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The abbreviated vigilance task and cerebral hemodynamics

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Transcranial Doppler sonography (TCD) and transcranial cerebral oximetry (TCCO) measures of cerebral blood flow velocity and oxygenation levels were collected during an abbreviated 12-min vigilance task. Both the TCD and TCCO measures showed higher levels of cerebral vascular activity in the right than in the left cerebral hemisphere; the cerebral laterality of vigilance occurs in an abbreviated task. Although there was a significant decline in performance over time, there was no significant change in the physiological measures over time during the abbreviated vigil. This latter finding does not match the physiological changes detected in long-duration vigils.

Vigilance or sustained attention concerns the ability of observers to detect brief and unpredictable signals over time (Davies & Parasuraman, 1982; Warm, 1984). This aspect of human performance is of particular interest to psychologists because of the critical role that it occupies during many daily activities, including occupational tasks (Howell, 1993; Parasuraman, 1986; Proctor & Van Zandt, 1994; Wickens, Gordon, & Liu, 1998). Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies have reported that changes in cerebral blood flow occur during the performance of sustained attention or vigilance tasks (Parasuraman, Warm, & See, 1998). These studies are limited, however, by the failure to correlate brain activity with performance efficiency, most probably due to the high cost and restrictive environments associated with PET and fMRI (Parasuraman et al., 1998).

Such limitations may be circumvented when studying brain systems in vigilance by employing transcranial Doppler sonography (TCD)—a relatively inexpensive and noninvasive procedure that allows for continuous monitoring of cerebral blood flow velocity in the main-stem intracranial arteries, the middle, anterior, and posterior cerebral arteries (Aaslid, 1986). Several studies have shown that there is a close relation between mental activity and cerebral blood flow velocity as measured by TCD; cerebral blood flow velocity is more rapid when observers engage in a wide variety of information-processing activities than during rest or baseline periods (Duschek & Schandry, 2003; Stroobant & Vingerhoets, 2000; Tripp & Warm, 2007; Vingerhoets & Stroobant, 1999a, 1999b). Moreover, since the diameters of the main-stem intercranial arteries remain largely unchanged under varying task demands, the hemovelocity

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changes in these arteries do not result from their own vascular activity but, instead, from changes in the blood demanded by their perfusion territories, and thus changes in cerebral metabolism are due to cerebral activation (Duschek & Schandry, 2003; Stroobant & Vingerhoets, 2000; Tripp & Warm, 2007; Vingerhoets & Stroobant, 1999a, 1999b).

Recent vigilance studies (Hitchcock et al., 2003; Schnittger, Johannes, Arnavaz, & Munte, 1997; Warm & Parasuraman, 2007) indicate that the temporal decline in signal detections that typifies vigilance performance—the vigilance decrement—is accompanied by a parallel decline in cerebral blood flow velocity. They also indicate that the absolute level of blood flow velocity in vigilance tasks is positively related to the psychophysical and cognitive demands placed upon observers and that these effects are lateralized to the right cerebral hemisphere (Hitchcock et al., 2003; Warm & Parasuraman, 2007), a result consistent with PET and fMRI studies indicating right hemisphere functional control of vigilance performance (Parasuraman et al., 1998).

Another nonrestrictive alternative to PET and fMRI is the measurement of cerebral blood oxygen saturation using near infrared spectroscopy or transcranial cerebral oximetry (TCCO; Toronov et al., 2001). Results with this technique show that tissue oxygenation increases with the information-processing demands of the task being performed (Punwani, Ordidge, Cooper, Amess, & Clemence, 1998; Toronov et al., 2001). Hence, one might expect that along with cerebral blood flow velocity, cerebral oxygenation would also be related to vigilance performance. An examination of that proposition was one major goal for this study.

Given the ubiquitous role of vigilance in daily activities, it is important to understand the factors that contribute to performance efficiency and stress on such tasks. One complicating factor in this regard is the inconvenience associated with their long duration. Vigilance tasks traditionally require observers to monitor displays continuously for periods of 30 min to several hours (Warm, 1993). Prolonged testing time slows the pace of data collection, increases the temporal commitment required of participants, which is of ethical and economic concern, and limits the inclusion of vigilance in testing batteries involving other performance tasks.

