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A Comparison of Cerebral Hemovelocity and Blood Oxygen Saturation Levels During Vigilance Performance

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ABSTRACT

This study compared measures of cerebral blood flow velocity (CBFV) and blood oxygen saturation (rSO_2), during the performance of a 40-min vigilance task. Observers monitored a simulated air-traffic control display for flight path deviations which occurred in a unidirectional or a multidirectional context. CBFV and rSO_2 measures were secured from the medial cerebral arteries in the left and right cerebral hemispheres and from the corresponding frontal lobes, respectively.

Performance efficiency was greater in the unidirectional than the multidirectional condition and declined over time in both conditions, more so in the multidirectional condition. This pattern of results was paralleled in different ways by the two hemodynamic measures. A result of this sort challenges the assumption of a close tie between cerebral blood flow and oxygen saturation (Siesjo, 1978) and supports recent findings (Mintun et al., 2001) that cerebral blood flow and oxygen levels are not tightly coupled in active brain states.

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CHAPTER 1

Introduction

The Problem of Vigilance

Vigilance in a Modern World. Vigilance or sustained attention concerns the ability of observers to detect infrequent and unpredictable signals over extended periods of time (Warm, Parasuraman, & Matthews, 2008). That aspect of human performance is important to human factors/ergonomic specialists because of the vital role that vigilance occupies in automated human-machine systems (Adams, 1987; Craig, 1984; Davies & Parasuraman, 1982; Howell, 1993). Advancements in technology have transformed the roles of many workers from active controllers to system executives who monitor the functions of machines and intervene only in the event of potential problems or malfunctions (Sheridan, 1970, 1980). Consequently, vigilance is a critical component of human performance in a diverse array of work environments, including military surveillance, air-traffic control, cockpit monitoring, sonar monitoring, seaboard navigation, transportation security, border security, nuclear power plant regulation, industrial quality control, long distance driving, and agricultural inspection tasks (Dorian, Roach, Fletcher, & Dawson, 1997; Hancock & Hart, 2002; Hartley, Arnold, Kobryn, & Macleod, 1989; Johnson & Merullo, 2000; MacBride, Murillo, Johnson, & Banderet, 2007; Mackie, Wylie, & Smith, 1994; Satchel, 1993; Warm, 1984, 1993; Warm, Parasuraman, et al., 2008). Vigilance also contributes to performance efficiency in medical settings, including x-ray and cytological screening, and the inspection of anesthesia gauges during surgery (Daley & Wilson, 1993; Gill, 1996; Weinger & Englund, 1990).

While automation has reduced the information-processing load placed on observers and has enhanced productivity (Parasuraman, 1987; Warm, 1993; Wiener, 1984, 1985), it appears to have some negative aspects as well. Several studies have shown that accidents ranging in scale from minor to major are often the result of vigilance failures on the part of human operators (Hawley, 2006; Hawley, Mares, & Giammanco, 2005; Molloy & Parasuraman, 1996). One solution would be to design automated systems that eliminate the need for the human component. However, this is often unfeasible because human judgment is required in the event of system malfunction (Parasuraman, 1987). Hence, understanding the factors that influence vigilance performance and their underlying mechanisms is a critical human factors concern for system reliability and for public safety and health (Nickerson, 1992).

Historical Beginnings. The term vigilance was first used by Sir Henry Head (1923) to describe a state of maximum physiological and psychological readiness to react (Davies & Parasuraman, 1982; Warm, 1984). An early investigation of vigilance was carried out by Wayatt and Langdon (1932) who examined temporal factors in the performance of cartridge case inspectors looking for packaging flaws. However, the programmatic study of vigilance was not initiated until the Second World War when Norman Mackworth (1948; 1950/1961) was commissioned by the British Royal Air Force to investigate an unanticipated and potentially perilous problem in the performance of airborne radar observers searching for German submarines in the Bay of Biscay. After approximately 30 minutes on task, the observers began to miss signals on their “pulse position” radar sets indicating the presence of German U-boats on the surface of the sea below. As a result, the U-boats were free to interfere with Allied shipping. This problem had serious implications. First and foremost, it led to a heavy cost in terms of loss life and denial to the Allied forces of needed supplies of food, medicine, fuel, and materiel. In addition, the failure of signal detection on the part of well-trained and highly motivated observers pointed to a major deficiency in human effectiveness when working with what was then a newly developed radar technology to combat the U-boat threat (Warm, Dember, & Hancock, 1996).

To study this problem, Mackworth created a simulated radar display called the "Clock Test" wherein a black pointer moved along the circumference of a blank-faced clock devoid of any scale markings or reference points. Normally, the pointer made small 0.3 inch jumps to a new position once per second. Occasionally, it would execute a larger "double jump" of 0.6 inches. These larger jumps were the critical signals for detection. In Mackworth's experiments observers were tested individually in a prolonged and continuous task (two hours). Critical signals were clearly perceivable when observers were alerted to them but were not compelling changes in the operating environment. The signals appeared with low probability (approximately 3 to 6 percent of the time), in a temporally unpredictable manner, under conditions in which the observers were devoid of control over their occurrence. In general, this experimental setup has become the standard in vigilance research (Warm, 1984).

With the Clock Test in hand, Mackworth was able to confirm in controlled laboratory studies the field-generated observation that the quality of sustained attention is fragile, waning rapidly over time. He found that the frequency of signal detections declined by ten percent within the initial 30 min of the task and continued to drop off more gradually thereafter. The decline in performance over time, termed the *vigilance decrement* or *the decrement function,* has been replicated in a large array of subsequent experiments and is now the quintessential finding in vigilance research (Matthews, Davies, Westerman, & Stammers, 2000; See, Howe, Warm, & Dember, 1995; Warm, Parasuraman, et al., 2008). Much of the decrement typically appears within the first 15 min of watch (Teichner, 1974). However, when signal/noise discriminations are especially difficult, it can appear as rapidly as in the first five min (Helton, Dember, Warm,

& Matthews, 2000; Helton et al., 2007; Jerison, 1963; Neuchterlein, Parasuraman, & Jiang, 1983; Rose, Murphy, Byard, & Nikzand, 2002; Temple et al., 2000). The vigilance decrement has been found with both naïve and experienced observers and counter to Mackie's (1994) affirmation that it is an artificial laboratory phenomenon, the decrement occurs in operational settings as well (Baker, 1962; Colquhoun, 1967, 1977; Pigeau, Angus, O'Neill, & Mack, 1995; Schmidke, 1976).

The vigilance decrement has conventionally been considered to be brought about by a decline in arousal prompted by the understimulating nature of vigilance tasks (Frankmann & Adams, 1962; Heilman, 1995; Loeb & Alluisi, 1984). According to that view, the repetitious and monotonous nature of vigilance tasks reduces the action of brain systems needed for continued alertness. As a result, observers become lethargic and signal detection is reduced. More recent research has challenged the arousal model and shown that vigilance tasks impose substantial demands on the information processing resources of observers and are highly stressful (Warm, Parasuraman, et al., 2008). This view has emerged from studies of (1) neural measures of resource demand in vigilance, (2) perceived mental workload, and (3) task-induced stress. The present study was centered on the neurophysiological dimension. Along that line, it fits within the emerging "neuroegonomic" trend in human factors which seeks to identify the neural basis of human performance of which vigilance plays an important part (Parasuraman & Wilson, 2008).

Cerebral Hemodynamics

Brain Imaging: The PET and fMRI techniques. Efforts to identify neurophysiological factors that support vigilance performance have adopted two general approaches. One of these involves exploration of the electrophysiological and biochemical correlates of signal detection (Davies & Parasuraman, 1982; Gale, 1977; Haider, 1970; Hitchcock, 2000; Koelega, 1991;

Koelega & Verbaten, 1991; Milgram, Callahan, & Siwak, 1999; Parasuraman, 1984). The other, and the one of primary interest in this study, is the use of sophisticated brain imaging techniques to identify brain systems in the control of vigilance.

Concordant with a view proposed by Sir Charles Sherrington more than 100 years ago (Roy & Sherrington, 1890), a considerable amount of research in brain imaging using positron emission tomography (PET) and functional magnetic imaging (fMRI) techniques has shown that there is a close tie between cerebral hemodynamics and neural activity in the performance of mental tasks (Moore & Cao, 2007; Raichle, 1998; Risberg, 1986). The PET technique is founded on the principle that as mental activity is increased, there is an associated increase in blood flow to provide the oxygen and glucose required for metabolic activity within the central nervous system (Corbetta, 1998; Kandel, Schwartz, & Jessell, 2000; Papanicolaou, 1998). In order to provide functional images of brain activity, observers are infused intravenously with a radioactive form of glucose that is metabolized by the brain (Beatty, 2001). By means of a special detector, PET measures metabolic activity in different brain areas through differential accumulation of the radioactive tracer with the underlying rationale that the most active brain regions at any given time will use the most glucose and therefore accumulate the most radioactivity (Beatty, 2001; Kandel et al., 2000).

The fMRI technique makes use of a different source of information to provide images of brain function. That source is known as nuclear magnetic resonance wherein radio frequency waves are used to detect the magnetic properties of oxygenated and non-oxygenated hemoglobin to identify changes in regional cerebral blood flow associated with neural activity (Beatty, 2001; Calhoun, 2007; Haxby, Courtney, & Clark, 1998; Kolb & Wishaw,1990).

As described in a review by Parasuraman, Warm, and See (1998), studies utilizing the PET and fMRI techniques have identified multiple brain regions that may be involved in the performance of vigilance tasks. These regions include the frontal lobes, the cingulate gyrus, and brainstem structures.

