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The Effects of Modafinil and Over-the-Counter Stimulants on Two- and Three-Dimensional Visual Localization

James P. Gaska, Alex Van Atta, Marc D. Winterbottom, Steven C. Hadley

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Air Force Research Laboratory
711th Human Performance Wing
U.S. Air Force School of Aerospace Medicine
Aeromedical Research Department
2510 Fifth St., Bldg. 840
Wright-Patterson AFB, OH 45433-7913

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DR. JAMES McEACHEN	DR. RICHARD A. HERSACK
CRCL, Human Performance	Chair, Aeromedical Research Department

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14. ABSTRACT

Aerial refueling operators in the next generation of tankers (e.g., Boeing KC-46 for the U.S. Air Force, Airbus KC-30 for the Royal Australian Air Force, Boeing KC-10 for the Royal Netherlands Air Force, and KC-767 for the Japan Air Self-Defense Force) will use remote vision system technology and stereo displays in place of direct view crew stations. Thus, the effects of factors such as fatigue on performance with the use of this relatively new technology are of interest. In this study, we measure performance on a stereoscopic depth perception task to examine how fatigue due to sleep deprivation affects stereo depth performance. The results show that fatigue has a strong influence on stereo depth localization when pharmaceutical countermeasures are not used. The magnitude of the performance loss is nearly equivalent to that measured using the psychomotor vigilance test, which is the "gold standard" of fatigue metrics due to its high sensitivity. Because boom operators in the next generation of remote vision system aerial refueling tankers use stereo cues to perform their task, additional research concerning the effects of fatigue and fatigue countermeasures should be undertaken to better understand the potential safety risks and to develop methods to counter those risks.

15. SUBJECT TERMS
Remote vision system, stereo displays, aerial refueling, tankers, fatigue, fatigue countermeasures

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1.0 SUMMARY

Aerial refueling operators in the next generation of tankers (e.g., Boeing KC-46 for the U.S. Air Force, Airbus KC-30 for the Royal Australian Air Force, Boeing KC-10 for the Royal Netherlands Air Force, and KC-767 for the Japan Air Self-Defense Force) will use remote vision system technology and stereo displays in place of direct view crew stations. Thus, the effects of factors such as fatigue on performance with the use of this relatively new technology are of interest. In this study, we measure performance on a stereoscopic depth perception task to examine how fatigue due to sleep deprivation affects stereo depth performance. The results show that fatigue has a strong influence on stereo depth localization when pharmaceutical countermeasures are not used. The magnitude of the performance loss is nearly equivalent to that measured using the psychomotor vigilance test, which is the "gold standard" of fatigue metrics due to its high sensitivity. Because boom operators in the next generation of remote vision system aerial refueling tankers use stereo cues to perform their task, additional research concerning the effects of fatigue and fatigue countermeasures should be undertaken to better understand the potential safety risks and to develop methods to counter those risks.

2.0 INTRODUCTION

It is well established that fatigue due to insufficient sleep can result in decreased effectiveness and safety of aircrew. Decades of research have led to a better understanding of the factors that lead to performance loss, including the interaction between homeostatic and circadian processes [1,2], acute vs. chronic sleep loss [3], and interindividual differences [4]. This research has led to improved models of fatigue and performance loss [5] as well as improvements in fatigue countermeasures [6].

The psychomotor vigilance test or PVT [7] has become "gold standard" for assessing the effects of sleep deprivation because it is reliable and sensitive. A meta-analysis of the impact of short-term sleep deprivation [8] demonstrated that tasks that require vigilance had the largest effect size of all tasks included in the study. Therefore, although sleep deprivation has been shown to reduce performance on a variety of tasks, not all tasks are equally affected.

In this study, we measure performance on a stereoscopic depth perception task which, to our knowledge, has not been tested under sleep deprivation conditions. There is a renewed interest in the role of stereopsis and performance [9] because the next generation of aerial refueling tankers (e.g., Boeing KC-46 for the U.S. Air Force, Airbus KC-30 for the Royal Australian Air Force, Boeing KC-10 for the Royal Netherlands Air Force, and KC-767 for the Japan Air Self-Defense Force), aerial refueling operators, or boom operators will use remote vision system (RVS) technology and stereo displays in place of direct view crew stations. Several studies have demonstrated that viewing stereoscopic displays can induce discomfort [10-12]. In an experiment more directly related to military operational performance, Winterbottom and colleagues [13] have demonstrated that reported discomfort increases over a 2-hour period when continuously performing boom operator tasks in a KC-46 RVS refueling simulation.

