%</i>	0.93 (.002)	0.93 (.002)	0.90 (.002)	0.93 (.001)	0.92 (.002)
		<i>40%</i>	0.96 (.002)	0.93 (.001)	0.94 (.001)	0.93 (.002)	0.94 (.001)
		<i>No-cue</i>	0.95 (.003)	0.94 (.003)	0.91 (.004)	0.87 (.005)	0.92 (.004)
	<i>Low</i>	<i>100 %</i>	1.03 (.006)	1.00 (.006)	0.97 (.005)	0.93 (.005)	0.98 (.005)
		<i>80%</i>	1.02 (.003)	0.99 (.003)	0.98 (.002)	0.98 (.003)	0.99 (.003)
		<i>40%</i>	1.00 (.002)	0.98 (.002)	0.95 (.002)	0.94 (.001)	0.97 (.001)
		<i>No-cue</i>	0.94 (.002)	0.92 (.002)	0.92 (.003)	0.88 (.003)	0.91 (.003)
<i>Right</i>	<i>High</i>	<i>100 %</i>	1.01 (.002)	1.00 (.003)	0.99 (.003)	0.99 (.002)	1.00 (.002)
		<i>80%</i>	0.97 (.001)	0.94 (.002)	0.93 (.003)	0.93 (.002)	0.94 (.002)
		<i>40%</i>	1.01 (.001)	0.98 (.001)	1.03 (.075)	0.96 (.001)	0.99 (.020)
		<i>No-cue</i>	0.99 (.001)	0.98 (.001)	0.96 (.001)	0.92 (.004)	0.96 (.002)
	<i>Low</i>	<i>100 %</i>	1.02 (.003)	1.03 (.003)	1.05 (.002)	1.04 (.002)	1.03 (.002)
		<i>80%</i>	1.01 (.001)	0.99 (.001)	0.98 (.007)	0.98 (.001)	0.99 (.002)
		<i>40%</i>	0.98 (.001)	0.96 (.001)	0.94 (.001)	0.94 (.001)	0.95 (.001)
		<i>No-cue</i>	1.04 (.004)	0.98 (.004)	0.93 (.006)	0.86 (.007)	0.95 (.005)
		M	0.99 (.002)	0.97 (.002)	0.96 (.007)	0.94 (.003)	

An ANOVA of these data indicated that during the active vigil, hemovelocitv was significantly greater in the right hemisphere ($M=.98$) than in the left ($M=.95$), $F(1,112)= 4.24$, $p<.05$, and that the overall magnitude of the hemovelocitv scores declined significantly over time

(see tabled means), $F(2,197) = 34.14$, $p < .001$. There was also a tendency for hemovelocity to be greater in the low salience ($M = .98$) than in the high salience condition ($M = .95$), $F(1,112) = 2.93$, $p = .09$.

Although the analysis of the hemovelocity scores did not reveal a main effect for cueing, the effects of cueing upon blood flow became apparent over time, as indicated by a significant Cueing X Periods interaction, $F(5,197) = 4.78$, $p < .001$. This relation was modified by hemisphere, as indicated by a significant Cueing x Periods x Hemisphere interaction, $F(5,197) = 4.78$, $p < .001$, and also by salience, as indicated by a significant four-way interaction involving cueing, periods, hemisphere, and salience, $F(5,197) = 2.87$, $p < .01$. None of the remaining sources of variance in the analysis were significant ($p > .05$ in all cases). Following a procedure recommended by Keppel (1991), the four-way interaction was examined further by testing the effects of cueing, periods, and hemisphere in separate three-way ANOVA's computed from the data for each of the two salience conditions. The analysis based upon scores from the high salience condition revealed significant main effects for hemisphere, $F(1,56) = 6.07$, $p < .02$ and periods of watch, $F(2,95) = 11.80$, $p < .001$. Once again, mean hemovelocity was greater in the right hemisphere (.97) than in the left (.93), and the hemovelocity scores declined over time (M 's for periods 1-4 = .97, .96, .94, .94, respectively). None of the remaining sources of variance in this analysis was significant ($p > .05$ in each case).

The analysis based upon scores from the low salience condition also contained a significant main effect for periods (M 's for periods 1-4 = 1.01, .98, .97, and .95, respectively). In addition, the Cueing X Periods and the Cueing X Periods X Hemisphere interactions, which were not evident in the data of the high salience condition, re-emerged in the analysis of the low

salience condition $F(5,100)= 3.05$, $p<.02$ and $F(5,100)= 4.25$, $p <.001$, respectively. None of the other sources of variance in the low salience analysis was significant ($p>.05$ in each case).

