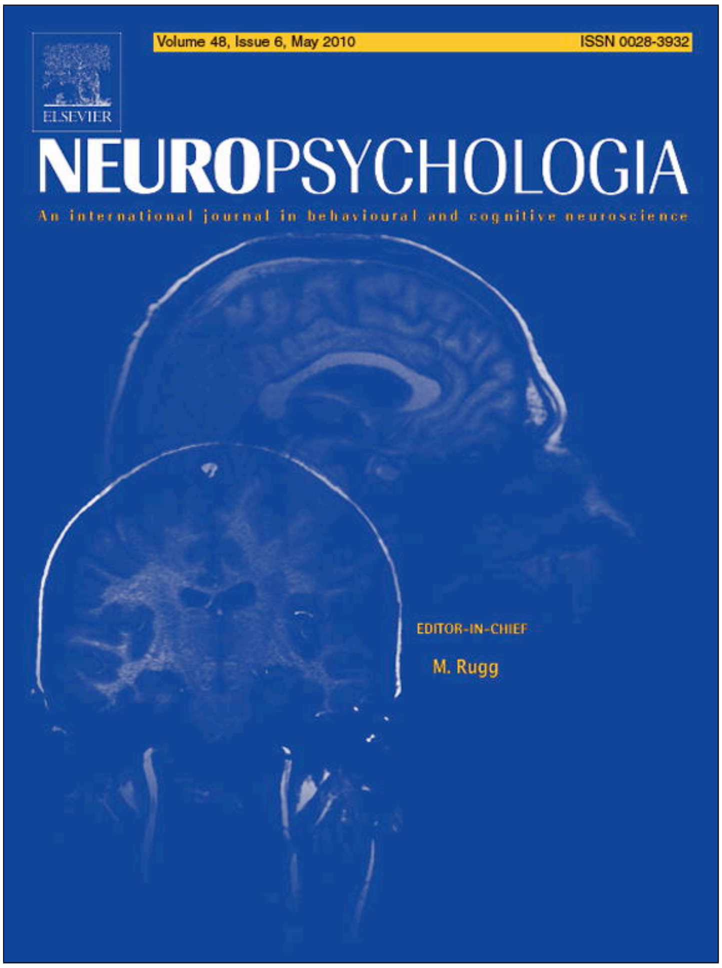
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# Cerebral lateralization of vigilance: A function of task difficulty

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ABSTRACT

Functional near infrared spectroscopy (fNIRS) measures of cerebral oxygenation levels were collected from participants performing difficult and easy versions of a 12 min vigilance task and for controls who merely watched the displays without a work imperative. For the active participants, the fNIRS measurements in both vigilance tasks showed higher levels of cerebral activity than was present in the case of the no-work controls. In the easier task, greater activation was found in the right than in the left cerebral hemisphere, matching previous results indicating right hemisphere dominance for vigilance. However, for the more difficult task, this laterality difference was not found, instead activation was bilateral. Unilateral hemispheric activation in vigilance may be a result of employing relatively easy/simple tasks, not vigilance per se.

## 1. Cerebral lateralization of vigilance: a function of task difficulty

Humans and other animals are often required to monitor the environment for prolonged periods of time for infrequently occurring critical events, while ignoring irrelevant stimuli. Researchers have labeled this as vigilance or sustained attention (Nuechterlein, Parasuraman, & Jiang, 1983; Warm, 1984). In real world scenarios, for example while driving a car or operating heavy machinery, the ability of a person to sustain attention to important events is vital for human safety and wellbeing. In laboratory settings, sustained attention tasks are useful for exploring and understanding the control of attention and attention deficits (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997).

One of the most consistent findings in the vigilance literature is its cerebral lateralization. Researchers have demonstrated increased blood flow and greater metabolic activity in the right as compared to the left hemisphere during sustained attention tasks with a variety of imaging techniques, including functional magnetic imaging (fMRI), positron emission tomography (PET), transcranial Doppler sonography (TCD), and functional near-infrared spectroscopy (fNIRS) (Berman & Weinberger, 1990; Buchsbaum et al., 1990; Cohen et al., 1988; Deutsch, Papanicolaou, Bourbon, & Eisenberg, 1987; Duschek & Schandry, 2003; Helton et al., 2007; Hitchcock et al., 2003; Lewin et al., 1996; Parasuraman, Warm, & See, 1998; Pardo, Fox, & Raichle, 1991; Reivich & Gur, 1985; Shaw et al., 2009; Stroobant & Vingerhoets, 2000; Warm, Matthews, & Parasuraman, 2009). Moreover, in vigilance studies with commissutomized (split-brain) patients using auditory, tactual, and visual stimuli, Diamond (1979a, 1979b) found superior performance for signals presented to the right hemisphere than to signals presented to the left hemisphere.

