Effects of Stereoscopic Depth on Vigilance Performance and Cerebral Hemodynamics

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**Objective:** We tested the possibility that monitoring a display wherein critical signals for detection were defined by a stereoscopic three-dimensional (3-D) image might be more resistant to the vigilance decrement, and to temporal declines in cerebral blood flow velocity (CBFV), than monitoring a display featuring a customary two-dimensional (2-D) image.

**Background:** Hancock has asserted that vigilance studies typically employ stimuli for detection that do not exemplify those that occur in the natural world. As a result, human performance is suboptimal. From this perspective, tasks that better approximate perception in natural environments should enhance performance efficiency. To test that possibility, we made use of stereopsis, an important means by which observers interact with their everyday surroundings.

**Method:** Observers monitored a circular display in which a vertical line was embedded. Critical signals for detection in a 2-D condition were instances in which the line was rotated clockwise from vertical. In a 3-D condition, critical signals were cases in which the line appeared to move outward toward the observer.

**Results:** The overall level of signal detection and the stability of detection over time were greater when observers monitored for 3-D changes in target depth compared to 2-D changes in target orientation. However, the 3-D display did not retard the temporal decline in CBFV.

**Conclusion:** These results provide the initial demonstration that 3-D displays can enhance performance in vigilance tasks.

**Application:** The use of 3-D displays may be productive in augmenting system reliability when operator vigilance is vital.

**Keywords:** vigilance, stereopsis, depth perception, neuroimaging, simulator sickness, stress

**INTRODUCTION**

Vigilance or sustained-attention tasks require participants to maintain their focus of attention and to detect infrequent and unpredictable critical signals over prolonged periods of time (Davies & Parasuraman, 1982; Warm, 1984; Warm, Finomore, Vidulich, & Funke, 2015). These assignments are of interest to human factors practitioners because vigilance is important for operators who monitor a wide range of automated systems in domains such as aviation, industrial process/quality control, medical monitoring/screening, airport/border security, and military surveillance (Warm et al., 2015; Warm, Parasuraman, & Matthews, 2008). A key finding in vigilance performance is the vigilance decrement, a decline in the speed and accuracy of signal detections with time on task (Warm, Parasuraman, et al., 2008).

Research has revealed that both the onset and severity of the vigilance decrement are affected by task demands. Factors that increase the psychophysical and information-processing demands of a task, such as reductions in signal salience, increases in the temporal and spatial irregularity of signals, and the number of stimulus events that need to be scanned in order to detect critical signals (increases in event rate), and the inclusion of secondary task loads, have been shown to lower overall vigilance performance and magnify the vigilance decrement (Helton et al., 2007; Parasuraman, 1979; Parasuraman et al., 2009; Parasuraman, Warm, & Dember, 1987; See, Howe, Warm, & Dember, 1995; Warm et al., 2015; Warm & Dember, 1998; Warm, Parasuraman, et al., 2008).

In addition to focusing on performance efficiency itself, investigators have employed a
noninvasive neuroimaging procedure known as transcranial Doppler sonography (TCD) to reveal neurophysiological changes that accompany the vigilance decrement. With this procedure, ultrasound signals are used to monitor cerebral blood flow velocity (CBFV) in the middle, anterior, and posterior cerebral arteries. TCD measures the difference in frequency between outgoing and reflected energy as it strikes moving erythrocytes. When a particular area of the brain is activated, as in the performance of mental tasks, by-products of that activity, such as carbon dioxide (CO₂), increase. The increase in CO₂ results in increased cerebral blood flow to the activated area to remove it (Aaslid, 1986). Consequently, TCD serves as a biomarker of neurological metabolism during task performance (Duschek & Shandry, 2003; Tripp & Warm, 2007). Studies using TCD have shown that CBFV varies directly with task demands, that the vigilance decrement is accompanied by a temporal decline in CBFV, and that these effects occur primarily in the right hemisphere, indicating a right hemispheric system in the functional control of vigilance (Shaw et al., 2009; Shaw, Finomore, Warm, & Matthews, 2012; Warm, Matthews, & Parasuraman, 2009; Warm & Parasuraman, 2007; Warm, Tripp, Matthews, & Helton, 2012).