The significant three-way interaction in the analysis of data from the low salience condition was parsed into separate two-way (Cueing X Periods) ANOVA's based upon the data for each cerebral hemisphere. The only significant source of variance in the analysis of data from the left hemisphere/low salience condition was a main effect for periods, $F(2,67)= 25.11$, $p<.001$, once again reflecting the decline in mean hemovelocity scores over time (M's for periods 1-4 = 1.00, 0.97, 0.96, and 0.93, respectively). The analysis of the right hemisphere/low salience condition contained a significant periods effect, $F(2,67)= 6.58$, $p<.01$, and also a significant Cueing X Periods interaction, $F(7,67)= 4.56$, $p<.01$, which is presented in Figure 4.

Figure 4. Hemovelocity scores as a function of periods of watch for the four cue-level groups. Data are from the right hemisphere/low salience condition.

Mean hemovelocity scores in the four cueing conditions are plotted in the figure as a function of periods of watch. The most notable aspect of the Cueing X Periods interaction

depicted in Figure 4 is its striking similarity to the Cueing x Periods interaction in the detection scores, illustrated in Figure 2.

As was the case with detection probability, the hemovelocity scores for the several cueing conditions were similar to each other during the early portions of the vigil but showed differential rates of decline over time, so that by the end of the vigil, blood flow was clearly highest in the 100% group followed in order by the 80%, 40%, and no-cue groups. In sum, hemovelocity scores taken from the right hemisphere under low salience conditions mirrored the effects of cueing on performance efficiency (signal detections) over time.

Energetic Arousal

Standard Scores. All pre-vigil and post-vigil comparisons of data from the energetic arousal (EA) scale of the DSSQ were made in terms of standard scores (z-scores) using equation 1:

$$z = \frac{(X_{phase} - \bar{X}_{normative})}{S_{normative}} \quad [1]$$

The normative means and standard deviations employed in the z-score transformations were based upon a British sample obtained from Matthews et al. (1999). This approach has the advantage of permitting a comparison of the energetic arousal scores in the present study with those of a substantial normative group who did not experience a vigilance task (N= 767).

Pre-Post Comparisons. Mean pre-vigil and post-vigil standard scores for all combinations of salience and cueing are presented in Table 5. The data are collapsed

Table 5.

Mean pre-vigil and post-vigil standard scores on the Energetic Arousal Scale for all combinations of salience and cueing. Standard errors are in parenthesis.

<i>Salience</i>	<i>Cue group</i>	<i>Phase</i>		<i>M</i>
		Pre-vigil	Post-vigil	
<i>High</i>	<i>100 %</i>	0.20 (.226)	0.17 (.268)	0.19 (.247)
	<i>80%</i>	0.49 (.183)	- 0.18 (.171)	0.16 (.177)
	<i>40%</i>	0.19 (.180)	- 0.73 (.239)	- 0.27 (.210)
	<i>No-cue</i>	0.62 (.179)	- 0.43 (.209)	0.10 (.194)
<i>Low</i>	<i>100 %</i>	0.31 (.241)	- 0.29 (.181)	0.01 (.211)
	<i>80%</i>	0.55 (.229)	- 0.31 (.208)	0.12 (.219)
	<i>40%</i>	0.13 (.218)	- 0.41 (.199)	- 0.14 (.209)
	<i>No-cue</i>	0.16 (.244)	- 0.79 (.237)	- 0.63 (.241)
<i>M</i>		0.33 (.212)	- 0.37 (.214)	

across recording site because there was no reason to expect this factor to have a meaningful impact upon the energetic arousal scores.

Perusal of the table will reveal that all of the pre-vigil means fell above a z-score of zero, while all but one of the post-vigil means fell below that reference value. For both phases of the study, the consistency of the distribution of means above or below the zero-point exceeded chance expectations based upon a one-tail binomial test ($p < .05$; Siegel, 1956). Clearly, the level of energetic arousal among observers in this study was generally higher than that of the normative sample at the outset of the experiment but generally fell below that of the normative sample at the conclusion of the vigil. It can also be seen in the table that the overall mean of the post-vigil z-scores was as far below the zero-point (approximately a third of a standard deviation) as the overall pre-vigil mean was above that point.

In order to examine the relative effects of the independent variables on energetic arousal, the data of Table 5 were subjected to a 2(salience) x 4(cueing) x 2(phase) ANOVA. With an

alpha level of .05, the only significant sources of variance in the analysis were the main effect for phase, $F(1,120) = 71.65$, $p < .001$, and the Cueing x Phase interaction, $F(3, 120) = 2.94$, $p < .05$.

The significant Cueing x Phase interaction is displayed in Figure 5. Scores for the cueing conditions are plotted separately for the pre-vigil and post-vigil phases of the experiment.

Figure 5. Mean Energetic Arousal z-scores, collapsed across hemisphere and salience, for the pre-task and post-task scores within each of the cue-level groups.