The frontal lobes of the human brain comprise all of the tissue rostral to the central sulcus and are responsible for a variety of "executive functions" involving attention and planning future action (Kandel et al., 2000; Kolb & Wishaw, 1990).

A number of PET and fMRI investigations have reported frontal lobe activation during the performance of a vigilance task and that such activation appears to be lateralized to the right prefrontal cortex (Berman & Weinberger, 1990; Buschbaum et al., 1990; Cohen, Semple, Gross, & Halcomb, 1988; Cohen, Semple, Gross, King, & Nordahl, 1992; Coull, Frackowiak, & Frith, 1998; Deutsch, Papanicolaou, Bourbon, & Eisenberg, 1987; Lewin et al., 1996; Pardo, Fox, & Raichle, 1991; Reivich & Gur, 1985). The laterality effects noted in these studies are consistent with the findings obtained with another neuroimaging technique known as the $xenon^{133}$ procedure (Berman & Weinberger, 1990; Deutsch, Papanicolau, Bourban, & Eisenberg, 1987). They are also consistent with psychophysical experiments which made use 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 (Hellige, 1993). These studies have shown that the beneficial effects associated with reductions in the temporal uncertainty of critical signal occurrences were more pronounced for stimuli delivered to the left ear/right hemisphere than for right ear/left hemisphere presentations and that the vigilance decrement was greater for signals delivered to the right hemisphere via the left ear than for those delivered to the left hemisphere via the right ear (Warm, Richter, Sprague, Porter, & Schumsky, 1980; Warm, Schumsky, & Hawley, 1976). In addition, studies by Diamond (1979a, 1979b) on patients in whom the connections between the cerebral hemispheres were severed have shown that such "split-brain" patients consistently performed more effectively with right as compared to left hemisphere signals on visual and tactual as well as auditory vigilance tasks.

The cingulate gyrus, which is located just above the corpus collosum and is part of the limbic system (Kandel et al., 2000; Kolb & Wishaw, 1990), has also been implicated in vigilance by brain imaging studies (Cohen et al., 1988, 1992; Coull, Franckowiak, & Grasby, 1996; Posner & Peterson, 1990). Contrary to the activation found in the frontal lobes, activity in this structure is reduced during the performance of a vigilance task. Posner and Peterson (1990) have suggested that since the cingulate gyrus has executive as well as target detection functions, reduced activation in this area may be needed to optimize performance in vigilance and other tasks in which targets occur infrequently.

The brainstem is continuous with the spinal cord and contributes to a variety of sensory and motor systems (Kandel et al., 2000). Two brainstem structures, the midbrain reticular formation and the left intralaminar region of the thalamus, have been implicated in vigilance. Using the PET procedure, Kinomora, Larsson, Gulas, and Roland (1996) found increased blood flow in the midbrain reticular formation and the left intralaminar region of the thalamus during the performance of somatosensory and visual vigilance tasks indicating that these structures play a role in the control of vigilance.

Problems with the PET and fMRI studies. Although the imaging studies described above have identified brain regions involved in vigilance, Warm and his associates (Parasuraman et al., 1998; Warm, Matthews, & Parasuraman, 2009; Warm & Parasuraman, 2007) have pointed out that there are major limitations to this research. They note that with the exception of two PET studies (Coull et al., 1998; Paus et al., 1997) the brain imaging studies have neglected to link the systems they have identified to performance efficiency, perhaps because of the high cost of using PET and fMRI during the prolonged running times typically involved in vigilance research. Thus, the *functional role* of the brain systems identified in the PET and fMRI studies remains largely unknown. Along that line, Gazzaniga, Ivry, and Mangun (2002) and Goldstein (2001) have emphasized the importance of linking imaging studies to performance for and understanding of cognitive neuroscience.

Other difficulties with the PET and fMRI studies are that they involve restrictive environments in which observers are required to remain almost motionless during the scanning procedure in order not to compromise the quality of the brain images (Corbetta, 1998) and fMRI acquisition is accompanied by loud noise. Observers in vigilance experiments rarely remain motionless, however. Instead, they tend to fidget during the performance of a vigilance task, more so as time on task increases (Galinsky, Rosa, Warm, & Dember, 1993), and acoustic noise can either degrade or enhance vigilance performance depending on the type of noise and the intensity involved (Becker, Warm, Dember, & Hancock, 1995; Hancock, 1984; Helton, Matthews, & Warm, 2009; Koelega & Brinkman, 1986; Lavine, Sibert, Gokturk, & Dickens, 2002). Hence, the conditions required for the effective use of the PET and fMRI techniques may not provide a suitable environment for linking changes in brain physiology with vigilance performance over a prolonged period of time. What is needed is an imaging technique that will avoid these limitations, such as Transcranial Doppler Sonography (TCD) and Near Infra-Red Spectroscopy (NIRS), the techniques featured in this investigation.

The TCD alternative

Basic principles of the TCD technique. As described by Tripp and Warm (2007), Transcranial Doppler Sonography is a noninvasive neuroimaging technique that utilizes ultrasound signals to monitor the mainstem intracranial arteries—the middle (MCA), anterior (ACA), and posterior (PCA) arteries. These arteries are readily isonated through a cranial "trans-temporal window" and exhibit discernable measurement characteristics that facilitate their identification. The technique uses a small 2mHz pulsed Doppler transducer to measure arterial blood flow. The transducer, which is typically worn in a headband, is placed immediately above the zygomatic arch along the temporal bone, a part of the skull that is functionally transparent to ultrasound. The depth of the pulse is adjusted until the desired intracranial artery is isonated. Most often, the MCA is utilized since it carries about 80% of the blood flow within each cerebral hemisphere (Netter, 1989; Toole, 1984). TCD measures the difference in frequency between the outgoing and reflected energy as it strikes moving erythrocytes (red blood cells). The magnitude of the shift in frequency is directly proportional to the velocity of the blood flow. As Warm and his associates (Warm et al., 2009; Warm & Parasuraman, 2007) have noted, the low weight and small size of the transducer and the ability to embed it in a convenient headband permit real-time measurement of cerebral blood flow while not limiting or being hampered by body motion. Therefore, TCD permits inexpensive, continuous, and prolonged monitoring of cerebral blood flow during task performance.

When a particular area of the brain becomes metabolically active, as is the case in the performance of mental tasks, by-products of this activity, such as carbon dioxide (CO_2), increase. This increase in CO_2 leads to a dilation of blood vessels serving that area, which results in increased blood flow to the region to remove the unwanted by-products (Aaslid, 1986; Hellige, 1993). Consequently, as indicated by Stroobandt and Vingerhoets (2000), TCD offers the possibility of measuring changes in metabolic activity during task performance. Along that line, it is important to emphasize, as Duschek and Schandry (2003) and Tripp and Warm (2007) have done, that the diameters of the ACA, MCA, and PCA remain largely unchanged under varying task demands, indicating that the hemovelocity changes in these larger arteries in which TCD measurements are obtained do not result from their own vascular activity. Instead, they derive from changes in blood demanded by their perfusion territories and thus changes in local neuronal activity. Unlike the PET and fMRI techniques, TCD does not provide information about changes in specific brain loci. However, it does provide gross hemispheric data with good temporal resolution (Aaslid, 1986) and compared to PET and fMRI, it can track rapid changes in blood flow dynamics that can be followed in real time under less restrictive and invasive conditions (Warm et al., 2009; Warm & Parasuraman, 2007).

In the past, TCD was used primarily in medicine for neurological diagnosis and for detecting the presence of intracranial vascular dysfunctions (Babikan & Wechsler, 1999; Bishop, Powell, Rutt, & Brouse, 1986; Caplan et al., 1990). Recent studies have indicated, however, that blood flow velocity in the MCA can be influenced by a variety of cognitively demanding tasks involving stimulus detection and anticipation, word association, solving mathematical problems, working with a complex performance battery, and making ethical decisions. In general, these activities accelerate blood flow velocity over resting baseline and these TCD measured changes are linked to the cognitive demand imposed by the tasks (see reviews by Duschek & Schandry, 2003; Klingelhofer, Sande, & Wittich, 1999; Stroobandt & Vingerhoets, 2000; Tripp & Warm, 2007). Because of its nonrestrictive and noninvasive nature, its good temporal resolution, its sensitivity to task demands, its potential for identifying lateralization effects, and evidence indicating an anatomical and functional linkage between areas that mediate perceptual and cognitive processes (Posner & Raichle, 1993), it appears that the TCD technique might be well suited to meet the need identified by Warm and his associates (Parasuraman et al., 1998; Warm et al., 2009; Warm & Parasuraman, 2007) to relate brain imaging to vigilance to performance.

TCD and the resource model. Warm and Parasuraman (2007) and Warm et al. (2009) have reported an extensive series of studies of TCD and vigilance that were carried out at the University of Cincinnati in conjunction with the Air Force Research Laboratory at Wright-Patterson Air Force Base. These studies were guided by a resource utilization model of vigilance in which it is assumed that a limited-capacity information-processing system allocates resources to cope with situations that confront it and that the vigilance decrement reflects the depletion of information processing resources or reservoirs of energy that cannot be replenished in the time available (Davies & Parasuraman, 1982; Parasuraman & Davies, 1977; Warm & Dember, 1998). Given that Cerebral Blood Flow Velocity (CBFV) might reflect the availability and utilization of information-processing assets needed to cope with a vigilance task, the model led to the expectation that the vigilance decrement should be accompanied by a decline in CBFV and that the absolute level of CBFV should vary directly with task demands. These expectations were tested in a series of experiments involving working memory, cueing, the temporal uncertainty of signals, and sensory integration.