As described by Ross, Russell, and Helton (2014) and Warm et al. (2015), these behavioral and neurological findings suggest that the vigilance decrement is best explained by the resource model proposed by Davies and Parasuraman (1982), which posits that the need to make continuous signal/noise discriminations depletes information-processing assets that cannot be replenished during task performance, leading to a temporal decline in performance efficiency. Recently, Hancock (2013) has argued that although resource-based accounts may explain the vigilance decrement, the ultimate cause is poor human factors design—the use of tasks that are not optimized for human capacities and limitations. According to Hancock, vigilance tasks typically employ stimuli for detection that are artificial and do not typify those that occur in the “natural” world. As a result, human performance is suboptimal. From this perspective, tasks that better approximate perception in natural environments should be more resistant to the vigilance decrement. This latter view is supported by research illustrating that biological motion cues, which are thought to be automatically processed due to their ecological significance for survival, are resistant to the vigilance decrement (Thompson & Parasuraman, 2012), as are targets embedded in natural scenes (Szalma, Schmidt, Teo, & Hancock, 2014; but see Head & Helton, 2012).

A visual dimension that has not been considered in the sustained-attention literature as yet, but might be employed in vigilance displays to approximate perception in the natural world, is stereopsis. Traditionally defined, stereopsis is the perception of depth created by binocular disparity, or a shift in the lateral position of corresponding monocular images formed on the two retinas (Howard & Rogers, 1995; Patterson, 2009a). As described by Fox (1978) and Patterson (2009b), the capacity for stereoscopic depth processing found in humans also occurs in many predators, such as falcons, cats, owls, and nonhuman primates. It provides members of the animal kingdom with an important means by which to interact with their surroundings and survive. Consequently, on the basis of Hancock’s (2013) suggestion that displays using stimuli that are part of daily life may offer a means to attenuate the vigilance decrement, we tested the possibility that monitoring a display wherein critical signals for detection were defined by a stereoscopic three-dimensional (3-D) image might be more resistant to the vigilance decrement and to temporal declines in CBFV than monitoring a display featuring a customary two-dimensional (2-D) image.

**METHOD**

**Participants**

The study was conducted at the Air Force Research Laboratory, Wright-Patterson Air Force Base (WPAFB). Thirty individuals (18 men, 12 women) with ages ranging from 18 to 32 years (\(M = 23.40\) years) were recruited from base personnel and the local population to serve in the study and were paid $30 for their participation. The study was approved by the WPAFB Institutional Review Board. All participants were right-handed by self-report and as measured by the Edinburgh Handedness Inventory (Oldfield, 1971).
The visual acuity of all participants was normal or corrected to normal in each eye (20/25 or better) as assessed using a Precision Vision Visual Acuity Chart. Participants who required visual correction wore contact lenses during the experiment because eyeglasses would interfere with TCD data collection. Additionally, participants were tested for stereoscopic visual acuity using a Stereo Optical Company Titmus Stereo Fly Test (SO-001 [SFT]; Fricke & Siderov, 1997). They were required to correctly detect 40 s of arc on the “graded circle” portion of the SFT to be included in the experiment.

All participants reported normal color vision and normal hearing and were required to abstain from drugs, including nicotine, caffeine, and medications, for 12 hr prior to the study (Stroobant & Vingerhoets, 2000). Individuals who failed to meet the requirements were excluded from the study.

**Experimental Design**

A 2 (task condition) × 2 (cerebral hemisphere) × 4 (period of watch) mixed design was employed. Fifteen participants, 9 men and 6 women, were assigned at random to each task condition.

**Hemovelocity Measurement**

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. The transducers were embedded in a plastic bracket and secured to the participant’s head by an adjustable plastic headband. 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 ultrasonic transmission gel was placed on the transducers to ensure transmission of the ultrasound signal. The distance between the transducer on the skin and the sample volume could be adjusted in 2-mm increments in order to isonate the middle cerebral artery (MCA). That artery carries about 80% of the blood flow to each cerebral hemisphere (Toole, 1984) and has been used in all previous studies of CBFV and vigilance (see Warm et al., 2012; Warm & Parasuraman, 2007). In the present study, the MCA was generally monitored at depths of 50 to 55 mm. Blood flow velocity measures were averaged and recorded automatically by the TCD unit at approximately 1 Hz.