Once again, the tendency for the scores to fall uniformly above the zero reference point in the pre-vigil phase and below that reference point at the end of the vigil is evident in the data. Indeed, the standard errors for each of the groups in the post-vigil phase did not overlap those of their respective pre-vigil groups. Separate ANOVAs for the pre-vigil and post-vigil phases revealed that the cueing groups did not differ significantly from each other prior to the start of the vigil, $F(3,124) < 1$, but that significant group differences were evident in the post-vigil phase $F(3,124) = 2.99$, $p < .05$. Supplementary Newman-Keuls tests, with

alpha set at .05 for each comparison, revealed that the scores for the 40% and no-cue conditions were significantly lower than those for the 100% cueing condition. All other comparisons were not significant. In sum, the Cue x Phase interaction in the Energetic Arousal scores has a marked resemblance to the Cue x Periods interactions found with signal detection (see Figure 2) and cerebral hemovelocity (see Figure 4).

CHAPTER 5

Discussion

Several investigations using Pet and fMRI procedures have been successful in demonstrating changes in cerebral blood flow and glucose metabolism during the performance of sustained attention or vigilance tasks (Parasuraman, Warm, & See, 1998). These studies have also identified several brain regions that are active during such tasks, including the *brain stem* (Kinomura, Larsson, Gulyas, & Roland, 1996), the *frontal cortex* (Berman & Weinberger, 1990; Buchsbaum, et al., 1990; Cohen et al., 1988; Deutsch et al., 1987; Lewin et al., 1996; Pardo, Fox, & Raichle, 1991; Reivich & Gur, 1985; Seidman et al., 1998) and the *cingulate gyrus* (Cohen et al., 1988; 1992; Posner & Peterson, 1990). However, with the exception of a study by Paus et al. (1997), in which a temporal decline in performance efficiency (the ubiquitous vigilance decrement) was accompanied by PET-measured declines in blood flow in several subcortical structures and the orbital frontal cortex, brain imaging studies have neglected to link the systems that they have identified to performance measures. Thus, as Parasuraman, Warm, and See (1998) have noted, the functional role of the brain systems identified in the imaging studies remains largely unknown. Likely reasons for this drawback are the cost of encumbering PET and fMRI equipment for the prolonged running times characteristic of vigilance research, the limitation in temporal resolution, and the noise inherent in fMRI.

In an effort to bridge the gap in our understanding of performance and brain systems and vigilance, Mayleben (1998) made use of TCD-measures of cerebral hemovelocity, an imaging technique with good temporal resolution that offers the dual advantages of low-cost and release from the restrictive environments associated with PET and fMRI procedures. Consistent with the findings of Paus and his associates (1997), Mayleben (1998) demonstrated that the vigilance

decrement, as reflected in a decline in signal detections, was accompanied by a parallel decline in cerebral hemovelocity. He also reported that the overall magnitude and rate of hemovelocity decline was closely tied to the differential information-processing demands of the tasks employed. The results of the Mayleben study were generally consistent with a resource model of vigilance proposed by Parasuraman and his associates which holds that demanding tasks consume more information-processing assets than their less demanding counterparts and that the vigilance decrement results from the depletion of information-processing resources that are not replenished in the time available (Davies & Parasuraman, 1982; Parasuraman, 1979; Parasuraman, Warm, & Dember, 1987). Accordingly, Mayleben suggested that cerebral blood flow might represent a metabolic index of the utilization of information-processing assets.

The purpose of the present study was to extend the line of research initiated by Mayleben (1998) into the linkage between TCD-measured hemovelocity, task demands, and vigilance performance by manipulating two other variables that could be tied conceptually to a resource utilization model: salience and cueing.

Within the Parasuraman resource model, it seemed reasonable to assume that more processing resources would need to be dedicated to the detection of low salience (low signal-to-noise ratio) as compared to high salience (high signal-to-noise ratio) signals. Accordingly, it was anticipated that as in the case of the Mayleben (1998) experiment, the more demanding condition (low signal salience) would be associated with elevated blood flow levels and a more pronounced blood flow decrement over time in comparison to the less demanding (high salience) condition. Given the findings of Hitchcock and his associates (1999) that reliable cueing reduces the observing/decision making demand placed upon observers over time, it was also anticipated that in the presence of perfectly reliable cueing, the temporal decrement in blood flow would be

attenuated in comparison to a non-cued condition and also in comparison to conditions in which cueing was less than perfectly reliable, since observers in such conditions would not be relieved of the need to attend continuously to the vigilance display. Finally, in view of previous brain-imaging and psychophysical findings indicating that vigilance performance is controlled by the right cerebral hemisphere (Berman & Weinberger, 1990; Buchsbaum et al., 1990; Cohen et al., 1988; 1992; Davis, 1988; Deutsch et al., 1987; Lewin et al., 1996; Mayleben, 1998; Pardo, Fox, & Raichle, 1991; Reivich & Gur, 1985; Warm et al., 1976; 1980), it was also anticipated that the hemovelocitv effects in this study would be predominantly right-lateralized.