When the cognitive load of a task increases, however, the brain would be advantaged by being able to activate both hemispheres, thus gaining additional processing power. That shift to bilateral activation could be in parallel, or more likely, coordinated with increased interhemispheric communication (Banich, 1998; Luck, Hillyard, Mangun, & Gazzaniga, 1989; Scalf, Banich, & Erickson, 2009; Scalf, Banich, Kramer, Narechania, & Simon, 2007). This has been demonstrated in imaging studies; complex tasks are marked by bilateral activation whereas simple tasks are more lateralized (Klingberg, O'Sullivan, & Roland, 1997). Visual field studies have also demonstrated performance improvements in bilateral presentation of material for complex, but not simple tasks (Passarotti, Banich, Sood, & Wang, 2002; Weissman & Banich, 2000; Yoshizaki, Weissman, & Banich, 2007). Further, older adults exhibit greater bilateral activation than younger adults on tasks and this has been suggested to reflect a compensation mechanism for decreased pro-

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cessing capacity due to aging (Reuter-Lorenz, Stanczak, & Miller, 1999).

The ability to activate bilaterally, or de-lateralize, may also be the case during difficult vigilance assignments. Indeed, lateralization of vigilance does not appear to be a mammalian universal. Recent research indicates dolphins are able to maintain constant levels of vigilance for at least five days (Ridgway et al., 2006, 2009). This achievement is presumably interrelated to dolphins' ability to alternate sleep and activation across their hemispheres in order for them to be able to swim continuously and breathe (Lyamin, Manger, Ridgway, Mukhametov, & Siegal, 2008). Presumably, dolphins can maintain vigilance with either hemisphere while the other hemisphere is in a sleep state. Moreover, while vigilance performance is relatively degraded for signals presented to the left hemisphere in comparison to the right hemisphere in commissurotomy (split-brain) patients, they are not completely incapable of detecting left hemisphere directed signals (Diamond, 1979a, 1979b). Indeed, even people with complete right hemispherecotomies do not become entirely unvigilant (Chiricozzi, Chieffo, Battaglia, Iuvone, & Acquafondata, 2005). While the human left hemisphere may not be as efficient at vigilance as the right, the left is not entirely incapable of playing a role in maintaining vigilance. Especially when the processing load goes up during vigilance the mammalian brain, dolphin or otherwise, may be able to share the load across hemispheres to compensate for the increased information-processing demand.

In order to test the hypothesis that lateralization of sustained attention is a function of task difficulty, we made use of a less invasive and restrictive alternative to PET and fMRI, the measurement of cerebral blood oxygen saturation using functional near infrared spectroscopy (fNIRS; Toronov et al., 2001) to measure cerebral tissue oxygen saturation during vigilance tasks. Previous 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). Helton et al. (2007) have recently employed this technique with a short duration vigilance task. They found right cerebral lateralization when participants actively performed the task, but not when participants merely observed the vigilance display without a work imperative. In the current study, we added a condition of increased task difficulty to Helton et al. (2007), by reducing the signal salience (perceptual conspicuity) of the target. In a previous meta-analysis, See, Howe, Warm, and Dember (1995) demonstrated that the most important psychophysical factor for performance in vigilance is the signal salience of the target stimuli. Performance efficiency in vigilance varies directly with the psychophysical strength or conspicuity of the stimuli, e.g. signal salience (Warm & Jerison, 1984). Therefore, we manipulated signal salience to increase task load.

