Proceedings of the Human Factors and Ergonomics Society Annual Meeting
http://pro.sagepub.com/

Effects of Signal Regularity and Salience on Vigilance Performance and Cerebral Hemovelocity

Todd D. Hollander, Joel S. Warm, Gerald R. Matthews, William N. Dember, Raja Parasuraman, Edward M. Hitchcock, Christina A. Beam and Lloyd D. Tripp

Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2002 46: 1654
DOI: 10.1177/154193120204601727

EFFECTS OF SIGNAL REGULARITY AND SALIENCE ON VIGILANCE PERFORMANCE AND CEREBRAL HEMOVELOCITY

[1]Todd D. Hollander, [1]Joel S. Warm, [1]Gerald R. Matthews, [1]William N. Dember, [3]Raja Parasuraman, [2]Edward M. Hitchcock, [12]Christina A. Beam, and [1]Lloyd D. Tripp

[1]*Department of Psychology, University of Cincinnati, OH*
[2]*National Institute of Occupational Safety and Health, Cincinnati, OH*
[3] *The Catholic University of America, Washington, D.C.*

ABSTRACT

The signal regularity effect - enhanced performance efficiency when critical signals for detection appear in a temporally regular as opposed to an irregular manner- has a long history in vigilance research. However, the precise conditions under which this effect can be elicited have not been identified. Toward that end, this study demonstrates that the effect is limited to low salience signals, perhaps because the effort needed to generate veridical temporal expectancies is unnecessary with high salience signals. Additionally, using signal detection theory indices (*d'* & *c*) and neuroimaging of cerebral blood flow via transcranial Doppler sonography, this study also shows that the signal regularity effect is rooted in sensing rather than decision-making factors and that it is localized in the right cerebral hemisphere.

INTRODUCTION

Operators of many human-machine systems, such as radar and sonar monitors, air traffic controllers, airport security personnel, quality-control inspectors, and anesthesiologists are required to maintain a high level of sustained attention or vigilance in order to detect transient signals over prolonged periods of time and take effective action when needed. Failure to detect important signals can have serious implications for safety, productivity, and health. Accordingly, a key concern for human factors specialists is to identify the variables that influence performance efficiency in vigilance tasks (Wickens & Hollands, 2000; Warm, 1993).

The *signal regularity effect,* a well-established finding (Warm & Jerison, 1984), refers to enhanced performance efficiency when the temporal intervals between critical signals for detection occur in a regular and predictable fashion as opposed to an irregular and unpredictable one. It has been accounted for by the *expectancy model* that describes observers as temporal averaging instruments who form expectancies as to the approximate schedule of critical signal appearances on the basis of task-related experience (Baker, 1963). Readiness to detect a signal is assumed to be positively related to the level of expectancy.

While the signal regularity effect has been known for some time, experimental exploration of the precise psychophysical context under which it can be elicited has been ignored. That context, however, might be crucial in the observation of the effect. For example, as Davies and Tune (1969) suggested several years ago, the signal regularity effect may be limited to situations in which signal salience is low, since under high salience conditions, the information-processing effort needed to develop veridical expectations may be unnecessary for adequate signal detection. One aim for the present study was to provide a long-needed test of that possibility.

The present study was also designed to identify brain systems involved in the signal regularity effect (Parasuraman, Warm, & See, 1998). Toward that end, we used transcranial Doppler sonography (TCD), a non-invasive neuroimaging technique that employs ultrasound, to monitor cerebral blood flow in the middle cerebral arteries (MCAs; Aaslid, 1986). When an area of the brain becomes metabolically active, as in the performance of mental tasks, by-products of this activity, such as carbon dioxide, increase, which, in turn, results in increased blood flow to the region (Aaslid, 1986). Consequently, TCD can serve as a metabolic index of information processing; as such, it has provided insights into the cerebral organization underlying cognitive tasks involved in reading, mathematical computation, spatial imaging, and face recognition (Stroobant & Vingerhoets, 2000). It has also served in a similar fashion with regard to vigilance tasks (Hitchcock et al., in press; Mayleben, 1998). Since expectancy formation in vigilance requires observers to store and retrieve information about the temporal sequence of signals (Davies & Tune, 1969), one might anticipate a higher level of cerebral blood flow under conditions that foster expectancy formation (regular signals) than those that do not (irregular signals). Moreover, given recent findings by Tulving and his associates (Tulving et al., 1994) that memory retrieval is primarily a right-brain function, one might also anticipate that the regularity-based hemovelocity (blood flow) in vigilance will be greater in the right as compared to the left hemisphere. These possibilities were also tested in the present study.