The results of the study were not entirely concordant with these expectations, but they were generally consistent with them. As in several prior investigations (Adams, 1956; Becker et al., 1995; Corcoran et al., 1977; Gluckman, 1988; Guralnick, 1972; Loeb & Binford, 1963, Parasuraman & Mouloua, 1977; Thurmond et al., 1970; Tickner et al, 1972; Wiener, 1964), high-salience signals were detected significantly more often than low-salience signals, and this result was accompanied by a strong tendency ($p = .09$) for blood flow to be greater in the context of the latter (high demand) than the former (low demand). While the expectations regarding performance, blood flow, and time on task were not confirmed in regard to the salience factor in and of itself, they were verified in complex interactions involving cueing, time, hemisphere, and salience.

The principal finding with regard to cueing and performance was a Cue x Time interaction. Performance efficiency remained stable over time in the 100% reliable cueing condition but declined over time in the remaining conditions, so that by the end of the vigil, performance efficiency was clearly best in the 100% reliable group followed in order by the 80% reliable, 40% reliable, and no-cue groups. In a strikingly similar manner, hemovelocitv scores,

which were comparable for the several cueing conditions during the early portions of the vigil, showed differential rates of decline over time, so that by the end of the vigil, blood flow was clearly highest in the 100% reliable group followed in order by the 80% reliable, 40% reliable, and no-cue groups. This result, however, was restricted to data taken from the right hemisphere under low salience conditions. The fact that the result was limited to low salience signals is consistent with a recent study indicating that brain systems involving glucose metabolism need to be sufficiently challenged in order for measurable physiological changes to emerge in cognitive and attentional processing tasks (Korol & Gold, 1998) and also with reports that the right hemisphere is dominant over the left when viewing conditions are difficult (Hellige, 1993). Restriction of the cue/time/salience hemovelocitv findings to the right hemisphere, coupled with the finding of a generally higher overall level of blood flow in that hemisphere as compared to the left, is consistent with expectations about right hemisphere control of vigilance. On a broader level, it is also consistent with the notion that the right hemisphere is implicated in metacontrol processes involving the allocation of attentional resources to task demands (Hoptman & Davidson, 1994; Tucker & Williamson, 1984).

Although the concordance of the results for signal detection and brain blood flow across the differential cueing/time/salience conditions fits well with a resource model of vigilance and with Mayleben's (1998) view that brain blood flow may represent a metabolic index of the utilization of information-processing assets, an account of the present results along this line can be challenged in several ways. For example, one may note that observers find vigilance tasks to be stressful as revealed through measures of boredom and frustration (Hitchcock et al., 1999; Scerbo, 1998; Scerbo, Greenwald, & Salwin, 1992; Warm, 1993; Warm, Dember, & Hancock 1996). Consequently, the differential rates of decline in hemovelocitv over time among the

several cueing groups in the low salience condition may reflect task disengagement rather than the diminished availability of information-processing assets. Such a possibility is unlikely, however, given the substantially higher false alarm rate seen throughout the vigil in the no-cue and the 80% reliable and 40% reliable cueing groups in comparison to the 100% reliable group. Arguably, observers in these conditions would not be making such a high rate of false alarms if they had disengaged from the task.

Still another potential challenge to an account of the present data in terms of a resource model comes from the finding that brain blood flow velocity is sensitive to changes in blood pressure and cardiac output (Caplan et al. 1990). Assuming that stress can have an impact upon these indices (Lacey, 1967), one could argue that the cue/ time/salience hemovelocity findings do not reflect information processing per se, but instead, some sort of gross change in systemic vascular activity that happened to be detected through the measurement of cerebral blood flow. The lateralization of the relations between cueing, time and salience in the hemovelocity data, however, strongly challenges such a view by demonstrating an anticipated site-dependency that is consistent with earlier brain imaging and psychophysical findings (Berman & Weinberger, 1990; Buchsbaum et al., 1990; Cohen et al., 1988; 1992; Davis, 1988; Deutsch et al., 1987; Lewin et al., 1996; Mayleben, 1998; Pardo, Fox, & Raichle, 1991; Reivich & Gur, 1985; Warm et al., 1976; 1980).