**Apparatus and Testing Environment**

Testing took place in a sound-dampened booth containing the Nicolet TCD unit and an HP Compaq computer that was used for presentation of the vigilance task and the Simulator Sickness Questionnaire (SSQ), which will be described later. The computer was equipped with an 81.28-cm LG Cinema 3-D display monitor (Model D2342) and speakers. Participants sat directly in front of the computer monitor at a viewing distance of 76.20 cm, which was the distance recommended by the LG Corporation for optimum viewing of 3-D imagery. Participants in both experimental conditions were required to wear polarized LG 3-D lenses (Model FPG-200F), which were clipped to the TCD headband. The lenses were necessary for participants in the 3-D condition to perceive the stereoscopic image. Participants in the 2-D condition also wore the lenses to equate image contrast, luminance, and chromaticity across the 2-D and 3-D conditions.

In order to restrict head movements from affecting the perceptual quality of the 2-D or 3-D signal, each participant’s head was centered in a head frame (a 25.00-cm-wide, 38.50-cm-tall rectangular aperture) that was positioned 76.20 cm from the computer monitor. Figure 1 shows an observer seated within the head frame while viewing the vigilance display.

**Procedure**

Experimental sessions began with the previously described tests of visual acuity. The TCD headset was then applied, after which participants were asked if they felt well and comfortable wearing the equipment (they all said yes). Participants then engaged in a 5-min resting baseline phase during which CBFV measures were recorded. Following baseline measurement, computerized task instructions were presented to participants and were followed by a training vigil (described later).
In both the training and testing phases of the study, participants were presented with a simulated fuel transfer scenario, within which they were individually responsible for monitoring and maintaining a “safe” pressure level. The pressure level was represented by a green gauge (transluminance = 59.57 cd/m²), which was centrally presented upon a dark gray background (transluminance = 11.61 cd/m²). As shown in Figure 2, the gauge consisted of a single green line representing the gauge needle (width = 0.53 cm, 0.40° of visual angle [VA]; height = 4.68 cm, 3.52° of VA). The “needle” was confined within a green circle (diameter = 7.63 cm, 5.73° of VA; boundary edge width = 1.07 cm, 0.80° of VA).

Normally, the gauge needle was vertically aligned within the green circle, which represented a “safe” pressure level (neutral stimulus) and required no input from participants. As illustrated in Figure 2, the presence of a “dangerous” pressure level—the critical state for detection—was indicated in one of two ways. For participants in the 2-D condition, it was represented by a needle that was rotated clockwise from vertical by 2.50°. In the 3-D condition, the needle remained upright, but stereoscopic depth was manipulated such that the needle appeared to “pop out” of the screen toward the observer with a binocular disparity of 21 arc minutes, which induced a perceived depth of about 5.25 cm in front of the screen (Cormack & Fox, 1985; Patterson, 2009a). Critical signals in the 3-D case were in the form of apparent displacement of the gauge needle toward rather than away from the observer because previous studies have reported that target detection is superior when stimuli appear to “pop out” at an observer compared to when they appear to be farther away or at the point of fixation (Anderson & Kramer, 1993; Kasai & Morotomi, 2001; O’Toole & Walker, 1997). Changes in the apparent size of the needle induced by changes in apparent depth would not have been a factor in critical signal detection in the 3-D condition because the needle did not increase in size as it appeared to come toward the observer. Participants in both experimental conditions were instructed to respond by pressing the space bar on the computer keyboard only when they detected a “dangerous” pressure level.

The training phase lasted for 5 min and was intended to familiarize participants with the task. During training, a computerized female voice presented at 48 dBA provided feedback regarding correct detections, misses, and false alarms. The display was updated 30 times per minute (i.e., once every 2 s) with a dwell time of 200 ms. Participants were allowed 2,000 ms from the onset of a critical signal to respond. These timing parameters resulted in presentation of 150 events during...
the training vigil, 20 of which were critical signals (signal probability = 13.33%). Participants were required to detect at least 18 of the 20 critical signals and make no more than 10 false alarms in this phase of the study to be considered for inclusion in the final analysis. All participants in both experimental conditions met this dual criterion.

Following training, participants completed a 40-min main vigil, divided into four continuous 10-min periods of watch. Timing parameters were identical to those of the training phase, resulting in the presentation of 300 events per 10-min period. During the main vigil, signal probability per period was reduced to 6% (18 critical signals occurred during each period of watch), and audio feedback was removed (i.e., observers completed the vigil in silence). Participants were informed that the frequency of occurrence of “dangerous” pressure levels during the main vigil might differ from what they encountered during training. As in the practice phase, they were allowed 2,000 ms from the onset of a critical signal to respond.