Posner (1978) has argued that task duration is an arbitrary dimension in vigilance. Accordingly, he raised the possibility of researchers generating shorter vigilance tasks that demonstrate the same features as do long-duration vigils. The most well known short-duration task is the Continuous Performance Task (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956), often used in applied settings with clinical populations. The CPT requires observers to detect either a single letter (usually X) or a more mentally demanding letter sequence (usually X following A). The critical signal occurs intermittently at random positions within a repeated 31-letter series, although there have been subsequent modifications to shorten the letter series. The letter stimuli appear at a rate of one per second, and critical-signal probability is 20% or higher. Observers are commonly tested for a 10-min period or a combination of 10-min periods, although task time varies. Studies with the CPT have shown that individuals with brain damage and those with other clinical conditions perform more poorly than normal controls (Ballard, 1996; Berch & Kanter, 1984; Damos & Parker, 1994; Davies & Parasuraman, 1982). However, studies with the CPT often ignore the essential features of long-duration vigilance tasks, such as the performance decrement (Davies & Parasuraman, 1982).

Nuechterlein, Parasuraman, and Jiang (1983) developed an 8-min vigilance task that provides some support for a short-duration analog to long-duration vigilance tasks. The task consists of the rapid (60 per min) repetitive presentation of blurred numerals 0 through 9 and employs a visual mask to reduce figure–ground contrast. The critical signal for detection is the numeral 0. Observers' performance efficiency on this task declines within 5 min of watch. Neuchterlein's task, however, requires highly specialized projection equipment. To date, some of the strongest support for there being a short-duration analog to long-duration vigils comes from work with a 12-min task devised by Temple et al. (2000). That task is modeled after the one developed by Neuchterlein and his associates. However, it is computerized and does not require the specialized projection equipment of the Nuechterlein et al. task. The Temple task consists of the rapid (57.5/min), repetitive presentation of the letters O, D, and a backwards D, employing a visual mask of small circles to reduce figure–ground contrast. The critical signal for detection in this task is the letter O. Studies with this abbreviated vigilance task have consistently demonstrated a decline in performance efficiency over the 12-min period of watch that appears to mirror the vigilance decrement found with long-duration tasks (Helton, Dember, Warm, & Matthews, 1999; Helton et al., 2004; Helton, Warm, Matthews, Corcoran, & Dember, 2002; Matthews, Warm, Dember, Mizoguchi, & Smith, 2001; Rose, Murphy, Byard, & Nikzad, 2002; Temple et al., 2000). In addition, the abbreviated task also demonstrates high operator stress as measured by the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999) similar to the results found in the case of long-duration vigils (Helton et al., 1999, 2004; Matthews et al., 2001; Temple et al., 2000).

Temple et al. (2000) have also shown that the abbreviated vigil mirrors long-duration vigils in terms of its sensitivity to a psychophysical manipulation, *signal salience*, and a pharmacological agent, *caffeine*. The signal salience effect, in which performance efficiency varies directly with the psychophysical strength or conspicuity of the stimuli, is a prevalent finding in long-duration vigilance tasks (Warm & Jerison, 1984). Likewise, the abbreviated task also reveals the signal salience effect, with performance efficiency significantly improved by a more salient signal. The consumption of caffeine often enhances long-duration vigilance performance (Lieberman, 1992), and performance efficiency on the abbreviated task is enhanced when observers consume caffeine instead of a placebo. These results clearly support Posner's (1978) position that it is possible to construct an abbreviated vigilance task that exhibits the same effects as those observed in long-duration vigils.

The demonstration that the cerebral vascular dynamics associated with the abbreviated vigil duplicate those associated with long-duration vigils would provide additional evidence that the former represents a viable analog to the latter. Toward that end, the present study employed both the TCD and TCCO procedures with the abbreviated vigilance technique.