While the interactive effects of cueing, time and salience were limited to the right hemisphere, it is important to point out that the left hemisphere showed a decrement in blood flow over time that was independent of cueing in both the high and low signal salience conditions. Thus, the decline in blood flow over time observed in this study was ubiquitous in character, appearing in both hemispheres. Mayleben (1998) and Paus et al. (1997) also found

blood flow declines in both cerebral hemispheres. Evidently, vigilance performance is not completely lateralized. While the right hemisphere may have primary responsibility for the control of vigilance, both hemispheres play a role in the vigilance decrement. A view of this sort is consistent with Hellige's (1993) argument that even relatively simple tasks require the coordination of a number of information-processing subsystems as well as with the argument that a cooperative interaction model best describes the mode of central functioning in regard to the vigilance decrement (Allen, 1983; Hoptman & Davidson, 1994; Warm, Schumsky, & Hawley, 1976). Of course, that position is predicated on the assumption that the temporal decline in blood flow is based upon information-processing demand and is not simply the result of a general decline in arousal level (cf. Frankmann & Adams, 1962; Heilman, 1995). Such an assumption seems reasonable, since blood flow in the present study only declined over time when observers were confronted with a performance imperative; it remained stable over time in the passive observing condition, where the absence of meaningful activity should have led to a drop in hemovelocity under the classic arousal or activation model.

As noted in Chapter 1, recent thinking about the activation and resource models of vigilance has led to the view that these approaches are not necessarily mutually exclusive — arousal can be viewed as the agent responsible for the production of resources (Humphreys & Revelle, 1984; Parasuraman, Warm, & See, 1998; Warm, Dember, & Hancock, 1996). Support for that view comes from studies by Matthews and Davies (1998) showing that a self-report measure of arousal known as energetic arousal, which correlates with measures of autonomic activity during performance testing, may be linked to the availability of information-processing resources. Consequently, the present study made use of pre-post measures of energetic arousal, as indexed by the DSSQ (Matthews et al., 1999), to determine the degree to which changes in a

metabolic index of resource utilization (hemovelocity) were paralleled by changes in that arousal measure. Pre-vigil assessment of energetic arousal occurred immediately after observers were informed about the vigilance task they were to perform and about TCD measurement. The scores in all of the experimental groups at this time were uniformly higher than those of the DSSQ norm group, a result which may be attributable to heightened excitement brought about by observers' expectations of their upcoming requirement to contend with an unfamiliar task and a novel form of physiological measurement. Post-vigil, however, the energetic arousal scores fell below both those of the norm group and of the pre-test levels, indicating a task-related decline in energy. Of particular interest in this study was the significant Cueing x Phase interaction, in which the scores for the several cueing conditions were similar to each other pre-vigil, but dropped differentially post-vigil, with the ordering of the decline least for the 100% cueing group and greatest for the 40% and no-cue groups. The Cue x Phase interaction in the energetic arousal data was highly reminiscent of the Cue X Periods interactions found in the signal detection and hemovelocity data. Accordingly, the results of this study lead to the conclusion that performance-related changes in blood flow and energetic arousal may share common mechanisms.

All prior studies of cueing and vigilance have made use of completely veridical cueing regimens (Aiken & Lau, 1967; Annett, 1966; Annett & Clarkson, 1964; Annett & Patterson, 1966; 1967; Hitchcock et al., 1999; Weiner & Attwood, 1968). The present study represents the initial experimental effort to examine the effects of less than reliable cueing on vigilant behavior. In addition to its implications for testing theoretical ideas about resource utilization, this manipulation also has practical ramifications for the use of cueing in automated systems designed to forewarn monitors of impending untoward events in the operational world. Examples

of such systems are those that prompt combat pilots to take notice of an enemy weapon system's radar lock or of equipment problems in their aircraft (Barnette, 1988). While the reliability of some of these operational systems is less than perfect (Ellis, McGreevy, & Hitchcock, 1987; Merwin, O'Brien, & Wickens, 1997), one might take the position in designing them that some cueing is better than none. The present results suggest that such a stance warrants careful consideration. Highly reliable cueing appears to be effective in maintaining performance, blood flow, and energy, in contrast with the decline in these measures seen in the no-cueing condition. The benefits of partial cueing were considerably less pronounced. Therefore, implementation of less than reliable cueing in operational systems may not be cost-effective.

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APPENDIX A
Instructions sets for the vigilance tasks

Verbatim Instructions to participants in the HIGH signal salience conditions.

Instruction set 1:

During this experiment, you will be taking on the role of air-traffic controller. Your task will be to monitor a radar screen with various flight regions marked across its face. Two black lines will represent jet aircraft flying at the same speed and altitude in either a Northeast-Southwest or Northwest-Southeast direction toward a city located at the center of the radar screen. (note: this will become more clear you when you see the examples that follow).

Normally, the flight paths of the aircraft will enable them to pass each other with a safe distance between them. You do not need to make any response all to a *safe path*. Occasionally, however, the aircraft will be traveling toward each other on the same line, and they will collide unless you, the air-traffic controller, sends a warning. Hence, your job is to respond by pressing the spacebar whenever the aircraft are on a *collision path*. But you should not press the spacebar indiscriminately- respond only when the aircraft appear to be on a collision path.