SSQ

Upon concluding the 40-minute vigil, participants in both display conditions completed a computerized version of the SSQ, a measure of simulator sickness (Kennedy, Lane, Berbaum, & Lilienthal, 1993). It was administered to determine if the stereoscopically presented stimuli resulted in symptoms of such sickness, as has occasionally been reported in previous studies (e.g., Burks, Harper, & Bartha, 2014; Yang & Sheedy, 2011) and in surveys of the 3-D media-viewing public (see McIntire, Havig, & Geiselman, 2014). The SSQ consists of 16 items, rated on a 0-to-3 scale, where 0 indicates no presence of a symptom and 3 indicates severe experience of that symptom. These items map onto three subscale dimensions: Oculomotor Symptoms, Disorientation, and Nausea. Scoring of the SSQ involves summing the ratings for items that correspond to each subscale and multiplying the sums by a constant specific to each subscale (see Kennedy et al., 1993).

Equating 2-D and 3-D Difficulty

A preliminary study with 7 participants was conducted to ensure that there was no difference in discriminability between the 2-D and 3-D critical signals. A two-alternative forced-choice paradigm was used in which 100 stimulus pairs were sequentially presented to each participant. One member of each stimulus pair represented a neutral “safe” event; the other was a critical signal indicating a “dangerous” event; their order of presentation was varied at random for each participant. On each trial, participants were required to indicate which of the two events was “dangerous.” Fifty trials were collected in the 2-D and 3-D conditions, with the order of conditions balanced as evenly as possible between participants. Arcsine transforms of the percentage of correct discriminations were analyzed using a 2 (task condition) × 2 (block order) mixed-model analysis of variance (ANOVA). This analysis revealed that discrimination accuracy did not differ significantly between the 2-D (M = 97.71%) and 3-D (M = 98.57%) task conditions; the effect of block order and its interaction with task conditions also were nonsignificant (p > .05 in each case). Thus, any differences found between the 2-D and 3-D conditions during vigilance performance were due to the demands of the vigilance task itself and not to initial levels of difficulty that existed under fully alerted conditions.

RESULTS

Performance Efficiency

Mean percentages of correct detections in the 2-D and 3-D conditions are presented as a function of periods of watch in Figure 3.

The figure shows that the level of signal detections was greater in the 3-D than in the 2-D condition and that detection scores in the 2-D condition declined over time whereas those in the 3-D condition maintained relative stability. To test the reliability of these trends, the percentages of correct detections for both conditions were converted to arcsines and analyzed for statistical significance by means of a 2 (task condition) × 4 (period of watch) mixed-model ANOVA. The analysis revealed a significant main effect for task conditions, F(1, 28) = 11.37, p = .002, ηp² = .29, and for periods of watch, F(2,52, 70.56) = 12.34, p < .001, ηp² = .31. Additionally, the interaction between these two factors was significant,
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$F(2.52, 70.56) = 7.08, p = .001, \eta^2_p = .20$. Supplementary single-factor ANOVAs revealed that the effect of periods of watch was significant in the 2-D condition, $F(2.27, 31.81) = 16.07, p < .001, \eta^2_p = .53$, but not in the 3-D condition, $F(2.65, 37.15) = 1.24, p > .05, \eta^2_p = .08$. In this and all subsequently reported ANOVAs, Box’s epsilon was employed as necessary to correct for violations of the sphericity assumption (Field, 2009).

A preliminary examination of the false alarm scores revealed that errors of commission were rare in this study. The mean false alarm rate in all experimental conditions was less than 1% throughout the vigil. Consequently, false alarms were not analyzed further.

**Cerebral Hemodynamics**

Cerebral hemovelocity scores can range extensively across individuals based on characteristics such as sex and/or age (Adams, Nichols, & Hess, 1992). To control for that variability, the CBFV values for all observers in this study were expressed as a proportion of the last 60 s of their 5-min resting baseline. This baseline index was recommended by Aaslid (1986) and has been utilized in previous studies of cerebral hemovelocity and vigilance (see Warm et al., 2012; Warm & Parasuraman, 2007).