METHOD

Eighty students (40 men and 40 women) from the University of Cincinnati served as observers. All had normal or corrected-to-normal vision and were right-handed. Two levels of signal salience (high and low) were combined factorially with two levels of signal periodicity (regular and irregular) to produce four experimental conditions. Sixteen observers (equated for sex) were assigned at random to each condition.

All observers participated in a 40-min vigil (divided into 4 continuous 10 min periods) during which they monitored a simulated air-traffic display adopted from Hitchcock et al. (1999). It consisted of a "city" (a solid red circle, 10.5 mm in diameter, luminance = 23.7 cd/m^2 banded by a thin white border 0.75 mm thick x 12 mm in diameter) ringed by three circular white "outer markers" (0.75 mm thick; 28mm, 53 mm, and 83 mm in diameter, respectively; luminance = 79.2 cd/m^2) and two "jet aircraft" (represented by two 1mm x 25 mm lines), all of which were presented on a light gray background (luminance = 29.6 cd/m^2). In all conditions, the display was updated 30 times/min with a dwell time of 300 msec. The Michaelson contrast ratio (Coren, Ward, & Enns, 1999) of the aircraft to their surrounding background was 98% in the *high salience* condition and 2% in the *low salience* condition. Critical signals for detection (emergency events) were cases in which the two aircraft were aligned on a collision path over the center of the city. In all conditions, twenty signals were presented per 10-min period of watch. In the *regular signal* condition, inter-signal intervals were fixed at *one critical signal every* 30 sec; in the irregular signal condition, inter-signal intervals ranged from 12 to 60 sec, with a mean of 30 sec. Observers indicated detection of critical signals by pressing the spacebar of a computer keyboard.

TCD-determined hemovelocities in the left and right middle cerebral artery (MCA) were measured during a 5-minute baseline rest period and throughout the sustained attention task using a Nicolet/EME/TC2-64B TCD unit. Half the participants (equated for sex) in each signal salience/signal regularity combination had measurements taken from the left MCA and half from the right MCA. An important element in a study of this sort is the need to show that the time-based declines in blood flow are indeed task-linked. Toward that end, blood flow velocities were collected from either the left or right MCA in an additional group of 16 participants (control group) who simply looked at the display for 40 min without an information-processing imperative.

RESULTS

Percentages of correct detections and false alarms were used to determine signal detection theory indices of perceptual sensitivity (*d'*) and response bias (*c*; Macmillan & Creelman, 1991). The index *c* was employed instead of the more traditional index ß because it has been found to be a more effective measure of response bias than ß in vigilance experiments (See, Warm, Dember, & Howe, 1997). Mean *d'* scores in the regular and irregular signal conditions are plotted as a function of time on task in Figure 1. Signal salience (circles, triangles) and signal regularity (filled and unfilled symbols) are the parameters.

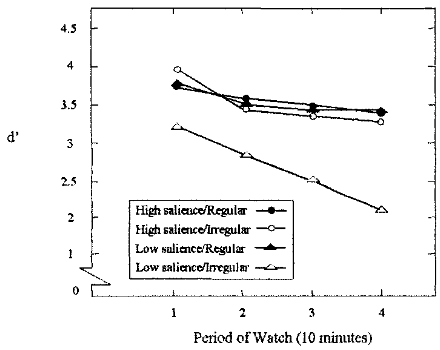

Figure 1. Mean d' scores in all experimental conditions as a function of time on task.

It is evident in the figure that the effects of signal regularity depended upon salience. Perceptual sensitivity was superior for the regular (filled symbols) as compared to the irregular (unfilled symbols) signal condition but *only* in the context of low salience signals (triangles not circles). These impressions were supported by an analysis of variance (ANOVA) of the detection data that revealed a significant main effect for regularity, $F(1,60) = 8.60$, $p < .01$, and a significant Regularity x Salience interaction $F(1, 60) = 8.50$, $p < .01$. In addition, the analysis also revealed that the d' scores varied directly with signal salience, $F(1, 60) = 8.46$, $p < .05$, that the quality of perceptual performance declined significantly over time, $F(2, 151) = 23.88$, $p < .001$ and that the vigilance decrement depended upon signal regularity, $F(3, 180) = 3.28$, $p < .05$. The decrement was greater for the irregular than for the regular signal condition. All other sources of variance in the ANOVA of the d' scores lacked statistical significance ($p > .05$). In this and all subsequent ANOVAs, Box's epsilon was used when appropriate in calculating degrees of freedom for repeated measures factors to correct for violations of the sphericity assumption (Maxwell & Delaney, 1990).