Press the spacebar to view examples of the safe and unsafe flight paths.

[presentation of example flight paths]

Verbatim Instructions to participants in the LOW signal salience conditions.

Instruction set 1:

During this experiment, you will be taking on the role of air-traffic controller. Your task will be to monitor a radar screen with various flight regions marked across its face. Two faint lines will represent jet aircraft flying at the same speed and altitude in either a Northeast-Southwest or Northwest-Southeast direction toward a city located at the center of the radar screen. (note: this will become more clear you when you see the examples that follow).

Normally, the flight paths of the aircraft will enable them to pass each other with a safe distance between them. You do not need to make any response all to a *safe path*. Occasionally, however, the aircraft will be traveling toward each other on the same line, and they will collide unless you, the air-traffic controller, sends a warning. Hence, your job is to respond by pressing the spacebar whenever the aircraft are on a *collision path*. But you should not press the spacebar indiscriminately- respond only when the aircraft appear to be on a collision path.

Press the spacebar to view examples of the safe and unsafe flight paths.

[presentation of example flight paths]

Subsequent instruction sets are similar for both high and low signal salience conditions.
Instruction set 2:

A short practice session will now follow in order to acquaint you with the display and the responses required from you. During this practice you will receive feedback about your performance. The computer will say “YES” if you correctly press the spacebar when the planes are approaching the city along a collision path. The computer will say “NO” if you respond when the flight paths of the aircraft are not in line with each other, because the planes will be approaching the city along a safe path, and in these cases you do not need to make any response at all. The computer will say “MISS” if you accidentally fail to press the spacebar after a collision path occurs.

Also, please do not press the spacebar indiscriminately, respond only when the aircraft appear to be on a collision path. Also, it is important not to respond while the radar screen is on wait until after it has flashed off the computer screen before pressing the spacebar.

Any questions ?

After the curtain has been closed, you may press the to begin the practice session.

[five-minute practice session]

Another practice session similar to the first one will now follow. Once again, when the flight paths of the aircraft are not in line with each other, the planes will be approaching the city along a safe path, and you do not need to make any response at all. And again, when the flight has the aircraft *are* in line with each other, the planes will be approaching the city along a collision path, and you need to respond by pressing the spacebar, but do not press the spacebar indiscriminately, respond *only* when the aircraft appear to be on a collision path

Remember also the importance of not responding while the radar screen is on, wait until after it has flashed off the computer screen before pressing the spacebar

Any questions ?

[presentation of example flight paths]

After the curtain has been closed, you may press the to begin the practice session.

[five-minute practice session]

Instruction set 3:

The experimental session will now follow. During the experiment, all of the signals that you will see will be the same as those during the practice sessions.

However, there will be no feedback during this session.

Remember, when the flight paths of the aircraft are in line with each other, the planes will be approaching the city along a *collision path*, and you need to respond by pressing the space bar. Also, just as before, you should not press a spacebar indiscriminately, respond only when the aircraft appear to be on a collision path

The screens that follow will again demonstrate the safe and unsafe paths.

[presentation of example flight paths]

Verbatim Instructions to participants in the 100% Cueing conditions.**Instruction set 4:**

During this part of the experiment, the computer will say “LOOK” in order to warn you that a *collision path* will appear in one of the next five radar screens that you will see. Collision paths will occur only after you have received as warning and never at any other time during the session.

Therefore, collision paths will always be cued by the warning for you to “LOOK”. When the warning does not occur, you need not be concerned that the aircraft might be flying on a collision path. It is however necessary that you remain in close proximity to the computer so you are able to respond to the warnings and a timely manner.

So remember, when the flight paths of the aircraft are in line with each other, the planes will be approaching the city along a *collision path*, and you need to respond by pressing the spacebar. As before, do not respond while the radar screen is on, wait until after it has flashed off the computer screen before pressing the spacebar.

Any questions?

After the curtain has been closed, you may press the to begin the experimental session.

[40-minute vigilance task]

Verbatim Instructions to participants in the 80% Cueing conditions.

Instruction set 4:

During this part of the experiment, the computer will say “LOOK” in order to warn you that a *collision path* will appear in one of the next five radar screens that you will see. The automation which provides this cue is not perfectly reliable.

The warning to “LOOK” will still accurately precede 80% of all the potential collision paths. Consequently, the warning to “LOOK” will be a “False alarm” 20% of the time, and more importantly, 20% of the potential collision paths will occur or without any cue to “LOOK”.

So remember, signals may not always occur on cue, and may appear at other times.