In the current study, we examine the effects of chronic sleep deprivation fatigue and pharmaceutical countermeasures on the performance of a stereoscopic depth perception task (three-dimensional (3D) task) as well as a task that requires locating a feature in the display plane (two-dimensional (2D) task). In addition to examining the main effect of pharmaceuticals,

we are interested in determining if there is differential effect of fatigue for 2D vs. 3D (stereoscopic) location tasks. This study was part of a larger study [14] that addressed concerns of the Air Force Special Operations Command commanders about the consumption of over-the-counter stimulants such as caffeine in addition to “go pills” such a modafinil, which may be prescribed for certain missions.

3.0 METHODS

This study was approved in advance by the Air Force Research Laboratory Institutional Review Board (Protocol #NAMRUD.2012.0003).

3.1 Participants

All participants were male, between the ages of 18 and 35, on a day-shift schedule for the past 3 weeks, and recruited from active duty military populations. Participants were highly physically fit and were required to score in the top 20% of military fitness tests. Resting heart rates was required to be 70 bpm or lower, resting blood pressure could not exceed 139/89 mmHg, and the maximum allowable body fat percentage was 22%. All participants were Department of Defense healthcare beneficiaries.

Although the initial protocol specified that up to 44 participants would be tested, scheduling and recruitment difficulties resulted in only 19 participants being studied.

3.2 Equipment

All tests reported here consisted of computer-generated test images with observer responses measured using a game pad. The observers were seated approximately 0.8 meter from the display in a darkened room. The display (ASUS VG27H8) was equipped with an emitter that synchronized shutter glasses (NVIDIA 3D Vision 2), allowing independent stimulation of the left and right eye at 60 Hz for each eye. The shutter glasses allowed generation of stereoscopic images at an arbitrary depth by manipulation of the retinal disparity of corresponding image features (vertical lines). The glasses were worn only in the 3D tests described below. They were removed for the 2D test.

3.2.1 2D Contrast Threshold. In a given trial, the observer was presented with one of the four Landolt C images shown in Figure 1. The participant was instructed to signal the location of the gap in a Landolt C stimulus (up, down, left, or right) by pushing a button on the game pad. The test consisted of 30 trials, and the Quest adaptive procedure [15] was used to estimate contrast threshold defined as the contrast corresponding to a 72% correct response rate.

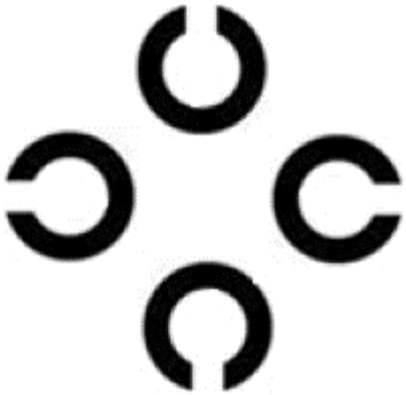

Figure 1. 2D contrast threshold test images.

3.2.2 3D (Stereo) Contrast Threshold Test. The participant was required to push the arrow keys on a keyboard to signal the depth (near or far) of a test bar relative to that of two flanking reference bars (Figure 2). The test consisted of 30 trials, and the Quest adaptive procedure [15] was used to estimate contrast threshold defined as the contrast corresponding to an 81% correct response rate.

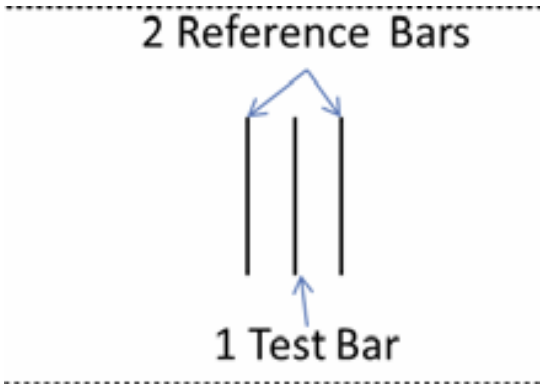

Figure 2. Configuration of 3D test.