## 2. Methods

### 2.1. Participants

Fifty-seven students (30 men and 27 women) served as participants in this experiment. All were enrolled in introduction to psychology courses at a Midwestern United States university and participated to fulfill a class requirement. All of the participants had normal or corrected-to-normal vision and were right-handed as indexed by the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were required to abstain from caffeine, nicotine, or medication for 12 h prior to their participation in the study (Stroobant & Vingerhoets, 2000). They ranged in age from 18 to 37 years (*M* = 20.0, *SD* = 3.28).

### 2.2. Procedure

The 57 participants were assigned at random to one of the three conditions: hard vigil, easy vigil or control condition. Ten men and 9 women, therefore, served in each of the three conditions. Participants were tested individually in a 2.85 m × 4.35 m × 2.42 m windowless laboratory room. Ambient illumination in the room was .22 cd/$m^2$ and was provided by a single 11-W incandescent bulb housed in a portable light fixture. The light was positioned above and behind the seated participant in order to minimize glare on the visual display terminal (VDT) used for the task presentation. The VDT was mounted on a table approximately 40 cm from the seated participant. All participants were briefed regarding the nature of the task and the physiological measurement to be employed (fNIRS) and they provided informed consent prior to their inclusion in the experiment.

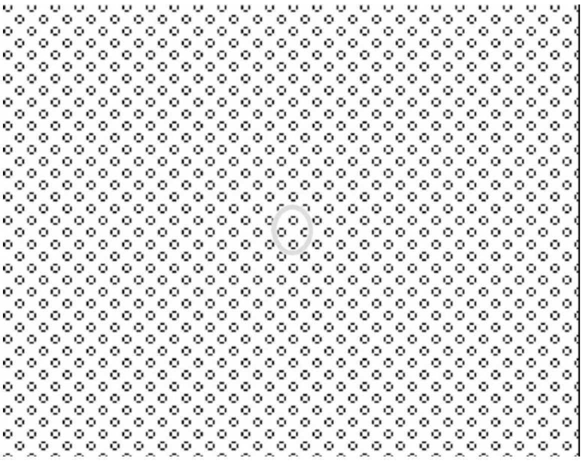

**Fig. 1.** The vigilance display. In the actual task, the central letter would be much lighter relative to the background; it is enhanced here for display purposes.

Prior to the beginning of the main task, participants were instrumented with sensors for the left and right frontal lobes using a commercially available INVOS 4100 Near Infrared Cerebral Oximeter (Somanetics, Troy, MI). NIRS uses light in the near-infrared spectrum (700–1400 nm) to determine properties of biological tissue. Because oxyhemoglobin ($O_2$Hb) and deoxyhemoglobin (HHb) have distinct optical absorption characteristics, fNIRS can be used to determine the relative amounts of $O_2$Hb and HHb in the cerebral tissue. The relative amounts of $O_2$Hb and HHb can be used to calculate regional oxygen saturation (r$SO_2$). Moreover, the well established relationship between a decrease in HHb (thus, an increase in r$SO_2$) and an increase in the blood-oxygentated-level dependent (BOLD) signal of fMRI suggests that both fMRI and fNIRS are similar measures of cerebral activation (see Ekkekakis, 2009; Gratton & Fabiani, 2007 for more details regarding fNIRS). The near-infrared sensors were positioned on the participant's forehead and care was taken to avoid the sinus cavities and hair that might interfere with the signal. The sensors were secured in place by an attached adjustable Velcro strap. 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). Participants were acclimated to the NIRS procedure during a 5-min baseline period. They were seated in front of the VDT (which was blank) and asked to refrain from speaking and to minimize body movement while they breathed regularly and maintained relaxed wakefulness. To minimize participant anxiety, they were instructed that the NIRS procedure is a non-invasive and painless method for measuring cerebral oxygen saturation. Cerebral oxygenation during the final 60 s of the baseline period provided a baseline index (Aaslid, 1986).