EXPERIMENT 1: THE TCD MEASURE

Method

Participants

A total of 24 undergraduate students (12 men and 12 women) from introductory psychology classes at the University of Cincinnati served as observers for course credit. All of the observers had normal or corrected-to-normal vision and were right-handed as indexed by the Edinburgh Handedness Inventory (Oldfield, 1971). Observers were required to abstain from caffeine, nicotine, or medication for 12 hours prior to their participation in the study (Stroobant & Vingerhoets, 2000).

Procedure

Of the 24 observers, 6 (3 males and 3 females) were assigned at random to each of four conditions resulting from the factorial combination of vigilance assignment (work-imperative vigilance condition and control) and hemisphere (right and left). Observers were tested individually in a 2.85 × 4.35 × 2.42-m windowless laboratory room. Ambient illumination in the room was 0.22 cd/m^2. It was provided by a single 11-W incandescent bulb housed in a portable light fixture and positioned above and behind the seated observer in order to minimize glare on the visual display terminal (VDT) used for stimulus presentation. The VDT was mounted on a table at eye level approximately 40 cm from the seated observer.

Following the procedure outlined by Temple and his associates (2000), observers inspected the repetitive presentation of 8 × 6-mm light-gray capital letters consisting of an O, a D, or a backwards D, centered on a VDT. The letters appeared in 24-point Avante Garde font. They were exposed for 40 ms at a rate of 57.5 events/min against a visual mask consisting of unfilled circles on a white background. The mask encompassed the entire visual field .The circular elements of the mask were 1 mm in diameter and were outlined by black lines (0.25 mm thick). The contrast between the black outlines of the circles and the white background of the screen was 92%, as indexed by the Michaelson equation for spatial modulation: [(maximum luminance – minimum luminance)/(maximum luminance + minimum luminance)] × 100 (Coren, Ward, & Enns, 1999). Mask elements were separated by 3mm in the horizontal and vertical directions and by 2.5 mm diagonally. As indexed by the Michaelson equation, the contrast ratio between the letter stimuli and the background was 45%. By virtue of interposition, the letter stimuli appeared to lie behind the circles of the mask. Critical signals for detection were the appearance of the letter O. The order of presentation of the three letter stimuli was varied randomly within each period of watch for each observer in all experimental conditions with the restriction that the critical signal occurred with a probability $p = .20$, and the nonsignal letters occurred with a probability of $p = .40$. Participants signified their detection of critical signals by pressing a key labeled "SIG" on an electronic response pad located in front of them. No response was required for the nonsignal letters (D and backwards D). Responses occurring within 1 s after the onset of the critical signal were recorded as correct detections (hits). All other key presses were recorded as errors of commission (false alarms). Observers in the control condition were required to simply stare at the vigilance display on the computer screen for 12 min with no work imperative.

Blood flow hemovelocities in the left and right middle cerebral arteries (MCAs) were measured by means of a commercially available Nicolet/Multi-Dop X4 TCD unit (Nicolet/EME, Madison, WI, USA). To enable recording of hemovelocities, observers wore a 2- MHz ultrasound transducer embedded in a plastic bracket that 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 blood flow signal. The MCA, which was monitored at depths of 45–55 mm, typically has a hemovelocity range of 50–65 cm/s. The TCD unit permitted depth adjustment in 5-mm increments as needed for isolating the MCA. This artery was selected because it carries 80% of the blood flow within each cerebral hemisphere (Toole, 1999) and because it was the artery used in all prior vigilance/blood flow velocity studies (Hitchcock et al., 2003; Schnittger et al., 1997; Warm & Parasuraman, 2007). Details of the insonation technique and the correct identification of the MCA can be found in several sources (Aaslid, 1986; Duschek & Schandry, 2003; Tripp & Warm, 2007). Time-averaged blood flow velocities were displayed automatically by the TCD unit every 4 s. These values were channeled into a computer located outside the testing area for later analysis. During testing, the investigator was isolated from the observer and had no direct contact with the observer. Observers were acclimated to the TCD procedure during a 5-min baseline period in which they were seated in front of the VDT (which was blank) and were asked to refrain from speaking and to minimize body movement while they breathed regularly and maintained relaxed wakefulness. To reduce anxiety, observers were instructed that the TCD procedure is a noninvasive and painless method for measuring cerebral blood flow velocity (Stroobant & Vingerhoets, 2000). Hemovelocity during the final 60 s of the baseline period provided a baseline index typical of research using the TCD technique (Aaslid, 1986).