Inspection of the resting baseline data was accomplished using a 2 (task condition) × 2 (cerebral hemisphere) ANOVA, which indicated that CBFV values did not differ due to task condition, cerebral hemisphere, or an interaction of these factors ($p > .05$ in each case). Thus, subsequent effects in the two hemispheres associated with the need to monitor for 2-D or 3-D critical signals cannot be attributed to differences in the original resting baselines.

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

A 2 (task condition) × 2 (cerebral hemisphere) × 4 (period of watch) mixed-model ANOVA revealed that mean CBFV was greater in the right cerebral hemisphere ($M_{Right} = 98.07, SE_{Right} = 1.15$) than in the left hemisphere ($M_{Left} = 94.13, SE_{Left} = 0.92$), $F(1, 28) = 22.07, p < .001, \eta^2_p = .38$. Means and their associated standard errors (in parentheses) for Periods 1 through 4 were 97.55 (0.90), 96.68 (0.96), 95.89 (1.00), and 94.27 (1.11), respectively. There was no significant main effect for task condition, $F(1, 28) < 1.0$, but task condition was involved in two significant interactions: one with period of watch, $F(2.11, 59.01) = 3.23, p = .044, \eta^2_p = .10$, and the other with hemisphere, $F(1, 28) = 6.13, p = .020, \eta^2_p = .18$. The remaining sources of variance in the analysis were not statistically significant ($p > .05$ in each case).

The Task × Period interaction is displayed in Figure 4, wherein CBFV scores in the 2-D and 3-D conditions are plotted as a function of time on task. Single-factor ANOVAs indicated significant period effects in both the 2-D condition, $F(2.22, 31.03) = 6.78, p = .003, \eta^2_p = .33$, and the 3-D condition, $F(1.93, 27.00) = 11.60, p < .001, \eta^2_p = .45$. It is evident in the figure, however, that CBFV declined more rapidly in the 3-D task compared to the 2-D task.

The Task × Hemisphere interaction is presented in Figure 5. Perusal of the figure reveals that although CBFV was greater in the right than in the left hemisphere in both the 2-D and 3-D conditions, the hemispheric asymmetry was more pronounced in the latter than in the former case.

**SSQ Ratings**

Mean SSQ ratings for the 2-D and 3-D task conditions are presented for each subscale in
Table 2. Within each display condition, Bonferroni-corrected $t$ tests (familywise $\alpha = 0.05$, $df = 14$) indicated that the scores for the individual subscales were all significantly greater than zero (all $t$ values $> 4.85$, Cohen’s $d > 1.25$, in each case) signifying that observers in both display conditions suffered discomfort as evidenced by each of the three SSQ subscales. The SSQ scores in this study were generally high, exceeding the 95th percentile for each display condition/scale combination based on a normative sample of over 1,000 individuals reported by Kennedy et al. (1993). However, independent Bonferroni-corrected $t$ tests (familywise $\alpha = .05$, $df = 28$) of the difference between the 2-D and 3-D conditions within each subscale were all nonsignificant ($t = 1.04, 1.06, and 0.78$ for the Oculomotor, Disorientation, and Nausea subscales, respectively; $p > .05$ in each case) signifying that simulator sickness was not differentially affected by display type. The use of separate between-group comparisons for each subscale of the SSQ is consistent with prior studies using this scale (Hakkinen, Polonen, Takatalo, & Nyman, 2006; Stanney, Hale, Nahmens, & Kennedy, 2003).

**TABLE 1:** Mean Cerebral Blood Flow Velocity Scores (percentage of resting baseline) in Each Cerebral Hemisphere for the 2-D and 3-D Conditions in Each Period of Watch

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Note. Standard errors are in parentheses.

Figure 4. Mean cerebral blood flow velocity scores (percentage of resting baseline) in the 2-D and 3-D conditions in each period of watch. Error bars are standard errors.

**DISCUSSION**

In a cogent commentary on the vigilance literature, Hancock (2013) suggested that displays that approximate perception in the natural world may offer a means to attenuate the decline in signal detection over time that characterizes performance in sustained attention tasks. Consistent with that suggestion, Parasuraman and his associates (2009) have shown that monitoring performance is resistant to the vigilance decrement when signals for detection include ecologically significant stimuli, such as biological motion, and Szalma and his associates (2014) have found that targets embedded in natural scenes are also resistant to the vigilance decrement. Since the extraction of depth information from stereopsis provides humans with an important everyday means by which to interact with their surroundings (Fox, 1978; Patterson, 2009b), the present experiment was conducted to determine if monitoring for stereoscopic
depth changes would also be resistant to the vigilance decrement. This was indeed the case. The overall level of signal detection in the 3-D condition was significantly greater than in the 2-D condition, and it remained stable over time, whereas performance efficiency in the 2-D case declined significantly over time.