3.2.3 3D Diffusion Test. The stimulus configuration was similar to that used in the 3D contrast test (Figure 2). Again, the participant was required to push the arrow keys on a keyboard to signal the depth (near or far) of a test bar relative to that of two flanking reference bars (Figure 2). However, in this test, disparity was fixed at a relatively large disparity of 79 arcsec (which should be readily apparent to observers with normal stereo acuity) and contrast was fixed at a high value (0.98).

Six blocks with 50 trials per block were presented, and the speed and accuracy of the participant's response were measured. In three blocks, the vergence distance to the reference bars was the same as screen distance (0.8 meter) (1.25 diopters [D]). In the remaining three blocks, the vergence distance to the reference bars was increased to 0.93 meter (1.08 D). Because best stimulus focus is always at the screen distance, the accommodative distance and the vergence are the same in the first condition. However, when the observer is verged to the more distant reference bars, there is a vergence-accommodation (VA) mismatch of 1.25 – 1.08 = 0.17 D.

The Robust EZ diffusion model [16] was used to estimate performance variables from the speed and accuracy data. Four performance values were estimated:

- **Drift Rate:** This parameter estimates the rate of information accumulation. It is dependent on the quality of the stimulus and observer ability. In this study, the stimulus was fixed, so the drift rate represents the observer's ability to accrue information over time.
- **Boundary Separation:** This parameter estimates the amount of information an observer needs to make a decision and respond. Larger boundary separation values correspond to increased response caution.
- **Non-Decision Time:** This parameter estimates the time needed for all non-decision processes including sensory and motor transport times.
- **Mixture Proportion:** This variable estimates the proportion of total responses not contaminated by response lapses.

The Robust EZ diffusion model is a simplified version of the diffusion model developed by Ratcliff [2,17,18]. Prior to the development of diffusion models, it was more difficult to interpret reaction time data because of the speed-accuracy tradeoff; that is, an observer can increase response speed by reducing accuracy. One of the most important benefits of diffusion models is that they allow the experimenter to separately estimate an individual's sensitivity (drift rate) and caution or criterion (boundary separation).

3.3 Schedule

Participants were required to spend at least 7.5 hours in bed for the three nights prior to arriving at the Naval Medical Research Unit – Dayton research facility. This was confirmed by wrist monitors, and participants were not enrolled in the study until the requirement was met. The participants arrived at the test facility 2 days before the experimental period. During this time they were trained on the experimental test (three sessions) and allowed to sleep from 2100 to 0500. On the day of the experiment, they were awoken at 0500 and the final test concluded at approximately 1400 on the following day. Test times are shown in Figure 3 with the origin (0) equal to the start of the experimental day. The drug or placebo was administered at 2300 of the first day (hour 23 in the figure). Note that because the axis origin is equal to the start of the experimental day and the participants awoke at 0500, hour 38 in the figure corresponds to 33 hours of wakefulness.

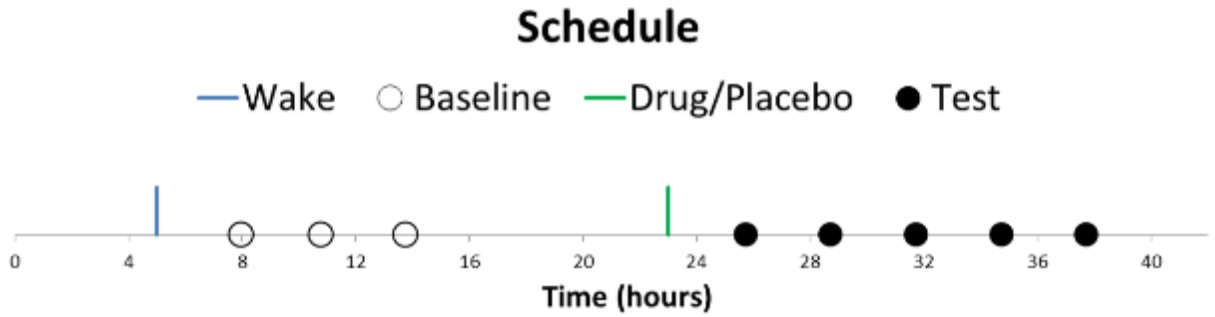

Figure 3. Testing schedule for baseline period (open circles) and test period (filled circles).