Results

An analysis of variance (ANOVA) of an arcsine transformation (Kirk, 1995) of the percentages of correct detections in the vigilance group revealed that there was a significant decline in signal detections over the total watch ($M_{\mathrm{Period1}}=96.38$, $M_{\mathrm{Period2}}=94.93$, $M_{\mathrm{Period3}}=89.86$, $M_{\mathrm{Period4}}=89.13$, $M_{\mathrm{Period5}}=87.68$, $M_{\mathrm{Period6}}=88.41$), $F(4, 39)=3.91$, $p=.012$. These data are displayed in the left panel of Figure 1. False alarms were rare in this study. The overall mean false-alarm rate was less than 1%. Consequently, false-alarm data were not examined further.

Hemovelocity scores were based upon percentage change relative to baseline. A score of 0 would reflect that there was no change in hemovelocity from the baseline measure taken prior to the experimental task. A 2 (task type) × 2 (hemisphere) × 6 (periods of watch) mixed ANOVA revealed significantly higher levels of blood flow velocity in the right ($M=1\%$) than in the left hemisphere ($M=-2\%$), $F(1, 20)=5.06$, $p=.036$, and a significant Task Type × Hemisphere interaction, $F(1, 20)=4.65$, $p=.043$. All other effects lacked statistical significance, $p > .05$. Mean blood flow velocity in the

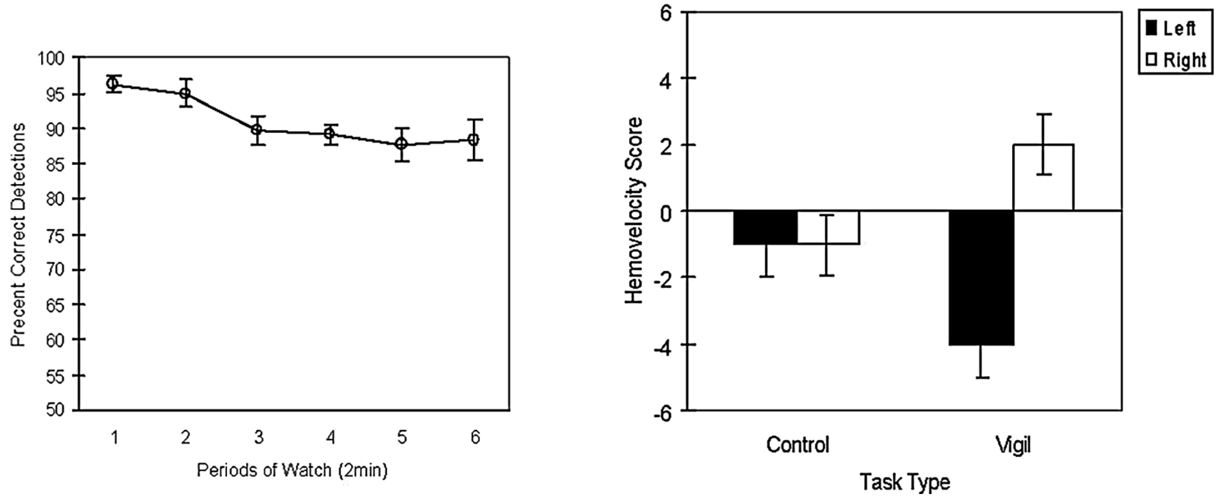

Figure 1. Experiment 1. Mean percentages of correct detections over time on the vigilance task (left panel) and mean hemovelocity scores by task type and hemisphere (right panel). Hemovelocity scores are based upon percentage change relative to baseline. Error bars are standard errors.

right hemisphere ($M=2\%$) was significantly greater than that in the left ($M=-4\%$) in the group that actively performed the vigilance task, $t(10)=3.28$, $p=.008$, while there was no hemispheric difference in blood flow velocity in the control group ($M_{\text{each hemisphere}}=-1\%$). The interaction is plotted in the right panel of Figure 1.