At this point, one might wonder about the mechanisms that underlie the ability of natural-like stimuli to resist the vigilance decrement. Two possibilities come to mind. Natural or natural-like stimuli may be more salient in terms of visual processing: It is known that configural displays, in which elements are organized so that the relations between system variables are represented by easily perceived features (Bennett & Flach, 2011) are also resistant to the vigilance decrement (Szalma, 2011). It may also be that attentional processes become restored, not just less depleted, due to salience after being engaged with natural scenes or with stimuli that approximate natural scenes, which facilitate resource replenishment according to attentional-restoration theory (Kaplan, 1995).

As described by McIntire et al. (2014) and by Yang and Sheedy (2011), a concern with the use of 3-D displays is induced simulator sickness in some observers. However, the fact that the scores on the SSQ, which measured self-reported simulator sickness, were elevated but equivalent in the 2-D and 3-D conditions indicates that the observed simulator sickness in this study was likely triggered by factors other than the conditions

![Figure 5](image-url). Mean cerebral blood flow velocity scores (percentage of resting baseline) in the left and right cerebral hemispheres for participants in the 2-D and 3-D conditions. Error bars are standard errors.

| TABLE 2: Mean Simulator Sickness Questionnaire Scores in the 2-D and 3-D Conditions |
|-----------------|-----------------|-----------------|
| Subscale        | Condition       | Oculomotor      | Disorientation | Nausea          |
| Condition       | 2-D             | 88.43 (9.29)    | 83.52 (14.18)  | 52.15 (7.67)    |
|                 | 3-D             | 75.80 (7.83)    | 63.10 (13.02)  | 43.88 (7.32)    |

Note. Standard errors are in parentheses.
employed to induce stereopsis. One possibility is task-induced stress.

Vigilance tasks have been found to be highly stressful as revealed through both physiological and self-report measures. On the physiological side, studies have shown that catecholamine levels (epinephrine and norepinephrine) circulating in the bloodstream are elevated during the performance of vigilance tasks (Lundberg & Frankenhaeuser, 1980), that observers show increased levels of muscle tension as time on task progresses (Galinsky, Rosa, Warm, & Dember, 1993), and that vigilance tasks induce tension headaches in sensitive observers (Hovanitz, Chin, & Warm, 1989). On the self-report side, observers have rated themselves as feeling less attentive and task engaged and more bored, strained, irritated, fatigued, and distressed after a vigil than prior to its start (Hovanitz et al., 1989; Matthews, Szalma, Panganiban, Neubauer, & Warm, 2013; Scerbo, 2001; Thackray, Bailey, & Touchstone, 1977). A comprehensive review of the stress induced by vigilance tasks can be found in Warm, Matthews, and Finomine (2008). The elevated SSQ scores in the present study may be another instance of the stress imposed upon observers by a vigilance task.

It is important to point out that despite a potentially elevated level of stress, observers in the 3-D condition were able to maintain a uniform high level of performance throughout the watch-keeping session and to do so within the context of a fast event rate (30 per minute), which normally degrades performance efficiency (Davies & Parasuraman, 1982; Warm et al., 2015). A result of this sort is testimony to the potency of a 3-D display in optimizing signal detection in a vigilance task. Along this line, it should be noted that although the configural display employed by Szalma (2011) attenuated the performance decrement, it, too, did not reduce the stress of the vigilance task. Evidently, while high salience can enhance performance efficiency in vigilance, it does not diminish what Hancock and Warm (1989) and Hockey (1997) have described as the energetic cost of stress in sustained attention.