For the primary task, which was 12 min in duration, participants inspected the repetitive presentation of 8 mm × 6 mm light gray capital letters consisting of either an O, a D, and a backwards D, centered on a video display terminal (VDT) as outlined by Temple et al. (2000). This task has been used in previous studies and demonstrates many characteristics similar to long duration vigilance tasks (Helton, Dember, Warm, & Matthews, 2000; Helton, Matthews, & Warm, 2009; Helton, Shaw, Warm, Matthews, & Hancock, 2008; Helton & Warm, 2008; Temple et al., 2000). The letter stimuli appeared in twenty-four-point Avante Garde font. The letters 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 (see Fig. 1). The mask encompassed the entire visual field. The circular elements of the mask were 1 mm in diameter and were outlined by 0.25 mm thick black lines. The contrast between the black outlines of the circles and the white background of the screen was 92 percent, as indexed by the Michaelson contrast ratio ([maximum luminance − minimum luminance/maximum luminance + minimum luminance] × 100; Coren, Ward, & Enns, 1999). Mask elements were separated by 3 mm in the horizontal and vertical directions and by 2.5 mm diagonally. In the high salience condition, the contrast between the letter stimuli and the background was 45 percent, as indexed by the Michaelson contrast ratio. In the low salience condition, the contrast between the letter stimuli and the background was 35 percent. Critical signals for detection were the appearance of the letter O. The 12 min watch was divided into six continuous 2 min periods. The order of presentation of the three letter stimuli (O, D, and backwards-D) was varied randomly within each period of watch for each participant in all experimental con-

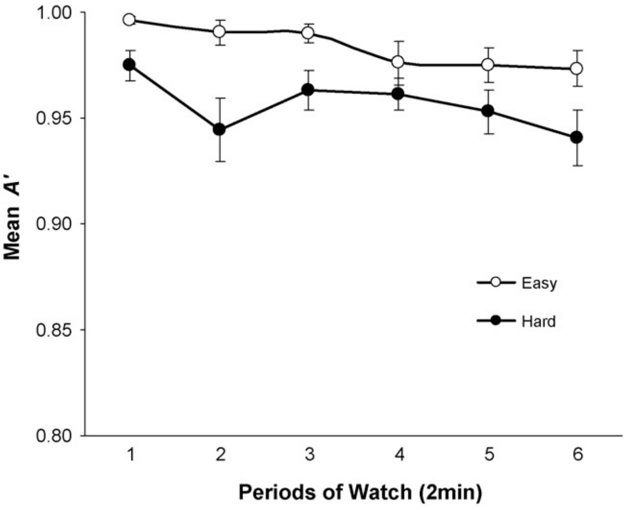

**Fig. 2.** Mean perceptual sensitivity *A*′ over time on the vigilance task. Error bars are standard errors.

ditions with the restriction that the critical signal occurred with a probability $p = .20$ and each of the non-signal letters occurred with a probability of $p = .40$ each. Participants signified their detection of critical signals by pressing a key on an electronic response pad located in front of them. No response was required for the non-signal 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). Participants in the control condition were required to simply stare at the vigilance display on the computer screen for 12 min with no work imperative. Participants surrendered their wristwatches, pagers, and/or cell phones at the outset of the experimental session and had no knowledge of its duration other than it would not exceed 60 min.

## 3. Results

### 3.1. Performance

The nonparametric signal detection measure *A*′ was calculated for each participant for each period based on the individual's hit and false alarm rates (see Macmillan & Creelman, 2005). An analysis of variance (ANOVA) of the *A*′ scores in the two active vigilance groups revealed that there was a significant decline in perceptual sensitivity over the total watch, $F(5, 180) = 5.37$, $p < .01$, $\varepsilon_p^2 = .13$. In addition, perceptual sensitivity in the easy condition ($M = .98$, $SD = .02$) was significantly higher than in the hard condition ($M = .96$, $SD = .04$), $F(1, 36) = 7.19$, $p = .01$, $\varepsilon_p^2 = .17$. There was, however, no significant interaction between salience and periods, $p > .15$. These data are displayed in Fig. 2.