EXPERIMENT 2: TCCO MEASURES

Method

Participants

A total of 38 undergraduate students (18 men and 20 women) from introductory psychology classes at the University of Cincinnati served as observers for course credit. As in the first experiment, all of the observers had normal or corrected-to-normal vision, were right-handed, and were required to abstain from caffeine, nicotine, or medication for 12 hours prior to their participation in the study.

Procedure

A total of 19 observers (9 men, 10 women) were assigned at random to the vigilance and control conditions employed in Experiment 1. The testing circumstances in this study duplicated those of the first experiment. TCCO measures from the left and right frontal lobes were secured simultaneously for each observer using a commercially available Somanetics (Troy, MI) INVOS 4100 Cerebral Oximeter. As in the first experiment, the appropriate sensors were embedded in a plastic bracket that was secured around the observer's head by an adjustable Velcro strap. The sensors were positioned on the observer's forehead so as to avoid sinus cavities and hair that might interfere with the signal. Signals from the sensors were channeled automatically to a computer for later analysis. The frontal lobe was employed because of previous evidence from PET and fMRI studies, which points to right dominance in this brain region during vigilance (Punwani et al., 1998). Cerebral oxygen saturation data were collected for three minutes prior to the experimental session to provide the baseline comparison.

Results

An ANOVA based on an arcsine transformation of the detection scores in the vigilance group revealed that there was a significant decline in signal detections over the total watch ($M_{\text{Period1}}=99.55$, $M_{\text{Period2}}=97.95$, $M_{\text{Period3}}=97.73$, $M_{\text{Period4}}=92.46$, $M_{\text{Period5}}=92.01$, $M_{\text{Period6}}=91.55$), $F(5, 90)=4.92$, $p=.001$. These data are presented in the left panel of Figure 2. As in Experiment 1, false alarms were rare in this study. Consequently, false-alarm data were not examined further.

Oxygen saturation scores were based upon percentage change relative to baseline. A score of 0 would reflect that there was no change in oxygenation from the baseline measure taken prior to the experimental task. A 2 (task type) × 2 (hemisphere) × 6 (periods of watch) mixed ANOVA of these scores revealed that significantly higher oxygen saturation levels occurred in the vigilance group ($M=4.0\%$) than in the control group ($M=2.0\%$), $F(1, 36)=5.74$, $p=.02$, and that there were significantly higher oxygen saturation levels in the right