In addition to performance efficiency, the present study was also designed to compare the effects of 2-D and 3-D displays on cerebral hemovelocity in vigilance performance. Some potentially important results in regard to stereo-scopic imaging emerged. In accord with several prior investigations, CBFV was greater in the right than in the left hemisphere when 2-D signals were involved, indicating a right hemisphere system in the functional control of vigilance when 2-D signals are to be detected (Shaw et al., 2009, 2012; Warm et al., 2009, 2012; Warm & Parasuraman, 2007). In the 3-D condition, CBFV was also greater in the right than in the left hemisphere, and the hemispheric difference was more pronounced in the 3-D than in the 2-D case. In this regard, it is important to note that the results of studies involving regional blood flow obtained via positron emission tomography (Fortin, Ptito, Faubert, & Ptito, 2002) and patients with hemispheric lesions (Carmon & Bechtoldt, 1969) have indicated the right hemisphere is dominant for stereopsis. This finding, coupled with a right hemispheric system in the functional control of vigilance, may account for the more pronounced right-hemispheric CBFV effect in the 3-D relative to the 2-D condition in the present study.

A key issue in regard to cerebral hemodynamics was the decline in CBFV scores over time. As in earlier studies with 2-D displays (Shaw et al., 2009, 2012; Warm et al., 2009, 2012; Warm & Parasuraman, 2007), CBFV scores showed a significant temporal decline in the 2-D condition of the present study, a result that paralleled the temporal decline in signal detections. In the 3-D case, the temporal decline in CBFV was also present. In fact, it was steeper than in the 2-D case. However, the parallel trend with performance efficiency was absent because signal detections were stable over time in the 3-D condition. This finding raises the question of how observers in that condition were able to maintain a stable level of performance over time in the face of a temporal decline in assumed cortical neuroactivity.

One possibility comes from the fact that although information from the two eyes is first brought together in the primary visual cortex, a vast array of cortical areas beyond the striate cortex are implicated in stereopsis. There is considerable interaction among neurons tuned for binocular disparity (Fortin et al., 2002; Kandel,
Schwartz, & Jessell, 2000), and stereoscopic depth perception entails a cue-integration process that scales or recalibrates binocular disparity magnitude in accord with viewing distance (Patterson & Martin, 1992). Moreover, Patterson and Silzars (2009) have suggested that stereoscopic depth perception feeds into higher brain systems that support intuitive cognition. Consequently, it is possible that the abundance and richness of neural structure and function attendant to stereopsis permitted observers in the 3-D condition to sustain performance efficiency even though there was a general reduction in CBFV (i.e., these results suggest a form of neural compensation). Alternatively, it is important to note that participants in this study were confronted with 3-D stimuli only when critical signals appeared. At all other times, they inspected 2-D images on the display. Consequently, the stereo information in the 3-D condition may have served as an exogenous stimulus-driven attention cue (Egeth & Yantis, 1997; Head & Helton, 2012), which may have compensated for the impairment in endogeneous alertness regulation engendered by the vigilance task.

From an operational perspective, the use of 3-D displays has been the subject of considerable interest in the human factors community (Burks et al., 2014; Patterson, 2007, 2009a, 2009b; Patterson & Martin, 1992). A comprehensive review by McIntire and his associates (2014) indicates that although not always the case, 3-D displays improved performance over 2-D displays in a wide variety of tasks requiring the localization, identification, or manipulation of objects. The present results provide the initial demonstration that 3-D displays can also enhance task performance when the maintenance of sustained attention or vigilance is a vital element. Given that a variety of engineering methods are available to produce stereoscopic 3-D displays (Burks et al., 2014; McIntire et al., 2014; Patterson, 2007), the design of such displays for operational vigilance tasks would likely require considerable thought and study. Nevertheless, the present results suggest that an effort of this sort may be productive in augmenting system reliability when operator vigilance is required.

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KEY POINTS

- The present results provide the initial demonstration that a stereoscopic 3-D display can enhance vigilance performance in comparison to a more traditional 2-D display.
- The overall level of signal detection and the stability of detections over time were greater when observers monitored for stereoscopically induced 3-D changes in target depth compared to 2-D changes in target orientation. Target changes were equated for difficulty under alerted conditions.
- Performance efficiency was enhanced by the 3-D display even though that display was associated with a greater temporal decline in cortical neuroactivity as indexed by CBFV, compared to the 2-D display.
- Right hemispheric specificity as indexed by CBFV was more pronounced when observers performed the vigilance task with the 3-D as compared to the 2-D display.
- Participants in both the 2-D and 3-D conditions reported high levels of task-induced discomfort/illness on the Simulator Sickness Questionnaire. However, ratings were not different across monitoring conditions, suggesting that elements intrinsic to vigilance, rather than differences in display technology, were the primary drivers of those ratings.

REFERENCES


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