The working memory experiment. In the initial study in this series, Mayleben et al. (1998) made use of successive and simultaneous-type vigilance tasks. The former are absolute judgment tasks in which observers need to compare current input with a standard retained in working memory in order to distinguish signal from non-signal stimulus events. Simultaneous tasks are comparative judgment tasks in which all of the information needed to distinguish signals from non-signal is present in the stimuli themselves and there is little involvement of recent memory for the signal feature (Davies & Parasuraman, 1982). Considerable evidence is available to indicate that because of the memory component, successive tasks are more capacity demanding than their simultaneous counterparts (Caggiano & Parasuraman, 2004; Parasuraman, Warm, & Dember, 1987; Warm & Dember, 1998; Warm et al., 2009). Observers in the Mayleben et al. study (1998) performed a 30-min vigil in which they viewed pairs of lines on a visual display. In the successive task, critical signals for detection were cases in which both lines were slightly longer than usual. In the simultaneous task, critical signals were cases in which one line was slightly longer than the other. Consistent with expectations derived from the resource model, the vigilance decrement, in terms of a drop off in signal detections over time, was accompanied by a parallel decline in CBFV and CBFV was greater in the context of the successive than the simultaneous task.

The finding of a concomitant temporal decline in performance and CBFV found in the Mayleben et al. (1998) study was also reported in an earlier experiment by Schnittger, Johannes, Arnavaz, and Munte (1997). However, a clear coupling between blood flow and performance could not be determined in that experiment because of the absence of a control for the possibility of spontaneous declines in CBFV over time such as may result from declines in arousal. More specifically, declines in cerebral activation over time could lead to a reduction in the production of CO_2 and the need for blood flow to remove the waste product. The Mayleben et al. (1998) study controlled for that possibility by utilizing a group of observers who viewed the dual-line display for the same time as the active experimental observers but without a work imperative. Under such conditions, CBFV remained stable over the testing period, showing that the temporal decline in CBFV in the experimental groups was indeed task-dependent.

Consistent with the PET, fMRI, psychophysical, and clinical neurophysiological studies described above, which pointed to right-brain superiority in the control of vigilance, the overall blood flow effects in the Mayleben et al. (1998) study were lateralized—hemovelocity was greater in the right than the left hemisphere, principally in the performance of the memory-based successive task. In addition to its implications for brain systems in the control of vigilance, the laterality effect supported the view that the performance/hemovelocity association in this study reflected information-processing per se rather than gross changes in systemic vascular activity that covaried with blood flow, such as changes in blood pressure and cardiac output (Caplan et al., 1990). Changes of this sort are not likely to be lateralized.

The cueing experiment. A key finding in regard to vigilance performance is that it can be improved by providing observers with consistent and reliable cues to signal occurrence. As has been demonstrated in several experiments, the principal consequence of cueing or forewarning is the elimination of the vigilance decrement (Davies & Parasuraman, 1982; Warm, 1993; Warm & Jerison, 1984). Hitchcock, Dember, Warm, Moroney, and See (1999) linked the cueing effects to resource theory by arguing that cued observers would need to attend to the display they are monitoring only when prompted about the imminent arrival of a signal and could therefore husband their information processing assets over time. By contrast, since non-cued observers are never certain as to when a critical signal might appear, they would have to process information on their displays continuously throughout the watch, thereby consuming more of their resources over time than their cued counterparts. With this idea in mind, Hitchcock et al. (2003) asked observers to monitor a simulated air traffic control display for 40 min in which critical signals for detection were planes traveling on a collision course. They speculated that in the presence of perfectly reliable cueing, the temporal decline in signal detection and

CBFV would be attenuated in comparison to a non-cued control condition and also in comparison to conditions in which cueing was not perfectly reliable, since in those conditions, observers would not be relieved of the need to attend continuously to the display they were required to monitor. Four cueing conditions were employed—100% reliable cueing, 80% reliable cueing, 40% reliable cueing, and a non-cued control. Performance efficiency was similar in all groups in the early portion of the vigil. As anticipated, 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 was clearly best in the 100% followed in order by the 80%, 40%, and no-cue groups. This pattern of results was mirrored exactly in the CBFV data. As in the case of signal detection, the hemovelocity scores for the experimental conditions were similar to each other early on in the vigil but showed differential rates of decline over time. By the end the vigil, CBFV was clearly highest in the 100% group followed in order by the 80%, 40%, and no-cue groups. Once again, these effects were lateralized to the right hemisphere and task-specific in nature—CBFV remained stable over time among observers who viewed the air-traffic control display for the same period of time as the active experimental observers but without a work imperative.

The temporal uncertainty experiment. It is typical in vigilance experiments for critical signals to be presented in a random manner within the temporal envelope of the watchkeeping session so that observers are faced with considerable temporal uncertainty about signal occurrences (Davies & Parasuraman, 1982; Warm & Jerison, 1984). Such uncertainty can be reduced by presenting critical signals in a temporally regular and predictable manner so that observers can form veridical expectancies about the time of arrival of critical signals and align attention with these expectations (Deese, 1955; Baker, 1959, 1963). A number of studies have verified the existence of a *signal regularity effect* in which performance efficiency is enhanced in the context of a temporally regular as compared to a temporally irregular signal schedule (Davies & Parasuraman, 1982; Helton et al., 2005; Warm, 1993; Warm & Jerison, 1984).

Hollander and his associates (Hollander, Warm, Dember, Matthews, & Parasuraman, 2002) recognized that the internal cues regarding the time of appearance of critical signals might serve to free observers from the need to continuously monitor the vigilance display, and thereby enable the conservation of information-processing resources. Thus, they hypothesized that the level of CBFV would remain more stable over time with temporally regular than temporally irregular signal presentations. To test that possibility, they employed the same air-traffic control display utilized by Hitchcock et al. (2003) during a 40 min. vigil. Signal detections were stable over time in a temporally regular signal condition while they declined over time in a temporally irregular signal condition and, as anticipated, CBFV was more stable over the course of the vigil in the temporally regular as compared to the temporally irregular signal case. As in the other studies in this series, these effects were restricted to the right hemisphere and the level of CBFV remained stable over time among control observers who monitored the air-traffic control display in the absence of a work imperative.

The sensory modality experiment. All of the studies described to this point were conducted in the visual modality. However, vigilance tasks can also be performed in the auditory modality and variations in the sensory modality of signals can lead to differences in vigilance performance. The overall level of performance in auditory tasks tends to be greater than in visual tasks and the vigilance decrement is less pronounced in the auditory than in the visual modality (Szalma et al., 2004; Warm & Jerison, 1984). Accordingly, Shaw et al. (2009) carried out an experiment to assess whether auditory vigilance tasks also exhibit a decline in CBFV as do comparable visual tasks or if the auditory modality is less susceptible to such decline in view of auditory superiority in vigilance performance. Toward that end, they had observers view 247.5 msec flashes of a white bar of light on a black background or listen to 247.5 msec bursts of white noise presented binaurally via earphones. Brief reductions in signal duration were the critical signals for detection in both conditions. The frequency of signal detections declined linearly over the course of a 40-min vigil in both modalities, and in both modalities, the linear decline in performance efficiency was accompanied by a similar decline in CBFV. As before, this effect was right lateralized and no temporal decline in CBFV was noted in control observers who were exposed to the visual or auditory stimuli without a work imperative.

In sum, these studies have successfully linked CBFV to vigilance performance and in so doing supported a resource model of performance efficiency in vigilance tasks. They have shown that the vigilance decrement is paralleled by a temporal decline in CBFV that generalizes across sensory modalities, that the absolute level of CBFV is directly related to several factors that influence the information-processing demands of vigilance tasks, and consistent with PET, fMRI, psychophysical, and clinical neurological studies, they have pointed to the operation of a right-hemispheric system in control of vigilance.

The NIRS Alternative

Basic principles of the NIRS technique. In addition to the TCD procedure, another noninvasive, nonrestrictive technique to gauge brain activity during vigilance performance is Near-Infrared Spectroscopy. Although the brain represents a small portion (2%) of human bodyweight, it consumes 20% of the body's oxygen requirement (Raichle & Gusnard, 2002). The NIRS technique is a noninvasive optical imaging procedure that utilizes tissue absorption of near-infrared wavelengths to measure cortical oxygen saturation levels (rSO_2). As described by

Gratton and Fabiani (2007), Norris (1977), and Tripp (2007), human tissue is translucent to near infra-red photons having wavelengths between approximately 650 and 1100 nm. Even small amounts of chemophores (colored material) will cause wavelength absorption of these photons which produces characteristic signatures in the spectrum of the emerging light. The red-colored hemoglobin molecules found within the erythrocytes circulating in the blood are the chemophores with the highest absorption in body tissue. Thus, in the NIRS technique, photons of near-infra red light penetrate the skull and diffuse into brain tissue. The parameters of this diffusion process are influenced by the absorption properties of the circulating erythrocytes. By measuring the quantity of returning photons as a function of wavelength, it is possible to infer the spectral absorption of the underlying tissue and reach conclusions about its average oxygenation (McCormick, Stewart, Dujovny, & Ausman, 1992; McCormick et al., 1991). The procedure is non-invasive and non-restrictive since the sensors needed to emit and record retuning light waves are housed in a headband and the recording equipment is isolated from the observer and does not restrict observer motion.

THE PRESENT STUDY

Several investigations have shown that the NIRS technique reveals aspects of neuronal activity in the brain and that brain rSO_2 increases with the information processing demands of the task being performed (Franceschini & Boas, 2004; Gratton & Fabiani, 2007; Punwani, Ordige, Cooper, Amess, & Clemence, 1998; Steinbrink et al., 2000; Tse, Tien, & Penney, 2006). Hence, one might expect that in addition to the TDC technique, the NIRS procedure could also provide a noninvasive measure of cerebral hemodynamics during vigilance performance.