4.0 RESULTS

A total of 24 individuals enrolled in the study. Of those 24 enrolled individuals, 5 did not meet the minimum sleep requirement prior to the in-lab studies. In addition, four individuals could not reliably perform the 3D stereo test and were excluded from analysis. The number of individuals in each group is shown in Table 1. Because the sample size for the individual drug groups was small, we collapsed the groups into Modafinil and No Modafinil groups with seven members in each group.

Table 1. Observers in Each Group

Treatment Group	N	Collapsed Group	N
Placebo	3	No Modafinil	7
Caffeine	4		
Modafinil	3	Modafinil	7
Modafinil + Caffeine	4		

4.1 Comparison of Contrast Sensitivity for Position and Depth Location

Figure 4 depicts contrast sensitivity for position and depth detection averaged across all observers and drug conditions. Contrast sensitivity is equal to the inverse of contrast threshold, so better performance corresponds to higher values (greater sensitivity). The horizontal lines correspond to the baseline average for each task, and error bars correspond to the 95% confidence interval for a two-tailed t-test. It can be seen that contrast sensitivity in the 2D position task is approximately 10 times (1 log10 unit) higher than the 3D stereo task. However, because the sizes of the stimuli for the two tasks are different, it is difficult to determine how much of the contrast sensitivity difference is due to differences between the 3D and 2D detection processes vs. stimulus parameters.

There is no detectable effect of fatigue on performance for the 2D position detection task. Sensitivity for the 3D task trends downward in the test period (last four points). However, the error bars are quite large and overlap the baseline average for all points.