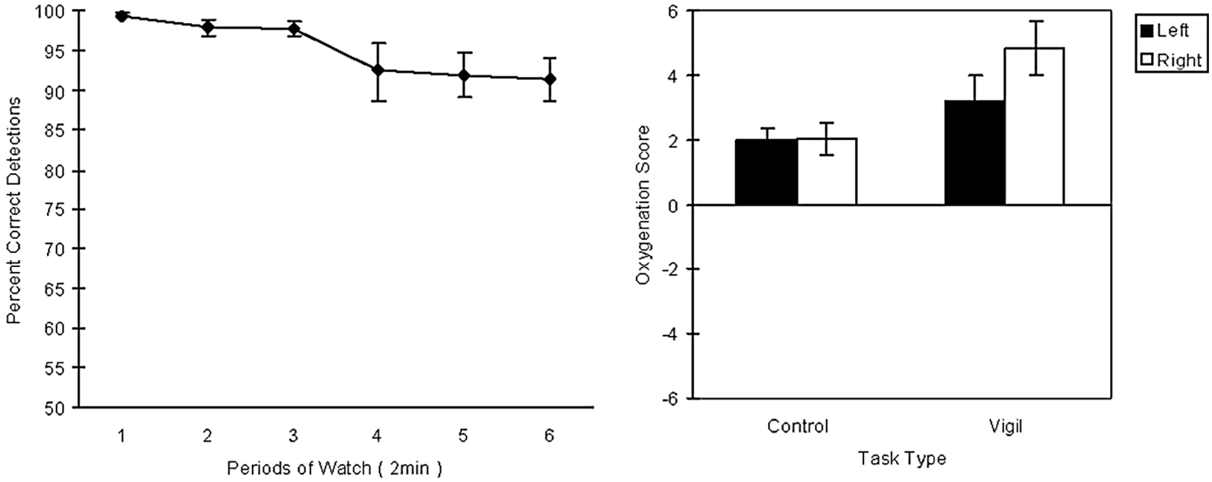

Figure 2. Experiment 2. Mean percentages of correct detections over time (left panel) and mean oxygenation scores by task type and hemisphere (right panel). Oxygenation scores are based upon percentage change relative to baseline. Error bars are standard errors.

hemisphere ($M = 3.5\%$) than in the left ($M = 2.6\%$), $F(1, 36) = 4.84$, $p = .03$. The Task Type × Hemisphere interaction was also statistically significant, $F(1, 36) = 4.01$, $p = .05$. All other effects lacked statistical significance, $p > .05$. For the vigilance group, the difference between the right ($M = 4.8\%$) and the left ($M = 3.2\%$) hemispheres was significant, $t(18) = 2.29$, $p = .03$, while this difference ($M_{\text{right}} = 2.1\%$; $M_{\text{left}} = 2.0\%$) was not significant for the control group, $p > .05$, as shown in the right panel of Figure 2.

DISCUSSION

Blood flow velocity and oxygenation were both found to be significantly higher in the right than in the left cerebral hemisphere among observers who performed the vigilance task while comparable hemispheric differences were absent among controls who observed the VDT display without the work imperative. The results of both experiments indicate that the brain systems that control the overall level of performance in the abbreviated vigil are right lateralized, a finding that is consistent with the outcome of earlier blood flow velocity studies featuring more traditional long-duration vigils (Hitchcock et al., 2003; Warm & Parasuraman, 2007) and with PET and fMRI investigations (Punwani et al., 1998). This parallel provides additional support for Temple et al.'s (2000) argument that the abbreviated vigil is a valid analog of more traditional long-duration vigilance tasks. It also confirms that laterality in vigilance is a generalized effect that appears in terms of both hemovelocity and blood oxygenation and that the TCCO procedure may be a useful supplement to the TCD approach in providing a noninvasive imaging measure of brain activity in the performance of a vigilance task.

An important point to consider in accounting for the present results is the possibility that they may have emanated from gross peripheral changes in systemic vascular activity linked to vigilance performance, such as variations in pulse rate, blood pressure, cardiac output, and heart rate (Caplan et al., 1990; Parasuraman, 1984), rather than to higher level cerebral activity. This possibility is unlikely, however, because prior work on vigilance and other tasks have shown that cerebral blood flow velocity changes are unrelated to changes in pulse rate, heart rate, respiration, blood pressure, or end tidal CO_2 during task performance (Schnittger, Johannes, Arnavaz, & Munte, 1997; Vingerhoets & Stoobant, 1999a, 1999b) and because gross changes in vascular activity are not likely to be hemispheric dependent. Along this line, it is important to note that blood flow velocity has been found to be higher in the right than in the left hemisphere in the performance of a variety of short-term visual–spatial cognitive tasks (Vingerhoets & Stoobant, 1999a, 1999b) leading to the possibility that the present findings, which also involve visual–spatial discriminations, might be material specific and not a general characteristic of vigilance performance. This possibility also seems unlikely, however, because right hemispheric dominance in the performance of vigilance tasks has been found with acoustic stimuli in experiments utilizing both PET and psychophysical (ear of input) measuring techniques (Cohen et al., 1988; Cohen, Semple, Gross, King, & Nordhal, 1992; Warm, Richter, Sprague, Porter, & Schumsky, 1980; Warm, Schumsky, & Hawley, 1976).