To date, the only experiment to investigate this possibility has been reported by Helton and his associates (Helton et al., 2007) who measured rSO_2 levels in the frontal lobes. Their study utilized an abbreviated 12-min vigil in which observers were asked to view the rapid (57.5/min) repetitive presentation of the letters O, D, and a backwards D in a background of small circles to reduce figure-ground contrast. The letter O was the critical signal for detection. They reported that, like the TCD procedure, the NIRS procedure also showed cerebral laterality in vigilance performance. The overall levels of both CBFV and rSO_2 were greater in right than the left hemisphere, a result consistent with the previous findings with CBFV in the long-duration vigilance tasks described above. However, while the vigilance decrement was present in their study, Helton and his associates (2007) did not find a corresponding temporal decline in either the CBFV or the NIRS measure. They noted that since the abbreviated vigilance task was only 12 min in length, that task may have been too brief for temporal changes in CBFV or cerebral oxygenation to be observed. It should also be noted that Helton et al. (2007) only utilized a single level of discrimination difficulty so their study did not permit a determination if, like CBFV, cerebral rSO_2 is also sensitive to differential information-processing demands in a vigilance task. Accordingly, the goal for the present study was to employ a longer vigil with different levels of discrimination difficulty to determine if the rSO_2 measure declines over time and if it parallels the CBFV measure in its sensitivity to the differential information-processing demands of the vigilance task.

In addition to learning more about the rSO_2 measure in vigilance, there is a theoretical reason for a study along these lines. Based on the assumption that the brain needs oxygen and that cerebral blood flow is the main homeostatic factor in the regulation of the oxygen supply, it has long been assumed that cerebral blood flow and oxygen metabolism are tightly coupled in both resting and active brain states (Siesjo, 1978). An assumption of this sort would lead to the expectation of similar findings with regard to CBFV and rSO_2 in a vigilance task. However, an extensive review of the literature based upon PET and fMRI studies and their own research with hyperemia showing that cerebral blood flow associated with physiological activation is regulated by factors other than local oxygen requirements led Mintun, Lundstrom, Snyder, Vlassenko, Shulman, and Raichle (2001) to challenge the coupling assumption. They argue that intact brain tissue has excess oxygen delivery compared with utilization and that during activation this excess oxygen can be used without a necessary increase in cerebral blood flow. The findings of Minturn et al. (2001) lead to the possibility that CBFV and rSO_2 may not necessarily show homologous changes in a vigilance task. Thus, the present study was designed to provide additional evidence for the debate regarding the coupling of cerebral blood flow and oxygen metabolism in activated brain states.

CHAPTER 2

Method

Participants

Thirty-six students (18 women and 18 men) from the University of Cincinnati served as observers for course credit. They ranged in age between 18 - 24 years with a mean of 19.16 years. All observers had normal or corrected-to-normal vision (via surgery or contact lenses) and normal hearing and were right handed as measured by the Edinburgh Handedness Inventory (see Appendix A, Oldfield, 1971). Observers were asked to abstain from caffeine, nicotine, or medication for 12 hours prior to participating in the study (Stroobandt & Vingerhoets, 2000). Human subject testing was approved by the Institutional Review Board of the University of Cincinnati.

Design

Twelve participants (6 women and 6 men) were assigned at random to each of two active vigilance conditions defined by the difficulty of the discriminations to be made as described below. The remaining 12 observers (6 women and 6 men) served as passive controls to assure that time-based changes in CBFV and rSO_2 were task-determined. All observers participated in a 40-min session divided into 4 continuous 10-min periods.

Apparatus

In the active vigilance conditions, observers assumed the role of Air Force controllers monitoring the flight pattern of a squadron of four jet fighters projected on a 17-in visual display terminal (VDT). As shown in Figure 1, the display consisted of an open circular field (9.53 cm in diameter) banded by a black border that was presented on a gray background (transluminance = 40.52 cd/m^2). The field contained a “sector” (a solid red circle measuring 2.54 cm in diameter (transluminance = 31.68 cd/m^2) ringed by an inner open circle (6.35 cm in diameter) formed by a black border. The entire field was divided into four equal 90° quadrants also defined by black lines. In all cases, the defining lines were 0.32 cm thick, their transluminance was 12.25 cd/m^2, and their contrast with the gray background based upon the Michaelson Contrast ratio (maximum luminance-minimum luminance/maximum luminance +minimum luminance; Coren, Ward, & Enns, 1999) was 53%. By the same measure, the contrast ratio of the red "sector" was 12%. Each quadrant of the display contained a black triangular icon (base = 1.35 cm, altitude = 0.95 cm, translumiance 12.25 cd/m^2, contrast with gray background = 53%) which represented a jet plane.

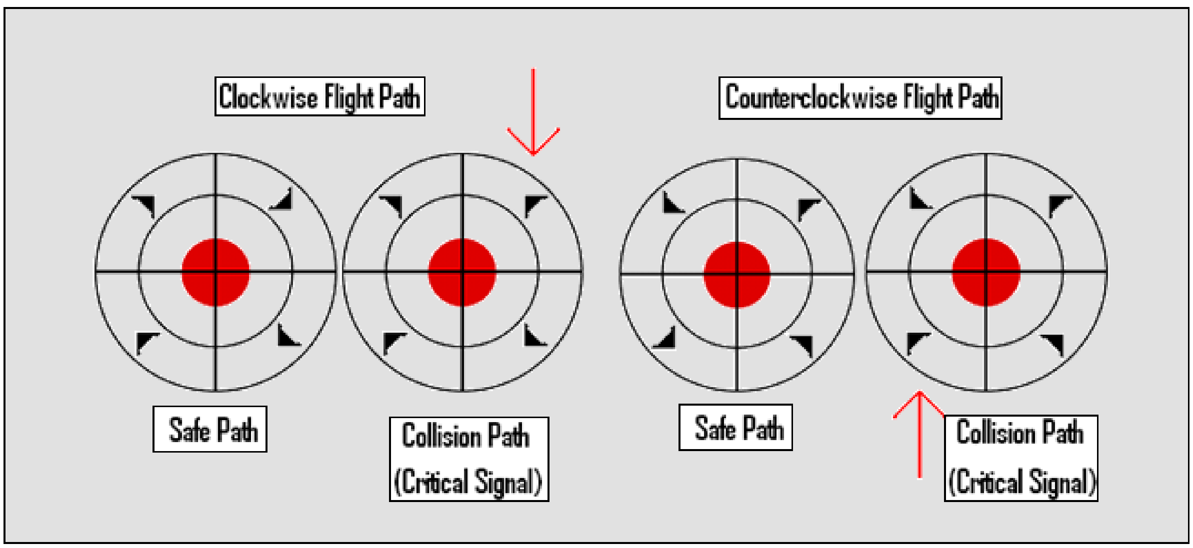

Figure 1. Examples of neutral events and critical signals in the flight path display

In the easier *unidirectional condition*, the squadron always flew in either a clockwise or a counterclockwise direction (defined by the "noses" of the planes), but not both, throughout the vigil. Hence, observers did not have to differentiate between flight directions on any given display exposure in order to detect critical signals. Critical signals for detection were cases in which one of the planes was flying in an inappropriate direction relative to the others so that a collision could occur. Six observers equated for sex were assigned at random to each flight path in the unidirectional condition. In the more difficult *multidirectional condition,* the planes could be flying in the clockwise or counterclockwise directions throughout the vigil so that on any given display exposure, the observers needed to differentiate between two possible flight directions in order to detect critical signals. As in the unidirectional condition, critical signals for detection in the multidirectional condition were cases where one of the planes was flying in an inappropriate direction relative to the current direction of the others so that a collision could occur. In the multidirectional condition, a plane that was at fault when the flight was in one direction would not be at fault when the flight was in the other direction. In both the unidirectional and the multidirectional conditions, the display was updated 30 times/min with a dwell time of 1000 msec.

Twelve critical signals occurred at random intervals during each period of watch with three signals appearing on each display quadrant (signal probability per period = .04). Observers indicated their detection of critical signals by pressing the spacebar on a computer keyboard. Responses occurring within 1000 msec after the appearance of critical signals were recorded automatically as correct detections. All other responses were recorded as errors of commission or false alarms. The lack of a response to a critical signal was recorded as a miss. Pilot work ensured that if observers were going to respond to a critical signal, they would do so within the 1000 msec window. Stimulus presentation and response recording were orchestrated by a Dell computer using SuperLab software.

Observers in the passive control group viewed the flight display without an information-processing imperative. These observers were not provided with a definition of critical (collision path) and neutral (safe path) events nor were they given any information about pressing keys on the keyboard. They were instructed to simply gaze at the display until the session ended. Four passive observers equated for sex were assigned at random to view one of the three versions of the flight path display (clockwise flight course, counterclockwise flight course, multidirectional flight course). Complete instructions for the active and passive conditions can be found in Appendix B.

Observers were tested individually in a 2.85 × 4.32 × 2.42 m windowless laboratory room. The VDT was mounted at eye-level on a table 60 cm directly in front of the seated observer (visual angle = 9.03^{o}). Ambient illumination in the testing room was 0.49 cd/m^2, 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 VDT. To curtail distraction, participants were separated from the experimenter and the TCD / NIRS equipment by a curtain dividing the width of the room in half.