### 3.2. Physiology

Previous studies recommend using a relative measure of regional oxygen saturation ($rSO_2$) measurement with the INVOS 4100 (Yoshitani, Kawaguchi, Tatsumi, Kitaguchi, & Furuya, 2002). Therefore, $rSO_2$ scores were based upon percent change relative to baseline. A score of 0 would reflect that there was no change in $rSO_2$ from the baseline measure taken prior to the experimental task. The $rSO_2$ scores for the three groups are plotted as a function of periods of watch in Fig. 3. Data from the two cerebral hemispheres are presented separately in each panel. A 3 (group condition: easy, hard and control) × 2 (hemisphere: left and right) × 6 (periods of watch) mixed-ANOVA revealed a significant group effect, $F(2, 54) = 3.41$, $p = .04$, $\varepsilon_p^2 = .11$ and a significant group by hemisphere interaction, $F(2, 54) = 3.26$, $p = .05$, $\varepsilon_p^2 = .11$. In addition, there was a significant effect for periods of watch, $F(5, 270) = 2.247$, $p = .05$, $\varepsilon_p^2 = .04$, and in particular, a significant quadratic trend for periods of watch, $F(1, 54) = 6.93$, $p = .01$, $\varepsilon_p^2 = .11$. All of the remaining sources of variance in the ANOVA were not significant, $p > .15$ in each case.

Supplementary t tests indicated that both the hard vigilance group ($M = 3.62$, $SD = 2.35$) and the easy vigilance group ($M = 4.02$, $SD = 3.17$) had significantly greater overall $rSO_2$ than the control group ($M = 2.02$, $SD = 1.79$), $t(36) = 2.37$, $p = .02$, $d = .79$ and $t(36) = 2.40$, $p = .02$, $d = .80$, respectively. The hard and easy vigilance group did not significantly differ in regards to overall $rSO_2$, $t(36) = .44$, $p = .66$. In addition, paired *t*-tests comparing right and left $rSO_2$ changes, revealed a significant difference only between the left hemisphere and right hemisphere for the easy task, $t(18) = 2.29$, $p = .03$, $d = .46$. This difference was not significant for the control or hard task, $p > .50$. The average $rSO_2$ scores for the three groups for both cerebral hemispheres are plotted in Fig. 4.

### 3.3. Relationship between $rSO_2$ and performance

In order to examine the relationship between the experimental condition (salience level), percent change $rSO_2$, and perceptual sensitivity, multi-step regression analyses were employed (Maxwell & Delaney, 2004). Models using both the experimental condition and overall percent change $rSO_2$ were used to predict average perceptual sensitivity. Step 1 employed the salience condition and the average of the right and left hemisphere $rSO_2$ scores to predict average perceptual sensitivity on the task. In step 2 the interaction term between experimental condition and percent change $rSO_2$ was introduced into the model. Right and left hemisphere scores were not entered into the analyses in order to curtail problems of multicolinearity (e.g. right $rSO_2$ correlates with the left $rSO_2$, $r = .62$, $p < .01$). The salience conditions were coded in the high signal

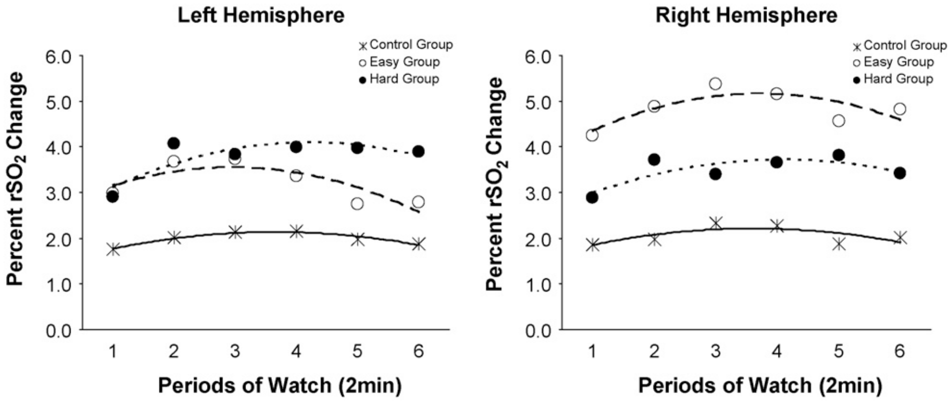

**Fig. 3.** Mean oxygenation scores for the left hemisphere and the right hemisphere over the periods of watch by task type. Oxygenation scores are based upon percent change relative to baseline. The quadratic line of best fit is displayed for each condition.