Contrary to the laterality effect, the results with regard to the vigilance decrement did not coincide with earlier findings from long-duration tasks. In previous studies investigating brain metabolism during long-duration vigils, the decrement in signal detections was accompanied by a decline in cerebral blood flow (Hitchcock et al., 2003; Warm & Parasuraman, 2007). Neither the blood flow nor the blood oxygenation measures changed significantly with time on task during the abbreviated vigil. Brain systems may need to be sufficiently challenged by task load in order for changes in glucose metabolism to be measurable (Korol & Gold, 1998). The declines in vigilance performance in these studies employing the abbreviated task were not as dramatic as those in Hitchcock et al. (2003), where the percentage of correct detections observed ranged from 95% to 55%.

The abbreviated vigilance task was, however, sufficiently demanding to elicit overall differences in hemispheric hemodynamics. It may be that cerebral vascular dynamics are structured so that overall hemispheric dominance emerges early in the time course of task performance but that temporally based declines in cerebral vascular activity require a considerable amount of time to become observable. Thus, the abbreviated 12-min vigil employed in this study, which was only about 30% as long as those employed in the earlier vigilance blood flow velocity studies, provided insufficient exposure to permit time-based declines in cerebral vascular hemodynamics to be observed.

Posner (1978) has affirmed that the development of an abbreviated vigil that is homologous to long-duration tasks would benefit research on sustained attention. Temple and his associates (2000) have offered a 12-min vigilance task that could potentially meet that goal. Previous research using this task has reported that it is susceptible to the performance decrement over time that is the most ubiquitous feature of long-duration vigilance tasks (Helton et al., 1999; Matthews et al., 2001; Rose et al., 2002; Temple et al., 2000). The present study confirmed the performance decrement. Moreover, the present results with the abbreviated vigil also mirrored previous findings with long-duration vigils in regard to differences in hemispheric activation. At first glance, these aspects of the present results substantiate the notion that the abbreviated vigil represents a solution to Posner's (1978) quest for a short-duration vigilance task that is homologous to the more cumbersome long-duration tasks.

There are theoretical reasons to suspect, however, that the abbreviated vigil is not completely homologous to its long-duration analogs. Certain duration-dependent aspects of sustained attention will be different. In the present case, there was no significant decline in cerebral blood flow or oxygenation during the abbreviated vigil. In previous studies employing longer duration vigils with similar numbers of participants these hemodynamic changes were significant (Hitchcock et al., 2003; Warm & Parasuraman, 2007). Additionally, in a previous study investigating the role of noise on vigilance, Helton et al. (2002) used high-intensity jet-aircraft noise during the abbreviated vigil and found that the presence of noise enhanced performance. In a study by Becker et al. (1995) the same high-intensity jet-aircraft noise degraded performance efficiency on a long-duration vigil. While performance on the abbreviated vigil is clearly homologous to that of its longer duration analogs in terms of the performance effects of time on task, signal salience, and hemispheric activation, it differs from its long-duration analogs in regard to temporal changes in cerebral hemodynamics and, in a previous study (Helton et al., 2002), noise.

Accordingly, prior to any effort to adopt this task as a means of telescoping the temporal demands of traditional vigilance tasks and incorporating it in test batteries or in brain imaging experiments, researchers need to be sure of the dimensions on which it does and does not mirror performance on the more traditional long-duration vigils. This note of concern may also extend to other attempts to create short-duration vigilance tasks, such as the CPT and, more recently, the Sustained Attention to Response Task (SART; Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). This does not, of course, preclude the use of abbreviated vigilance tasks in clinical or experimental settings, where their brevity is advantageous. This is only a note of caution that abbreviated vigils may not be similar to the more traditional long-duration vigils in all regards. On a positive note, this study does indicate that an abbreviated vigil elicits similar hemispheric differences to those typical in long-duration vigils, which is evidence supporting the suggestion that both abbreviated and long-duration vigils activate similar brain systems.

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