Within the two active flight conditions and the passive control condition, bilateral hemovelocity measurements were taken from the left and right medial cerebral arteries of all observers using a Nicolet Companion III TCD unit equipped with two 2 MHz ultrasound transducers. As illustrated in Figure 2, the transducers were embedded in a plastic bracket and secured to the observer’s head by an adjustable plastic strap. They were located dorsal and immediately proximal to the zygomatic arch along the temporal bone on either side of the skull. A small amount of Aquasonic-100 brand ultrasound transmission gel was placed on the transducers to ensure transmission of the ultrasound signal. The distance between the transducer face and the sample volume could be adjusted in 2 mm increments in order to isonate the MCA. In the present study, the MCA was generally monitored at depths of 50-55 mm. Blood flow velocity measures were averaged and recorded automatically by the TCD unit approximately once per sec. The unit also displayed the CBFV measures on a monitor so that the experimenter could peruse changes in CBFV in real time to note if problems occurred.

Consistent with the study by Helton et al. (2007), cerebral oxygenation was measured bilaterally from the frontal lobes by means of an INVOS 5100B cerebral oximeter. As illustrated in Figure 2, the oxygen sensors, placed beneath the adjustable plastic strap securing the transducers, were positioned on the left and right sides of the observer's forehead so as to avoid sinus cavities and hair that might interfere with the signals from the sensors. Cerebral oxygenation measures were averaged and automatically recorded by the NIRS unit every five sec.

Figure 2. Illustration of the positions of the Transcranial Doppler (TCD) and the Near-Infra red spectroscopy (NIRS) sensors in the observer's headband. The TCD sensors were located above the observer's left and right ears, the NIRS sensors were located on the left and right portions of the observer's forehead.

Procedure

All observers completed an informed consent form upon reporting for the experiment (see Appendix C). They then participated in a five-min resting baseline phase during which CBFV and blood oxygen measures were recorded while seated in front of a blank VDT.

Following the procedure outlined by Tripp and Warm (2007), they were asked to refrain from talking and to minimize body movement while breathing normally and maintaining relaxed wakefulness. Immediately after the baseline phase, all *active* observers took part in a 10-min practice session that duplicated the vigilance task that they were to perform. Participants were required to detect at least 60% of the signals in the practice phase to remain in the experiment. A computerized female voice provided feedback as to correct detections, misses, and false alarms during practice only. The main vigil commenced immediately after the conclusion of practice.

Observers in both the active and passive conditions surrendered their wristwatches, pagers, and cell phones upon entering the laboratory, and had no knowledge about the length of the experimental session other than it would not exceed 120 min.

CHAPTER 3

Results

Performance Efficiency

Detection probability. Mean percentages of correct detections in the Unidirectional and Multidirectional flight path conditions are plotted as a function of periods of watch in Figure 3.

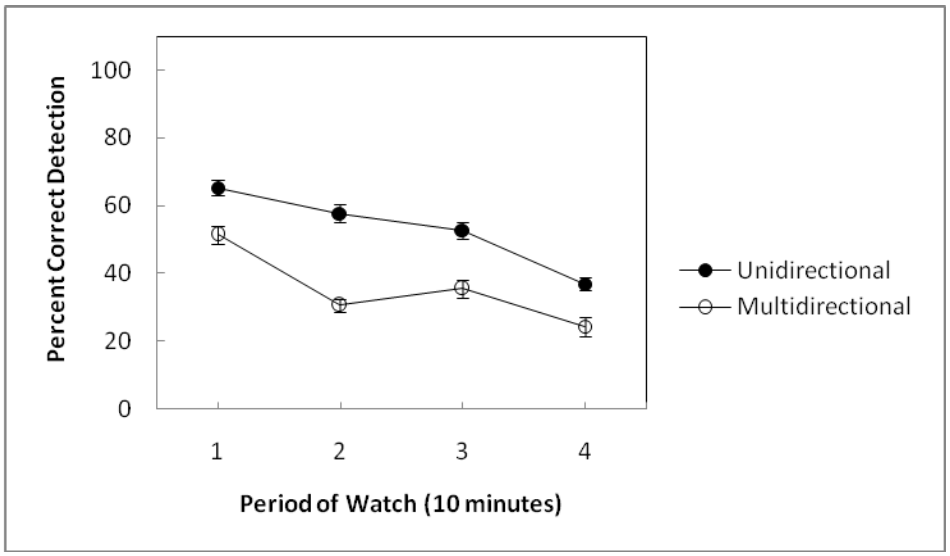

Figure 3. Mean percentages of correct detections in the unidirectional and multidirectional flight path conditions as a function of periods of watch. Error bars are standard errors.

It is evident in the figure that both conditions were difficult for the observers since the mean detection scores ranged from 65% to 24%. It is also evident in the figure that performance efficiency was greater in the unidirectional than in the multidirectional condition and that the frequency of signal detections declined over time in both conditions. These impressions were confirmed by a 2 (groups) × 4 (periods) mixed- analysis of variance (ANOVA) of the arcsines of the percentage scores (Kirk, 1995) which revealed significant main effects for flight path conditions, $F(1, 22) = 9.79$, $p = .005$, $\eta^2 = .31$, and periods of watch, $F(2.76, 60.73) = 21.53$, $p < .001$, $\eta^2 = .49$. The conditions × periods interaction was not significant, $p > .05$. In this and all subsequent ANOVAs, Box's epsilon was used when needed to correct for violations of the sphericity assumption (Maxwell & Delaney, 2004). Complete summaries of this and all subsequent analyses are presented in Appendix D.

False alarms. A preliminary examination of the false alarm scores revealed that errors of commission were rare in this study. The mean false alarm rates in the unidirectional and in the multidirectional conditions were less than 1.5% and 12.5% of all of the observers made no false alarms at all. Consequently, false alarms were not analyzed further.

Cerebral Hemodynamics

Control issues. Cerebral hemovelocity scores can range extensively across individuals based on such characteristics as sex or age (Adams, Nichols, & Hess, 1992). To control for this variability, the CBFV values, and also the rSO_2 values, for all observers in this study (active and passive) were expressed as a proportion of the last 60 sec of their 5-min resting baseline. This baseline index was recommended by Aaslid (1986) and utilized in the previous studies of cerebral hemovelocity and vigilance by Hitchcock et al. (2003), Hollander et al. (2004), Mayleben et al. (1999), and Shaw et al. (2009). Inspection of the baseline data indicated that for both the CBFV and the rSO_2 measures, the scores for the active and passive control conditions were similar in both the left and right cerebral hemispheres. Thus, subsequent CBFV and rSO_2 effects in the two cerebral hemispheres associated with active and passive observing and the need to monitor unidirectional compared to multidirectional flight patterns cannot be attributed to sampling artifacts in the original resting baseline. In addition, separate 2 (hemispheres) × 4 (periods of watch) repeated-measures ANOVAs of the data of the two cerebral hemodynamic measures among the passive control observers revealed no significant main effects or interactions with either measure, $p > .05$ in all cases, indicating that time-related changes in the

CBFV and the rSO_2 scores among the active observers were task-related. Cerebral blood flow velocity and rSO_2 scores for the passive control group are plotted as a function of time on task in the left and right panels of Figure 4, respectively. Cerebral hemisphere is the parameter in each instance.

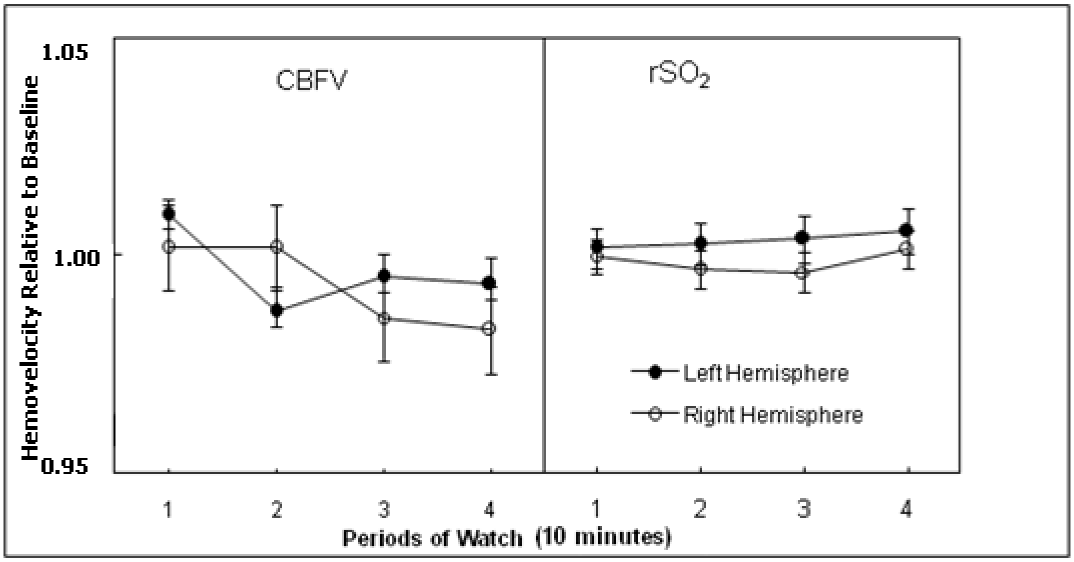

Figure 4. Hemovelocity and cerebral oxygen saturation scores relative to baseline in the right and left cerebral hemispheres for the passive control condition during each period of watch.

Cerebral blood flow velocity. Mean blood flow velocity scores and their associated standard errors for all combinations of flight path conditions, cerebral hemisphere, and periods of watch are presented in Table 1.

Table 1.
Hemovelocity scores in the right and left cerebral hemispheres for the Unidirectional and Multidirectional flight path conditions during each period of watch. Standard errors are in parentheses.