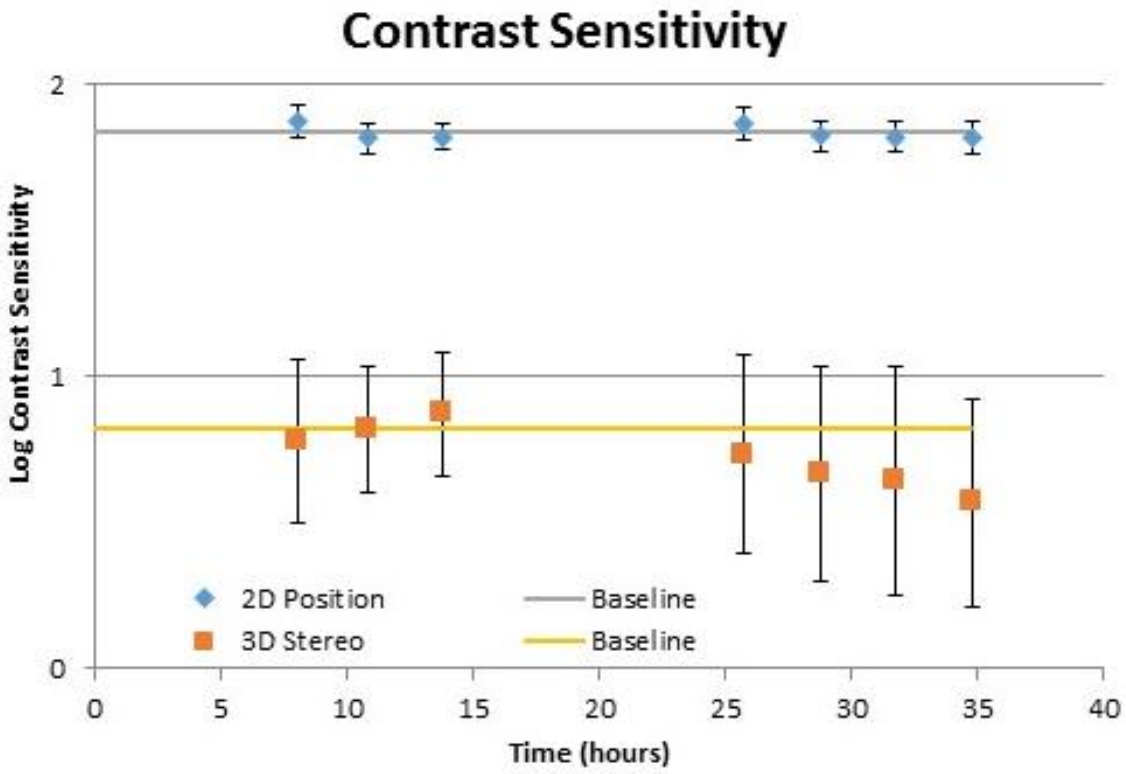

Figure 4. Contrast sensitivity for position and depth detection averaged over all observers and drug conditions.

4.2 Comparison of Modafinil and No Modafinil Groups

To facilitate the comparison of tasks and metrics, all results below are reported as the percent difference from the average baseline score. The average baseline score (b) of each observer was subtracted from the raw scores (r), normalized by the average score baseline score, and multiplied by 100.

$$PD = 100 \cdot \frac{r - b}{b}$$

The error bars again represent the 95% confidence interval for a two-tailed t-test. To avoid clutter, they are only attached to the No Modafinil data. Because the 3D contrast sensitivity data were so variable and the number of individuals in each group was small (7), the data were excluded from this analysis.

4.2.1 2D Contrast Sensitivity. Figure 5 plots 2D contrast sensitivity vs. time for the Modafinil and No Modafinil groups. As we have seen in Figure 4, where the data were averaged across drug conditions, there is little effect of fatigue on performance. Furthermore, there is no significant difference between the Modafinil and No Modafinil groups.