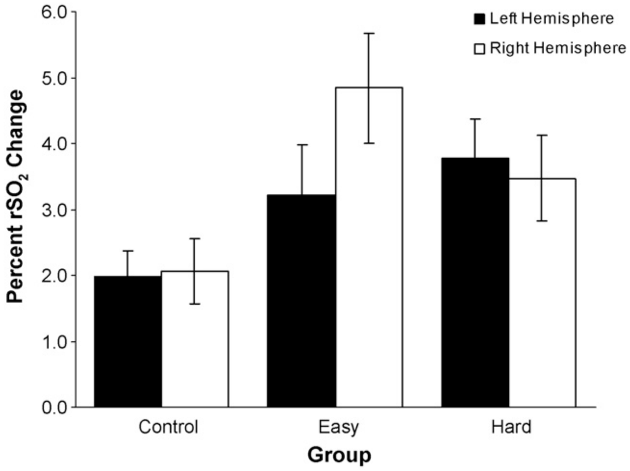

**Fig. 4.** Mean oxygenation scores for the left and right hemispheres for the three tasks. Oxygenation scores are based upon percent change relative to baseline. Error bars are standard errors.

salience condition as −1 and low signal salience condition as 1. The first step in the model was significant, $F(1, 35) = 4.07$, $p = .03$, $R^2 = .19$, and there was a significant change in $R^2$ for the Step 2 model (the interaction), $F(1, 34) = 4.77$, $p = .04$, $\Delta R^2 = .10$, overall model $R^2 = .29$. In Step 2, both the experimental condition, $\beta = -86$, $t = 3.35$, $p < .01$, and the interaction tern, $\beta = .57$, $t = 2.18$, $p = .04$, were significant. The significant interaction suggests that the predictive relation between oxygen saturation and performance is contingent on the difficulty of the task. In the easy task the simple bivariate correlation between average perceptual sensitivity and average percent change in oxygen was actually slightly negative, $r = -.15$, though not statistically significant, $p = .54$. In the hard task, however, the simple bivariate correlation between average perceptual sensitivity and average percent change in oxygen was positive, $r = .43$, and approached significance, $p = .06$.

## 4. Discussion

Cerebral oxygenation was right lateralized in the easier, high salience condition, but was not lateralized in the harder, low salience condition (see Fig. 4). As noted in the introduction of this report, researchers using different measures of hemispheric lateralization, including PET, fMRI, TCD, fNIRS, and functional tympanic membrane temperature have reported right hemisphere dominance during the performance of sustained attention tasks (Duschek & Schandry, 2003; Helton, Hayrynen, & Schaeffer, 2009; Helton et al., 2007; Helton, Kern, & Walker, 2009; Hitchcock et al., 2003; Parasuraman et al., 1998; Shaw et al., 2009; Stroobant & Vingerhoets, 2000). This lateralization may, however, reflect the discrimination difficulty of the targets. In the present investigation a challenging task was employed that demonstrates declines in perceptual sensitivity ($A'$) over very short durations (within 4–6 min), even in the higher salience condition (see Fig. 2). While there was a significant decline in perceptual sensitivity over periods of watch for both salience conditions, performance was significantly worse overall in the low salience condition. High salience performance was closer to the ceiling of $A' = 1.0$ (see Fig. 2). Indeed, only in the hard low salience condition did the relation between cerebral oxygenation and perceptual sensitivity approach significance ($r = .43$, $p = .06$), most likely because in the easy task there was not enough performance variability across participants.

Both vigilance tasks did increase overall cerebral oxygenation relative to the no-workload control task. Therefore, they did place processing demands on the brain beyond the mere act of simply looking passively at the same images on the VDT with no work imperative. Task lateralization may be efficient when easier targets are presented, but with difficult to discriminate targets bilateral activation may improve the brain's resolving power. An alternative possibility is that pattern recognition may have been left lateralized for this task and that the harder, low salience task simply placed more processing demands on the left hemisphere. If the more difficult, low salience, task simply increased demands on selective attention, an increase in left hemisphere activation would be consistent with previous research indicating a left lateral bias for selective attention (Chokron, Brickman, Wei, & Buchsbaum, 2000). While this alternative possibility cannot be ruled out entirely, there was, however, no significant difference in overall $rSO_2$ change between the two vigilance tasks ($p = .66$). Indeed the easier version actually had slightly greater overall $rSO_2$ change ($M = 4.02$) than the hard task ($M = 3.62$). It seems, therefore, unlikely that the hard task simply added processing load to the left hemisphere. Instead the results more strongly support the position that increasing task difficulty induces a processing strategy change, from unilateral to more bilateral activation.