Also, just as before, when the flight paths of the aircraft are in line with each other, the planes will be approaching the city along a *collision path*, and you need to respond by pressing the spacebar. As before, do not respond while the radar screen is on, wait until after it has flashed off the computer screen before pressing the spacebar.

Any questions?

After the curtain has been closed, you may press the to begin the experimental session.

[40-minute vigilance task]

Verbatim Instructions to participants in the 40% Cueing conditions.

Instruction set 4:

During this part of the experiment, the computer will say “LOOK” in order to warn you that a *collision path* will appear in one of the next five radar screens that you will see. The automation which provides this cue is not perfectly reliable.

The warning to “LOOK” will still accurately precede 40% of all the potential collision paths. Consequently, the warning to “LOOK” will be a “False alarm” 60% of the time, and more importantly, 60% of the potential collision paths will occur or without any cue to “LOOK”.

So remember, signals may not always occur on cue, and may appear at other times.

Also, just as before, when the flight paths of the aircraft are in line with each other, the planes will be approaching the city along a *collision path*, and you need to respond by pressing the spacebar. As before, do not respond while the radar screen is on, wait until after it has flashed off the computer screen before pressing the spacebar.

Any questions?

After the curtain has been closed, you may press the to begin the experimental session.

[40-minute vigilance task]

Verbatim Instructions to participants in the No-Cue conditions.

Instruction set 4:

During this part of the experiment, the computer will say “LOGGED” after you have responded by pressing the space bar. This indicates that your warning has been received by the aircraft, but the statement contains no evaluative information.

Remember, when the flight paths of the aircraft are in line with each other, the planes will be approaching the city along a *collision path*, and you need to respond by pressing the spacebar. As before, do not respond while the radar screen is on, wait until after it has flashed off the computer screen before pressing the spacebar.

Any questions?

After the curtain has been closed, you may press the to begin the experimental session.

[40-minute vigilance task]

APPENDIX B
Detailed summaries of all ANOVA tables

Table B1.
Analysis of Variance for Correct Detection scores

<u>Source</u>	<u>df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>p</u>
<u>Between Subjects</u>	127	-----			
Salience (A)	1	-----	6.711	9.08	<.01
Cueing (B)	3	-----	8.230	11.14	<.001
AB	3	-----	0.198	0.27	>.05
S/G	120	-----	0.739		
<u>Within Subjects</u>	384				
Period (C)	3	3	3.704	29.49	<.001
AC	3	3	0.197	1.57	>.05
BC	9	8	0.757	6.03	<.001
ABC	9	8	0.095	0.76	>.05
C x S/G	360	338	0.126		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.94

Table B2.
Analysis of Variance for False Alarm scores

<u>Source</u>	<u>df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>p</u>
<u>Between Subjects</u>	127	-----			
Salience (A)	1	-----	0.131	2.33	>.05
Cueing (B)	3	-----	1.035	18.39	<.001
AB	3	-----	0.136	2.48	>.05
S/G	120	-----	0.056		
<u>Within Subjects</u>	384				
Period (C)	3	2	0.023	2.90	<.05
AC	3	2	0.017	2.09	>.05
BC	9	7	0.004	0.49	>.05
ABC	9	7	0.011	1.34	>.05
C x S/G	360	292	0.008		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.81

Table B3.

Analysis of Variance for Cerebral Hemovelocity at Baseline

<u>Source</u>	<u>Df</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	127			
Saliency (A)	1	68.77	0.66	>.05
Cueing (B)	3	70.36	0.68	>.05
Hemisphere (C)	1	0.09	0.00	>.05
AB	3	19.74	0.19	>.05
AC	1	128.76	1.24	>.05
BC	3	77.16	0.74	>.05
ABC	3	53.66	0.52	>.05
S/G	112	104.11		

Table B4.

Analysis of Variance for Cerebral Hemovelocity for Passive Observer group

<u>Source</u>	<u>Df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	15	-----			
Hemisphere (A)	1	-----	0.013	0.29	>.05
Saliency (B)	1	-----	0.074	1.64	>.05
Gender (C)	1	-----	0.000	0.00	>.05
AB	1	-----	0.041	0.90	>.05
AC	1	-----	0.030	0.67	>.05
BC	1	-----	0.000	0.00	>.05
ABC	1	-----	0.003	0.07	>.05
S/G	8	-----	0.045		
<u>Within Subjects</u>	48				
Period (D)	3	1	0.011	0.47	>.05
AD	3	1	0.018	0.82	>.05
BD	3	1	0.019	0.83	>.05
CD	3	1	0.010	0.44	>.05
ABD	3	1	0.017	0.79	>.05
ACD	3	1	0.026	1.14	>.05
CBD	3	1	0.005	0.20	>.05
ABCD	3	1	0.019	0.88	>.05
D x S/G	24	9	0.023		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.37