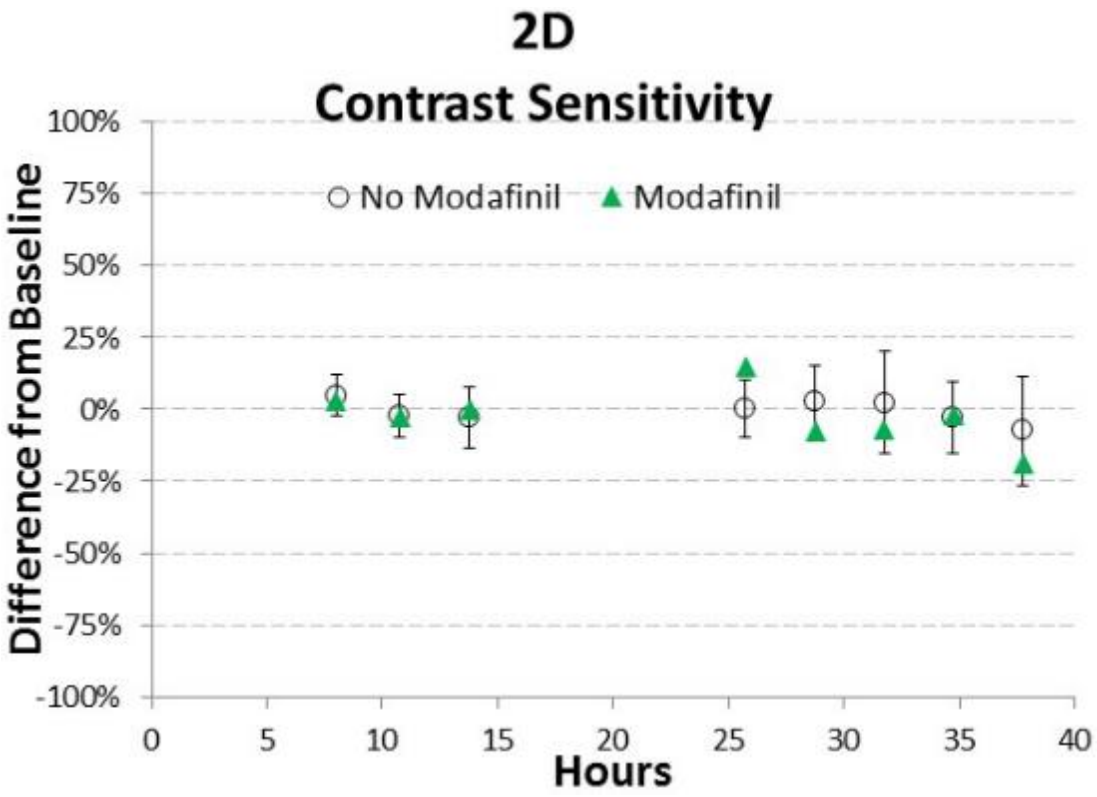

Figure 5. 2D Contrast sensitivity for Modafinil and No Modafinil groups.

4.2.2 VA Mismatch. As stated in the Methods section, observers were tested under two VA mismatch conditions: none and 0.17 D. Table 2 displays the results from paired t-tests for mean differences between the two conditions for the four diffusion model metrics. Data from all observers and test times were used in the analysis. The degrees of freedom for all tests are 151. The statistic was significant (at the $p<0.05$ level) only for the boundary separation metric. For all metrics, the mean difference between the conditions is small and would have little practical consequences. In the analysis that follows, the metrics from the two conditions were averaged.

Table 2. Paired t-test Results for Mean Differences Between Accommodation/Vergence Conditions

Metric	None – 0.17 D Difference	t-Stat	P(T≤t) Two-Tailed
Drift Rate	-0.007	0.799	0.456
Boundary Separation	-0.004	-2.438	0.016
Mixture Proportion	-0.010	-1.036	0.302
Non-Decision Time	0.001	1.812	0.072

4.2.2.1 Drift Rate. In the diffusion model, drift rate estimates the rate of information accrual and is related to the quality of the stimulus and observer sensitivity to the information – in this case 3D position. Because the stimulus quality (disparity) is fixed in this experiment, drift rate reflects observer sensitivity to 3D position information.

Figure 6 plots diffusion model drift rate vs. time for the Modafinil and No Modafinil groups. Over the first three test periods, there is a clear decrease in drift rate for the No Modafinil group that reaches a low of approximately 50% below baseline. The score for the third test period for the No Modafinil group is statistically lower than baseline, but the score for the Modafinil group is still above baseline. Over the last two test periods, the performance of the No Modafinil group improves as the Modafinil group decreases, and the performance of the two groups is indistinguishable at the last test period.