	Period (10 minutes)								
Condition	1		2		3		4		
	Right	Left	Right	Left	Right	Left	Right	Left	**Mean**
Unidirectional	**1.01**	**0.97**	**1.01**	**0.95**	**1.01**	**0.93**	**1.01**	**0.91**	**0.97**
	(0.013)	(0.011)	(0.007)	(0.013)	(0.012)	(0.013)	(0.009)	(0.014)	(0.012)
Multidirectional	**1.02**	**0.96**	**1.00**	**0.92**	**0.99**	**0.91**	**0.99**	**0.89**	**0.96**
	(0.009)	(0.013)	(0.011)	(0.016)	(0.007)	(0.013)	(0.017)	(0.013)	(0.012)
Mean	**1.01**	**0.97**	**1.01**	**0.93**	**1.00**	**0.92**	**1.00**	**0.90**	
	(0.011)	(0.012)	(0.009)	(0.015)	(0.010)	(0.013)	(0.013)	(0.014)	

A 2 (flight path condition) × 2 (hemisphere) × 4 (periods of watch) mixed-model ANOVA revealed significant main effects for hemisphere, $F(1, 22) = 67.84$, $p < .001$, $\eta^2 = .76$, and for time on task, $F(2.24, 49.28) = 13.30$, $p < .001$, $\eta^2 = .38$. In addition, there was a significant hemisphere × periods of Watch interaction, $F(1.80, 39.56) = 7.10$, $p = .003$, $\eta^2 = .24$. The overall difference in CBFV between the Unidirectional and Multidirectional conditions was not statistically significant and all of the remaining interactions in the analysis lacked significance, $p > .05$ in all cases.

The difference between the cerebral hemispheres is displayed in Figure 5 in which the CBFV scores are shown for the unidirectional and multidirectional task conditions. It is evident in the figure that for both task conditions CBFV scores were higher in the right than the left cerebral hemisphere.

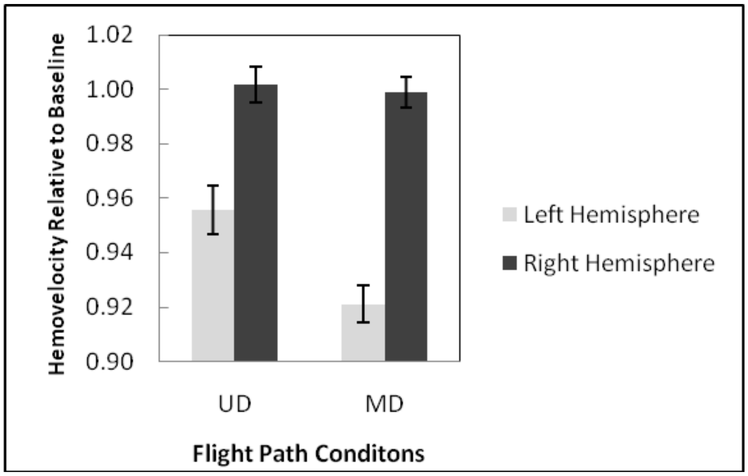

Figure 5. Cerebral blood flow velocity in the left and right hemispheres n the unidirectional (UD) and multidirectional (MD flight path conditions. Error bars are standard errors.

The Hemisphere × Periods of Watch interaction is illustrated in Figure 6 wherein the CBFV scores in the right and left cerebral hemispheres are plotted as a function of periods of watch. The figure shows that the temporal decline in CBFV was limited to the left cerebral hemisphere. Supplementary tests of simple effects indicated a significant time on task effect for the left hemisphere, $F(1.89, 43.51) = 19.15$, $p < .001$, $\eta^2 = .45$, but not the right, $F(1.97, 45.39) = 1.19$, $p > .05$.

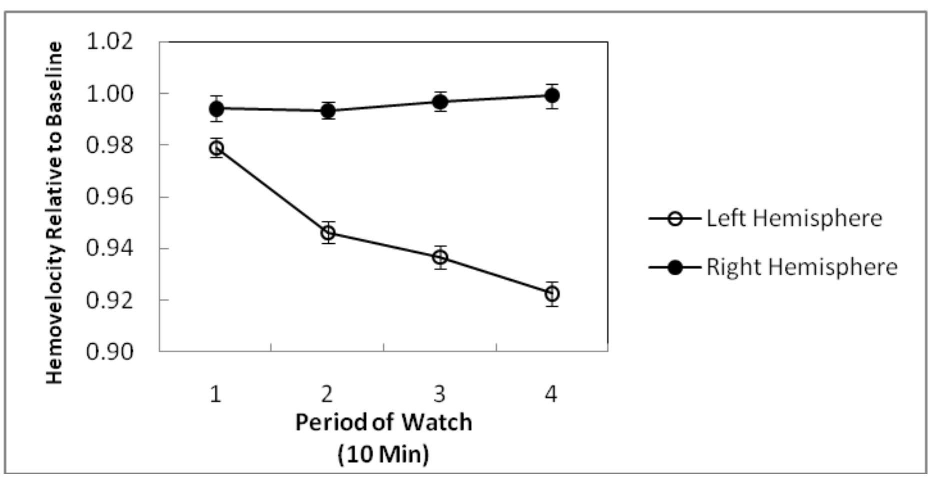

Figure 6. Cerebral blood flow velocity scores in the left and right hemispheres as a function of periods of watch. Error bars are standard errors.

Blood Oxygen Saturation. Mean oxygen saturation scores and their associated standard errors for all combinations of flight path conditions, cerebral hemisphere, and periods of watch are presented in Table 2.

Table 2.
Cerebral oxygen saturation scores in the right and left cerebral hemispheres for the Unidirectional and Multidirectional flight path conditions during each period of watch. Standard errors are in parentheses

Condition		Period (10 minutes) 1		2		3		4		
		Right	Left	Right	Left	Right	Left	Right	Left	**Mean**
Unidirectional		**1.02**	**1.00**	**1.03**	**1.01**	**1.03**	**1.02**	**1.02**	**1.03**	**1.02**
		(0.008)	(0.006)	(0.009)	(0.008)	(0.009)	(0.010)	(0.010)	(0.011)	(0.009)
Multidirectional		**1.04**	**1.04**	**1.04**	**1.04**	**1.05**	**1.05**	**1.05**	**1.05**	**1.05**
		(0.009)	(0.011)	(0.010)	(0.008)	(0.010)	(0.010)	(0.010)	(0.008)	(0.009)
	Mean	**1.03**	**1.02**	**1.04**	**1.03**	**1.04**	**1.03**	**1.03**	**1.04**	
		(0.009)	(0.009)	(0.009)	(0.008)	(0.009)	(0.010)	(0.010)	(0.010)	

A 2 (flight path condition) × 2 (hemisphere) × 4 (periods of watch) mixed-model ANOVA revealed significant main effects for flight path, $F(1,22) = 5.87$, $p = .024$, $\eta^2 = .21$, and for time on task, $F(2.23, 49.00) = 4.87$, $p = .009$, $\eta^2 = .18$. None of the other sources of variance in the ANOVA were significant, $p > .05$ in all cases.

The significant main effects are illustrated in Figure 7 in which the rSO_2 scores for the unidirectional and multidirectional flight path conditions are plotted as a function of time on task. It can be seen in the figure that the rSO_2 scores were higher in the multidirectional than the unidirectional flight path condition and that in both conditions rSO_2 increased over time on task.

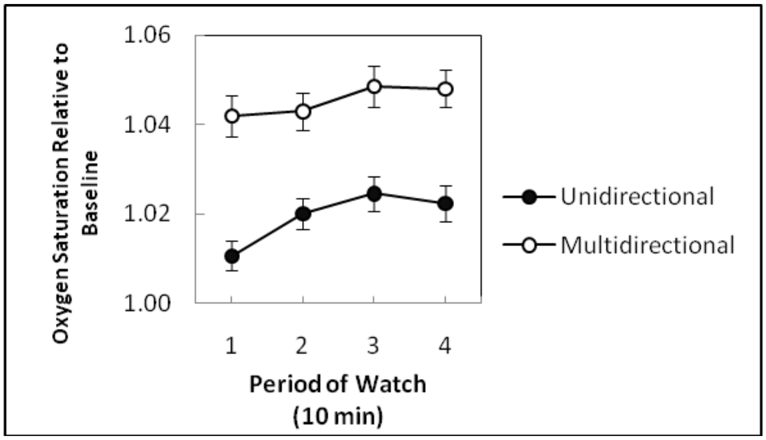

Figure 7. Cerebral oxygen saturation scores in the unidirectional and multidirectional flight path conditions as a function of period of watch. Error bars are standard errors.

Inter-measure correlations. To determine the degree of association between the CBFV and rSO_2 measures, product moment correlations between the measures were computed for each hemisphere for the two flight path conditions during each period of watch. These values are presented in Table 3. All of the correlations were non-significant, as was the global correlation between the measures in each hemisphere (right r = .14, left r = -.05), p >.05 in all cases.
It should be noted, however, that the sample size lacks statistical power for detection of small to moderate correlations.

Table 3.
Correlations between the Unidirectional and Multidirectional flight path conditions in all combinations of cerebral hemisphere and periods of watch.

	Period	**1**		**2**		**3**		**4**	
	Hemisphere	Right	Left	Right	Left	Right	Left	Right	Left
Condition									
Unidirectional		0.44	-0.37	0.18	-0.13	0.51	-0.13	0.33	0.04
Multidirectional		-0.20	0.27	0.04	0.40	0.16	0.21	-0.03	0.49

CHAPTER 4

Discussion

As summarized by Warm and Parasuraman (2007) and Warm et al. (2009) and described in Chapter 1 of this report, recent studies have shown that cerebral hemodynamics play an important role in an understanding of brain systems in vigilance. Along that line, the present study was designed to examine the coupling between two hemodynamic measures, CBFV and $rSO_{2,}$ during the performance of a vigilance task. The long standing assumption that cerebral blood flow is the main homeostatic factor in the regulation of the oxygen supply to the brain (Siesjo, 1978) would lead one to expect that these measures should yield similar results with regard to the effects of factors that influence performance efficiency, such as discrimination difficulty and time on task, and also with the hemispheric localization of control centers in vigilance. On the other hand, the data described by Minturn et al. (2001) showing that cerebral blood flow associated with physiological activation is regulated by factors other than local oxygen requirements would lead to the expectation that CBFV and rSO_2 may not necessarily yield similar effects in regard to task and cerebral laterality factors. The results of the present study support the latter view.