Table B5.
Analysis of Variance for Cerebral Hemovelocity during Active Vigilance

<u>Source</u>	<u>Df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	127	-----			
Hemisphere (A)	1	-----	0.107	4.24	<.05
Saliency (B)	1	-----	0.074	2.93	>.05
Cueing (C)	3	-----	0.059	2.31	>.05
AB	1	-----	0.008	0.30	>.05
AC	3	-----	0.014	0.53	>.05
BC	3	-----	0.029	1.18	>.05
ABC	3	-----	0.005	0.20	>.05
S/G	112	-----	0.025		
<u>Within Subjects</u>	384				
Period (D)	3	2	0.089	34.14	<.001
AD	3	2	0.000	0.02	>.05
BD	3	2	0.007	2.56	>.05
CD	9	5	0.012	4.78	<.001
ABD	3	2	0.001	0.55	>.05
ACD	9	5	0.006	2.41	<.05
CBD	9	5	0.002	0.63	>.05
ABCD	9	5	0.007	2.87	<.05
D x S/G	336	197	0.003		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.59

Table B6.
Analysis of Variance for Cerebral Hemovelocity within High Saliency

<u>Source</u>	<u>Df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	63	-----			
Hemisphere (A)	1	-----	0.086	6.07	<.05
Cueing (B)	3	-----	0.021	1.51	>.05
AB	3	-----	0.002	0.16	>.05
S/G	56	-----	0.014		
<u>Within Subjects</u>	192				
Period (C)	3	2	0.026	11.80	<.001
AC	3	2	0.001	0.464	>.05
BC	9	5	0.005	2.20	>.05
ABC	9	5	0.000	0.26	>.05
C x S/G	168	95	0.002		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.56

Table B7.

Analysis of Variance for Cerebral Hemovelocitv within Low Salience

<u>Source</u>	<u>Df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	63	-----			
Hemisphere (A)	1	-----	0.029	0.79	>.05
Cueing (B)	3	-----	0.067	1.84	>.05
AB	3	-----	0.016	0.44	>.05
S/G	56	-----	0.037		
<u>Within Subjects</u>	192				
Period (C)	3	2	0.069	22.81	<.001
AC	3	2	0.000	0.16	>.05
BC	9	5	0.009	3.05	<.05
ABC	9	5	0.013	4.25	<.001
C x S/G	168	100	0.003		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.60

Table B8.

Analysis of Variance for Cerebral Hemovelocitv for Left Hemisphere/Low Salience

<u>Source</u>	<u>Df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	31	-----			
Cueing (A)	3	-----	0.038	0.932	>.05
S/G	28	-----	0.042		
<u>Within Subjects</u>	96				
Period (B)	3	2	0.030	25.11	<.001
AB	9	7	0.001	1.12	>.05
B x S/G	84	67	0.001		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.80

Table B9.

Analysis of Variance for Cerebral Hemovelocitv for Right Hemisphere/Low Salience

<u>Source</u>	<u>Df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	31	-----			
Cueing (A)	3	-----	0.045	1.42	>.05
S/G	28	-----	0.032		
<u>Within Subjects</u>	96				
Period (B)	3	2	0.035	6.58	<.01
AB	9	7	0.024	4.56	<.01
B x S/G	84	67	0.005		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 0.51

Table B10.
Analysis of Variance for DSSQ Energetic Arousal scores

<u>Source</u>	<u>df</u>	<u>df_{adj.}</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	127	-----			
Salience (A)	1	-----	0.972	0.93	>.05
Cueing (B)	3	-----	1.742	1.67	>.05
AB	3	-----	0.834	0.80	>.05
S/G	120	-----	1.045		
<u>Within Subjects</u>	128				
Phase(C)	1	1	31.329	71.65	<.001
AC	1	1	0.085	0.19	>.05
BC	3	3	1.285	2.94	<.05
ABC	3	3	0.655	1.49	>.05
C x S/G	120	120	0.437		

Note: df_{adj.} = degrees of freedom obtained when Box's ϵ is used to correct for violations of sphericity. Box's ϵ = 1.00

Table B11.
Analysis of Variance for Pre-vigil DSSQ Energetic Arousal scores

<u>Source</u>	<u>Df</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	127			
Salience (A)	1	0.241	0.33	>.05
Cueing (B)	3	0.792	1.08	>.05
AB	3	0.529	.722	>.05
S/G	120	0.733		

Table B12.
Analysis of Variance for Post-vigil DSSQ Energetic Arousal scores

<u>Source</u>	<u>Df</u>	<u>MS</u>	<u>F</u>	<u>P</u>
<u>Between Subjects</u>	127			
Salience (A)	1	0.816	1.09	>.05
Cueing (B)	3	2.236	2.99	<.05
AB	3	0.959	1.28	>.05
S/G	120	0.749		