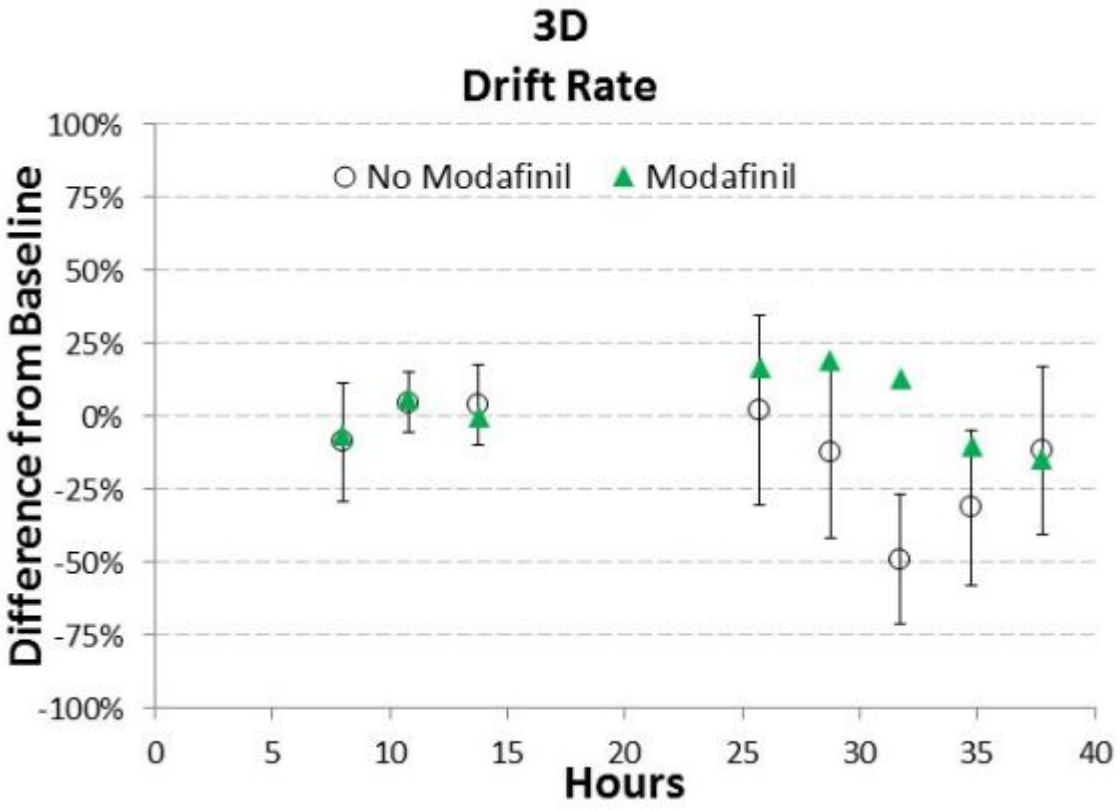

Figure 6. Diffusion model drift rate parameter for Modafinil and No Modafinil groups as a function of measurement time for the 3D task.

4.2.2.2 Boundary Separation. In the diffusion model, boundary separation estimates the information level required to decide if the 3D position of the test bar is nearer or farther than the reference bar. It is similar to the criterion in a signal detection task with higher separation values indicating increased observer caution.

Figure 7 plots diffusion model boundary separation estimates vs. time for the Modafinil and No Modafinil groups. The No Modafinil scores are greater than or equal to the Modafinil scores for all test periods. The score for the third test period for the No Modafinil group is statistically higher than the Modafinil group, which remains near baseline.

The boundary separation results are roughly the inverse of the drift rate results. Thus, for the third test period, the No Modafinil group is less sensitive and more cautious than during the baseline period.