In terms of performance efficiency, the overall level of signal detections in this study was greater in the unidirectional flight path condition than the multidirectional condition. A result of this sort is generally consistent with previous findings in vigilance that performance efficiency varies directly with the discriminability of the critical signals to be detected (Davies & Parasuraman, 1982; Warm & Jerison, 1984; Warm, 1993). In the multidirectional condition, observers needed to ascertain differential flight paths on different trials in order to detect critical signals, cases in which a plane was off course. In the unidirectional condition, only a single flight path was involved. In addition, as is typical in vigilance studies (See et al., 1995), the level of signal detections in this study declined significantly over time.

The two hemodynamic measures differed in regard to the ways in which they paralleled these performance findings. The CBFV measure did not show any significant differences with respect to task difficulty. However, the overall level of CBFV was lateralized to the right cerebral hemisphere and the vigilance decrement was accompanied by a decline in CBFV in the left hemisphere. In contrast, the rSO_2 measure was not lateralized, but it was responsive to overall task difficulty—rSO_2 values were higher for the multidirectional than the unidirectional condition. Moreover, rather than declining over time as was true of the CBFV measure, rSO_2 levels increased over time, and all of the correlations between these measures were not significant. Clearly, the CBFV and rSO_2 measures were uncoupled in this study and they cannot be viewed as corresponding indices of brain system effects in vigilance performance.

The finding that the overall level of CBFV was greater in the right than in the left hemisphere is consistent with previous findings with this measure (Helton et al., 2007; Hitchcock et al, 1999; Hollander et al., 2004; Mayleben et al., 1998; Shaw et al., 2009) and with the PET, fMRI, psychophysical, and clinical neurophysiological studies described in Chapter 1 pointing to a right hemispheric brain system that is involved in the functional control of vigilance. However, the results with the CBFV measure painted a more complex picture than just one hemisphere having "metacontrol" (Levy & Trevarthen, 1976) of sustained attention. The vigilance decrement in this study was lateralized to the left cerebral hemisphere. Previous studies with the CBFV measure by Mayleben et al. (1998), Hitchcock et al. (2003), Schnittger et al. (1997) and Schultz, Matthews, Warm, and Washburn (2009) have also found that the left hemisphere is involved in the vigilance decrement. Evidently, vigilance performance is not completely lateralized. As

Hitchcock and his associates (Hitchcock et al., 2003) have suggested, it is possible that the right hemisphere may have primary responsibility for the overall level of performance efficiency but that both hemispheres play a role in the vigilance decrement. An account of this sort would be consistent with Hellige's (1993) point that even relatively simple tasks require the coordination of a number of information-processing sub-systems and with the view that a cooperative interaction model may best describe the mode of central functioning in regard to the vigilance decrement (Allen, 1983; Hoptman & Davidson, 1994; Warm et al., 1976). Of course, an account of this sort is based upon the assumption that the temporal decline in CBFV was based upon information-processing demand and not upon a general decline in arousal. To be sure, the present study confirmed the finding of its predecessors (Helton et al., 2007; Hitchcock et al., 1999; Hollander et al., 2004; Mayleben et al., 1998; Shaw et al., 2009) that information-processing demand is the foundation for the decline in CBFV because the level of blood flow only dropped off in the active vigilance conditions and not in the passive control condition in which observers viewed the vigilance display for the same amount of time as the active observers but in the absence of an information-processing imperative.

It is important to note at this point that the notion of right hemisphere lateralization of overall vigilance performance may itself be open to question. Using the CBFV index, Schultz and her associates (2009) have reported overall left hemisphere dominance in a vigilance task that simulated military sentry duty wherein observers attended to a display consisting of a city street on which targets would appear within doorways, windows, or around corners. Moreover, Helton, Hayrynen, and Schaeffer (2009), using a local/global display format involving letters as discriminanda in a vigilance task, found right hemisphere dominance in the detection of global stimuli and left hemisphere dominance in the detection of local stimuli consistent with prior findings under alerted conditions that global discriminations are right lateralized and local discriminations are left lateralized (Delis, Robertson, & Efron, 1986; Lux, Marshall, Ritzl, Weiss, Pietrzyk, Shah, et al., 2004). It would appear that future investigations will be needed to determine the exact task characteristics that give rise to overall left and right hemisphere dominance in vigilance performance.

With regard to cerebral oxygenation, the finding that rSO_2 was significantly greater in the context of the multidirectional than the unidirectional flight path condition is consistent with several previous studies indicating that this measure is sensitive to the information-processing demands of the task being performed (Franceschini & Boas, 2004; Gratton & Fabiani, 2007; Punwani, Ordige, Cooper, Amess, & Clemence, 1998; Steinbrink et al., 2000; Tse, Tien, & Penney, 2006). On the other hand, the inability to confirm Helton et al.'s (2007) demonstration of right hemisphere dominance in vigilance with this measure and the finding that rSO_2 increased rather than decreased over time were unanticipated effects.

The problem of task-characteristic determinants of laterality in vigilance described above may also apply in the present case. Helton et al. (2007) made use of the letters O, D, and a backwards D placed against a masking background in an abbreviated 12-min vigilance task, whereas a simulated air traffic control display was used for 40 min in the present study. But what can account for the differences in the temporal courses of the levels of rSO_2 and CBFV in this study? One possibility is that these measures are in conflict. Another is that they tap different aspects of the vigilance decrement. Warm, Dember, and Hancock (1996) have shown that the temporal decline in performance efficiency in vigilance is accompanied by a corresponding increment in perceived mental workload. From a resource theory perspective, it would appear that observers exert increased effort over time to compensate for the loss of information-processing assets. While the CBFV measure reflects the temporal loss of such assets (Warm & Parasuraman, 2007; Warm et al. 2009), the rSO_2 measure, which is quite sensitive to task demands, may reflect the increased effort that accompanies the loss of resources. Thus, rather than viewing the present results as indicating conflicting hemodynamic outcomes, they can be interpreted as indicating that including the rSO_2 measure may provide a more complete picture of an observer's hemodynamic profile during vigilance performance than that afforded by CBFV alone.

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APPENDIX A:
THE EDINBURGH HANDEDNESS INVENTORY

Edinburgh Handedness Inventory[1]

Subject #:________________

Please indicate with a check (✓) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two checks (✓✓).

If you are indifferent, put one check in each column (✓ | ✓).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total checks:	LH =	RH =
Cumulative Total	CT = LH + RH =	
Difference	D = RH – LH =	
Result	R = (D / CT) × 100 =	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)		

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychololgia*, *9*, 97-113.

APPENDIX B:

INSTRUCTIONS FOR SUSTAINED ATTENTION TASKS

Instructions for Sustained Attention Tasks

Unidirectional Flight Paths

(Clockwise)

During this experiment you will be taking the role of an Air Traffic Controller. Your task will be to monitor an air traffic control display with four flight regions marked across the display. Within each of the four regions an aircraft will be flying in a clockwise direction. Normally the flight paths of the aircraft will be in the same clockwise direction, indicating a safe flight path. Occasionally, however, one of the aircraft will be traveling in a counterclockwise direction, and will collide with the other aircraft unless you, the Air Traffic Controller, send a warning. Hence, it is your job to identify when one of the aircraft is off course by pressing the spacebar to inform the squadron commander. But you should not press the spacebar indiscriminately – respond only when an aircraft is off course.

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

This is an example of a safe Clockwise flight path.

(Counterclockwise)

During this experiment you will be taking the role of an Air Traffic Controller. Your task will be to monitor an air traffic control display with four flight regions marked across the display. Within each of the four regions an aircraft will be flying in a counterclockwise direction. Normally the flight paths of the aircraft will be in the same clockwise direction, indicating a safe flight path. Occasionally, however, one of the aircraft will be traveling in a clockwise direction, and will collide with the other aircraft unless you, the Air Traffic Controller, send a warning. Hence, it is your job to identify when one of the aircraft is off course by pressing the spacebar to inform the squadron commander. But you should not press the spacebar indiscriminately – respond only when an aircraft is off course.

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

This is an example of a safe Counterclockwise flight path.

Multidirectional Flight Path

During this experiment you will be taking the role of an Air Traffic Controller. Your task will be to monitor an air traffic control screen with four flight regions marked across the display. Within each of the four regions an aircraft will be flying in a clockwise or counterclockwise direction. Normally the flight paths of the aircraft will be in the same direction, indicating a safe flight path. Occasionally, however, one of the aircraft will be traveling in the opposite direction of the other three aircraft, and will collide with the other aircraft unless you, the Air Traffic Controller, send a warning. Hence, it is your job to identify when one of the aircraft is off course by pressing the spacebar to inform the squadron commander. But you should not press the spacebar indiscriminately – respond only when an aircraft is off course.

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

These are examples of safe clockwise and counterclockwise flight paths.

All Flight Paths

This is an example of a collision flight path in Region 1.

This is an example of a collision flight path in Region 2.

This is an example of a collision flight path in Region 3.

This is an example of a collision flight path in Region 4.

Practice Instructions

A short practice session will now follow in order to acquaint you with the displays and the response required from you. During the practice you will receive feedback regarding your performance. The computer will say “HIT” if you correctly press the spacebar when one of the aircraft is flying off course. The computer will say “MISS” if you fail to press the spacebar when one of the UAV’s is flying off course. When you press the spacebar for a normal flight path, the computer will say “FALSE”.