An ANOVA of the response bias scores revealed that observers became more conservative over time (M's for periods 1-4 =.36, .47, .49 and .53, respectively), $F(2, 148) = 7.3$, $p < .01$. All other sources of variance in the analysis were not statistically significant ($p > .05$).

Throughout the vigil, the TCD unit calculated a hemovelocity average (cm/sec.) approximately every four sec. For each observer, the mean of the last 60-sec of the 5-min resting period was considered the observer's baseline hemovelocity score. In all analyses of the blood flow data, hemovelocity is expressed as a *percentage of this resting baseline* value.

Control observers' mean hemovelocity scores in the right and left cerebral hemispheres are plotted as a function of time on task in Figure 2. An ANOVA of the data of the control group revealed that blood flow remained stable over time and that there were no significant differences between the hemispheres, $p > .05$ in each case. Therefore, blood flow changes in the experimental groups can be interpreted as task-dependent.

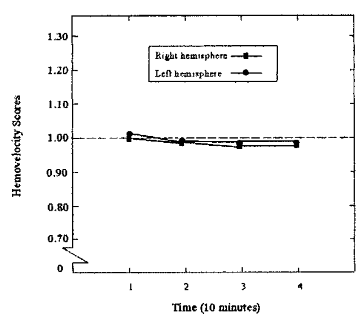

Figure 2. Control observers' mean hemovelocity scores in the right and left cerebral hemispheres as a function of time on task.

Mean hemovelocity scores for the experimental groups are plotted as a function of time in Figure 3. Data for the left and right cerebral hemispheres are presented separately in each panel. In both panels, signal salience and signal regularity are the parameters.

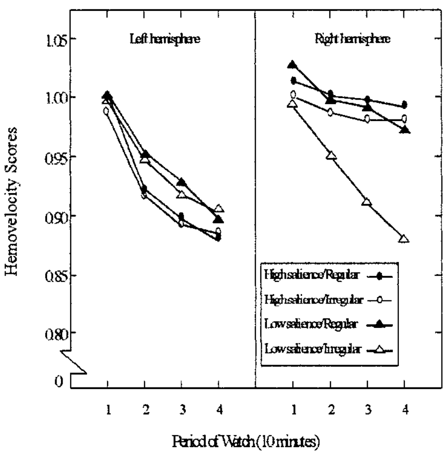

Figure 3. Mean hemovelocity scores for the experimental groups in the right and left cerebral hemispheres as a function of time on task.

Results for the *left hemisphere* show a decline in hemovelocity over time but little effect for signal salience or regularity. In contrast, results for the *right hemisphere* show a striking similarity between the blood flow data and the signal detection scores. As in the latter case, the scores are higher for the regular (filled) than the irregular (unfilled) signal condition, but primarily within the context of low salience signals (triangles). Separate ANOVAs were performed on the data of each hemisphere. The only significant source of variance in the *left hemisphere* was the main effect of time on task, $F(2, 53) = 37.07$, $p<.001$. The main effect of time was also significant in the *right hemisphere*, $F(2, 71) = 9.53$, $p <.001$. In addition there was a significant main effect for regularity in that hemisphere, $F(1, 28) = 6.20$, $p<.05$. The Regularity x Salience interaction and the other sources of variance in the analysis did not achieve statistical significance ($p>.05$).

DISCUSSION

Perceptual sensitivity in this study was greater in the regular than in the irregular signal condition, but only in the context of low salience signals. This result confirms Davies and Tune's (1969) suggestion that the signal regularity effect in vigilance is limited to low salience signals. It also fills a key gap in the psychophysical tapestry of vigilance by isolating one of the major contextual determinants of the signal regularity effect. The finding that variations in signal regularity were associated only with changes in d' and not with changes in *c* confirms a prior study by Warm, Dember, Murphy and Dittmar (1992), indicating that the regularity effect is rooted in sensing rather than decision-making factors.

Consistent with expectations derived from an earlier finding that memory retrieval is primarily a right-brain function (Tulving et al., 1994), the blood flow results indicated that the signal regularity effect is lateralized to the right cerebral hemisphere. While the significant Regularity x Salience interaction evident in the d' scores was not mirrored in the blood flow data, there was a trend in that direction that might have reached significance with a larger N. The agreement of the present findings with expectations from the Tulving et al. (1994) study fits nicely with the outcome of a study by Mayleben (1998), who found right hemisphere lateralization for absolute judgment (memory- based) vigilance tasks but not for comparative judgment tasks, in which reference to working memory was not needed for signal detection.