Researchers using transcranial Doppler sonography (TCD) have reported greater declines in right cerebral blood flow velocity (CBFV) from baseline values than left CBFV during the performance of vigilance tasks (Hitchcock et al., 2003; Shaw et al., 2009). In the present investigation, a significant quadratic trend in cerebral oxygenation over periods of watch was detected. Cerebral oxygenation at first increases and then decreases over the periods of watch, but we did not detect any significant differences between the task conditions or, more intriguingly, the hemispheres for this general trend over time. The inability to detect a differential effect on $rSO_2$ with time on task for the two hemispheres does not match previous results using transcranial Doppler sonography (TCD) measures of CBFV in longer duration vigils. There are, however, several plausible explanations for a lack of agreement between our results and previous studies using TCD. First, the vigilance tasks we employed in this study are shorter in overall duration than those employed by Hitchcock et al. (2003) and Shaw et al. (2009). Perhaps, total task duration is important for detecting differences in hemispheric activity over time during vigilance assignments. Second, in these previous studies using TCD, the researchers measured middle cerebral artery blood flow velocity. The fNIRS measure employed in this study would more likely reflect the hemodynamics of regions supplied by the anterior cerebral artery (Ekkekakis, 2009). Third, unlike TCD, fNIRS does not measure CBFV, but instead oxygen metabolism in the cerebral tissue.

One challenge regarding the present results is our inability to cleanly separate out the sustained attention process from other aspects of whole-task vigilance performance. We were, for example, unable to determine whether the shift to bilateral activation in the difficult task in comparison to the easy task was due to a shift in vigilance per se or another aspect of the task, such as pattern recognition. Future studies in which more than one measure of cerebral activity, for example studies combining fMRI, TCD, and fNIRS, may be helpful in resolving the whole-task versus process distinction in vigilance.

The present results do suggest that whole-task vigilance performance is not always strongly lateralized. The right-lateralization of vigilance may be the result of using relatively easy to detect or salient targets. The cerebral lateralization of vigilance with salient targets may increase overall performance when more than one tasks needs to be performed. In the real-world, demands for vigilance are more likely to be encountered in the context of multitasking, such as searching for predators while also foraging, than in the context of just a solitary vigilance assignment, for example, only searching for predators. Research comparing the performance of animals that can be lateralized and non-lateralized by manipulation, for example chickens and fish, have found performance deficits in non-lateralized animals required to simultaneously forage and detect predators (Dadda & Bisazza, 2006; Rogers, 2000). The hemispheres of the brain are separate, though interconnected information processors, enabling tasks to be shared or partitioned by the hemispheres to improve overall processing (Kinsbourne, 1982; Kinsbourne & Hicks, 1978). The division of labor between the hemispheres has been viewed as a way to increase overall computational capacity (Friedman & Polson, 1981). As Kinsbourne (1982, p. 413) stated, "When concurrent acts involve connected territories, they interfere with each other. When they are represented at a distance from each other in functional cerebral space, they interfere little and the capacity of the human operator appears correspondingly enhanced." Further Boles and Law (1998) have provided evidence that dual-task interference is most pronounced when two-tasks draw on similar processes within a hemisphere. There is minimal interference when different processes within or between hemispheres are required for two tasks. Therefore there may be an enhancement of overall performance if the brain can partition tasks to separate hemispheres and reduce the risk of processing overlap.

Difficult to detect targets, however, may shift processing to a more bilateral style. When the tasks are simple it may be useful for an animal to be able to partition foraging and predator detection, for example, to separate hemispheres. Unfortunately when one of these tasks becomes difficult, it may be useful to recruit the other hemisphere. This increase of recruitment due to task difficulty presumably comes with a cost. Increased task load typically impairs secondary task performance (Matthews, Davies, Westerman, & Stammers, 2000). People, like dolphins, may therefore be able to shift vigilance to both hemispheres when required. People are of course unlikely to be able to shift tasks across hemispheres as completely as dolphins, as dolphins have evolved unique capabilities due to their aquatic abode. Future studies should, however, pursue this line of research in order to answer not just the "what" and "how" questions of cerebral lateralization of vigilance, but also the difficult "why" question.

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