Remember, please do not respond indiscriminately – respond only when an aircraft appears to be on a collision course.

Do you have any questions?

You may press the spacebar to start the session once I ask you to begin.

End of Practice Instructions

The practice session has ended. Please notify the experimenter that you are finished with this part of the experiment.

Task Instructions

The experimental session will now follow. During the experiment, all the signals you will see will be the same as those during the practice sessions. You will not receive any feedback regarding your performance, however. Remember, when the one of the UAV’s is traveling off course, you will need to press the spacebar as quickly as possible. Also, just as before, you should not respond indiscriminately – respond only when a UAV is off course.

You may press the spacebar to start the session once I ask you to begin.

End of Task Instructions

Please notify the experimenter that you are finished with this part of the experiment.

APPENDIX C:
INFORMED CONSENT FORM

University of Cincinnati
College of Arts and Sciences
Department of Psychology
Consent to Participate in a Research Study
Principal Investigator: Joel S. Warm, Ph.D.
Email: warmjs@email.uc.edu; Telephone: (513) 556-5533

TITLE OF STUDY: Effects of Task Difficulty on Cerebral Hemovelocity, Blood Oxygen Saturation, Workload, and Stress During Vigilance Performance

INTRODUCTION: Before agreeing to participate in this research study, it is important that the following explanation of the proposed procedures be read and understood. It describes the purpose, procedures, benefits, risks, and discomforts of the study and the precautions that will be taken. It also describes the alternatives available and the right to withdraw from the study at any time. It is important to understand that no guarantee or assurance can be made as to the results of the study. It is also understood that failure to complete the session will in no way affect the course grade or class credit. Alternatives to research participation are described in the memo on "Research Participation Requirement" distributed to all introductory psychology students.

SPECIAL REQUIREMENTS: Participants in this study must be able to complete an experimental task that uses stimuli presented on a computer screen. For this reason, you may not participate in this study if your vision is impaired. Corrected vision is acceptable provided that you have your corrective lenses with you. Additionally, participants must be right handed to complete this study.

PURPOSE OF THE STUDY: This study will include 158 undergraduate participants from the University of Cincinnati. The purpose of this study is to examine the effects of task difficulty on cerebral blood flow and oxygenation.

After the completion of a stress questionnaire, you will be connected to a Transcranial Doppler and a Cerebral Oximeter while you respond to a visual display. Both the Transcranial Doppler and the Cerebral Oximeter are non-invasive devices that utilize ultrasound and infrared light, respectively, to measure the velocity of blood flow within arteries, and to determine the oxygen saturation, of your brain.

DURATION OF THE STUDY: This study will last approximately 90 minutes, and in any case will not exceed 120 minutes.

RISKS, DISCOMFORTS, AND PRECAUTIONS: There are no major risks or discomforts associated with this study. The Transcranial Doppler and Cerebral Oximeter have been used in numerous studies, and have not been found to cause any known risks or discomforts. However, you may feel mild discomfort due to the headpiece,. If this should happen, please inform the experimenter so that it can be adjusted and made more comfortable to you. Additionally, because the experiment involves you monitoring a computer screen, it may cause temporary eye strain. It is recommended that individuals with histories of seizures or migraines, or individuals on medications that directly affect the nervous system, such as anti-seizure medications, anti-psychotics, and anti-depressants not participate in this study. In the event that you become ill or injured from participating in this research study, emergency medical care will be provided for you. If you believe that you have been injured as a result of research, please contact Dr. Joel Warm at (513) 556-5533. You may also contact the Chair of the Institutional Review Board – Social and Behavioral Sciences, at (513) 558-5784.

BENEFITS: Participation in this study for those who are enrolled in an Introductory to Psychology class will earn 2 hours of experimental research credit. There is no other direct benefit from participating in the experiment, but your participation in this study may contribute to our knowledge of human performance during a vigilance task.

ALTERNATIVES: This pertains to participants who are currently enrolled in psychology 101, 102, or 103. If you decide not to participate in this research study, you may choose an alternative activity or a different research study as described in the Psychology Department's memo regarding the Research Participation Requirement.

CONFIDENTIALITY OF RECORDS: The confidentiality of your study records will be maintained. Agents of the University of Cincinnati will be allowed to inspect sections of the research records related to this study. The data from the study may be published; however, no identifiers such as name or social security number will be used. Your identity will remain confidential unless disclosure is required by law.

RIGHT TO WITHDRAW: Your participation in this study is voluntary. You are free to discontinue your participation at any point of time, without affecting your participation credit.

AVAILABILITY OF INFORMATION: If you have any questions concerning this study, you may contact Dr. Joel S. Warm at (513) 556-5533. The University of Cincinnati Institutional Review Board – Social and Behavioral Sciences reviews all non-medical research projects that involve human participants to be sure the rights and welfare of participants are protected. If you have questions about your rights as a participant, you may contact the Chairperson of the University of Cincinnati Institutional Review Board – Social and Behavioral Sciences at (513) 558-5784. If you have a concern about the study, you may also call the UC Research Compliance Hotline at (800) 889-1547.

LEGAL RIGHTS: Nothing in this consent form waives any legal right you may have, nor does it release the investigator, the institution, or its agents from liability for negligence.

I HAVE READ THE INFORMATION PROVIDED ABOVE. I VOLUNTARILY AFREE TO PARTICIPATE IN THIS RESEARCH STUDY. I WILL RECEIVE A COPY OF THIS SIGNED AND DATED CONSENT FORM FOR MY INFORMATION.

____

Participant Signature   Date

____

Signature of Person Obtaining Consent   Date   Role in Study

APPENDIX D:
ANALYSIS OF VARIANCE SUMMARY TABLES

Table D1.

Analysis of Variance of correct detections (Arcsin transformed)*					
Source	df	df_{adj}	MS	F	p
Between subjects					
Flight Path (A)	1	-	3.937	9.793	0.005
Error	22	-	0.402		
Within Subjects					
Periods (B)	3	2.760	1.723	21.537	**<.001**
A × B	3	2.760	0.104	1.300	0.056
Error	66	60.729	0.080		

df_{adj} = degrees of freedom obtained when Box's ? is used to correct for violations of sphericity.
Box's € = .902

*Values are taken directly from SPSS printout. Note: SPSS carries calcualations out to many decimal places. For brevity, values are rounded in table to three decimal places.

Table D2.

Analysis of Variance of hemovelocity scores for passive observers					
Source	df	df_{adj}	MS	F	p
Within subjects					
Period (A)	3	2.046	21.122	1.681	**> .05**
Error	33	22.505	12.562		
Hemisphere (B)	1	-	2.394	0.043	**> .05**
Error	11	-	56.321		
A × B	3	1.730	14.959	1.138	**> .05**
Error	33	19.035	13.142		

df_{adj} = degrees of freedom obtained when Box's ? is used to correct for violations of sphericity. Box's € = .902

*Values are taken directly from SPSS printout. Note: SPSS carries calcualations out to many decimal places. For brevity, values are rounded in table to three decimal places.

Table D3.

Analysis of Variance of oxygen saturation scores for passive observers

Source	df	df_{adj}	MS	F	p
Within subjects					
Period (A)	3	1.683	1.223	0.235	**> .05**
Error	33	18.515	5.211		
Hemisphere (B)	1	-	5.738	1.452	**> .05**
Error	11	-	3.951		
A × B	3	1.647	0.693	1.010	**> .05**
Error	33	18.117	0.686		

df_{adj} = degrees of freedom obtained when Box's ? is used to correct for violations of sphericity. Box's € = .902

*Values are taken directly from SPSS printout. Note: SPSS carries calcualations out to many decimal places. For brevity, values are rounded in table to three decimal places.

Table D4.

Analysis of Variance of hemovelocity scores for active observers

Source	df	df_{adj}	MS	F	p
Between subjects					
Flight Path (A)	1	---	102.215	2.164	**> .05**
Error	22	---	47.237		
Within Subjects					
Periods (B)	3	2.240	195.412	13.296	**<.001**
A x B	3	2.240	13.580	0.992	**> .05**
Error	66	49.286	14.697		
Hemisphere (C)	1	-	2687.041	67.840	**<.001**
A x C	1	-	4.263	0.108	**> .05**
Error	22	-	39.608		
B x C	3	1.780	96.101	7.098	**< .05**
A x B x C	3	1.798	9.459	0.699	**> .05**
Error	66	39.559	13.539		

df_{adj} = degrees of freedom obtained when Box's ε is used to correct for violations of sphericity. Box's € = .902

*Values are taken directly from SPSS printout. Note: SPSS carries calculations out to many decimal places. For brevity, values are rounded in table to three decimal places.

Table D5.

Analysis of Variance of oxygen saturation scores for active observers

Source	df	df_{adj}	MS	F	p
Between subjects					
Flight Path (A)	1	---	5.872	2.164	**< .05**
Error	22	---	55.038		
Within Subjects					
Periods (B)	3	2.227	13.621	4.872	**< .05**
A x B	3	2.227	2.247	0.084	**> .05**
Error	66	49.004	2.796		
Hemisphere (C)	1	-	32.935	2.212	**> .05**
A x C	1	-	29.172	1.959	**> .05**
Error	22	-	14.888		
B x C	3	1.668	0.673	0.248	**< .05**
A x B x C	3	1.668	2.380	0.876	**> .05**
Error	66	36.699	2.717		

df_{adj} = degrees of freedom obtained when Box's ε is used to correct for violations of sphericity.
Box's € = .902

*Values are taken directly from SPSS printout. Note: SPSS carries calculations out to many decimal places. For brevity, values are rounded in table to three decimal places.