Although the right hemisphere may have primary responsibility for the control of some vigilance effects, the blood flow results indicate that both cerebral hemispheres play a role in the vigilance decrement. This result has also been reported by Hitchcock et al. (in press) and is consistent with the view that a cooperative interaction model best describes the mode of central functioning in regard to the decrement (Allen, 1983; Warm, Schumsky, & Hawley, 1976).

REFERENCES

Aaslid, R. (1986). Transcranial Doppler examination techniques. In R. Aaslid, (Ed.), *Transcranial Doppler sonography* (pp. 39-59). New York: Springer-Verlag.

Allen, M. (1983). Models of hemispheric specialization. *Psychological Bulletin, 93*, 73-104.

Baker, C.H. (1963). Further toward a theory of vigilance. In D.N. Buckner & J.J. McGrath (Eds.), *Vigilance: A symposium* (pp. 127-170). New York: McGraw-Hill.

Coren, S., Ward, L.M., & Enns, J.T. (1999). *Sensation and perception (5th ed.).* Fort Worth : Harcourt Brace.

Davies, D.R., & Tune, G.S. (1969). *Human Vigilance Performance*: New York: American Elsevier.

Hitchcock, E.M., Dember, W.N., Warm, J.S., Moroney, B.W., & See, J.E. (1999). Effects of cueing and knowledge of results on workload and boredom in sustained attention. *Human Factors, 41*, 365-372.

Hitchcock, E.M., Warm, J.S., Matthews, G.R., Dember, W.N, Shear, P.K., Tripp, L.D., Mayleben, D.W., Rosa, R.R., Parasuraman, R. (in press). Automation cueing modulates cerebral blood flow and vigilance in a simulated air traffic control task. *Theoretical Issues in Ergonomics Science.*

Macmillan, N.A., & Creelman, C.D. (1991). *Detection theory: A user's guide.* Cambridge: Cambridge University Press.

Mayleben, D.W. (1998). *Cerebral bloodflow velocity during sustained attention.* Unpublished doctoral dissertation, University of Cincinnati, Cincinnati, OH.

Maxwell, S.E., & Delaney, H.D. (1990). *Designing experiments and analyzing data.* Belmont, CA: Wadsworth.

Parasuraman, R., Warm, J.S., & See, J.E. (1998). Brain systems of vigilance. In R. Parasuraman, (Ed.), The *attentive brain.* (pp.221-256). Cambridge, MA: MIT Press.

See, J.E., Warm, J.S., Dember, W.N., & Howe, S.R. (1997). Vigilance and signal detection theory: An empirical evaluation of five measures of response bias. *Human Factors*, 39, *14-29.*

Stroobant, N., Vingerhoets, G. (2000). Transcranial Doppler ultrasonography monitoring of cerebral hemodynamics during performance of cognitive tasks: A review. *Neuropsychology Review, 10,* 213-231.

Tulving, E., Kapur, S., Craik, F.I., Moscovitch, M., & Houle, S. (1994). Hemispheric encoding/retrieval asymmetry in episodic memory: Positron emission tomography findings. *Proceedings of the National Academy of Sciences USA, 91,* 2016-2020.

Warm, J.S., Dember, W.N., Murphy, A.Z., & Dittmar, M.L. (1992). Sensing and decision-making components of the signal-regularity effect in vigilance performance. *Bulletin of the Psychonomic Society, 30,* 297-300.

Warm, J.S., Schumsky, D.A., & Hawley, D.K. (1976). Ear asymmetry and temporal uncertainty in sustained attention. *Bulletin of the Psychonomic Society, 7*, 413-416.

Warm, J.S. (1993). Vigilance and target detection. In C.D. Wickens & B. Huey (Eds.), *Teams in transition: Workload, stress, and human factors.* (pp. 139-170). Washington, DC: National Research Council.

Warm, J.S., & Jerison H.J. (1984). The psychophysics of vigilance. In J.S. Warm (Ed.), *Sustained attention in human performance* (pp. 35-42). Chichester, UK: Wiley.

Wickens, C.D., & Hollands, J.G. (2000). *Engineering Psychology and human performance.* (3rd Ed.) New Jersey: Prentice Hall.