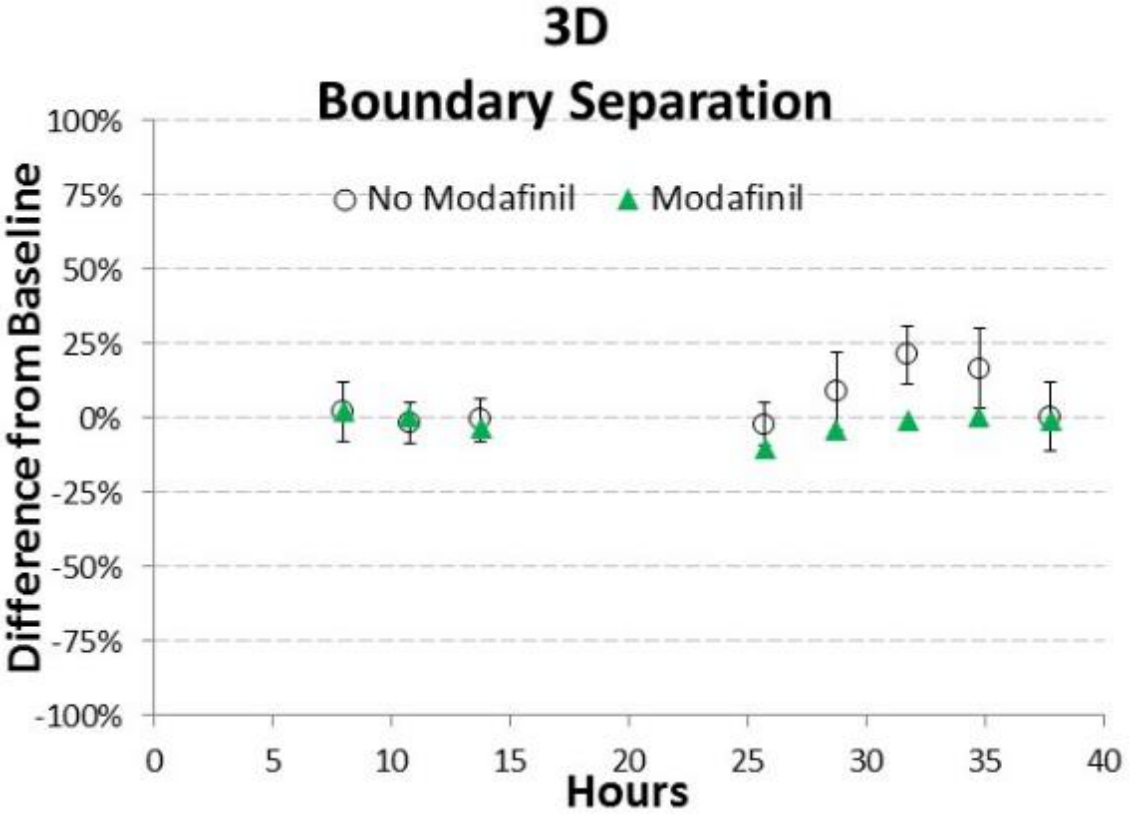

Figure 7. Diffusion model boundary separation parameter for Modafinil and No Modafinil groups as a function of measurement time for the 3D task.

4.2.2.3 Mixture Proportion. Mixture proportion estimates the proportion of total responses not contaminated by response lapses. Higher numbers indicate fewer response lapses.

Figure 8 plots diffusion model mixture proportion estimates vs. time for the Modafinil and No Modafinil groups. Scores during the test period are not significantly different from baseline for either group.

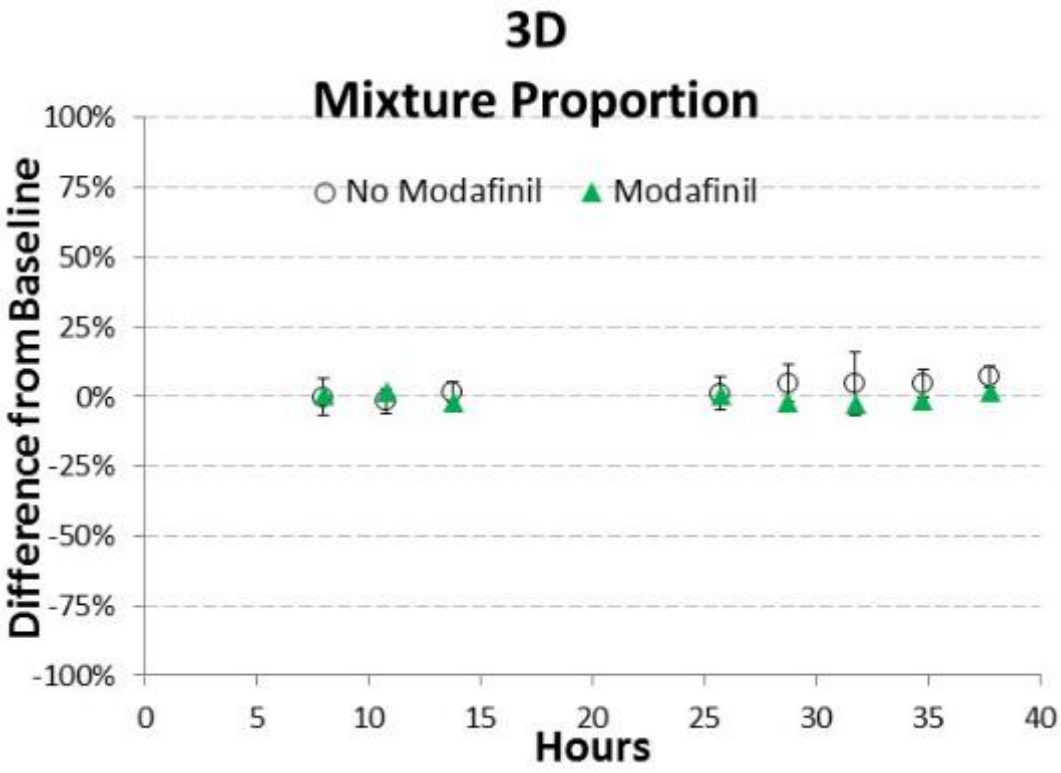

Figure 8. Diffusion model mixture proportion parameter for Modafinil and No Modafinil groups as a function of measurement time for the 3D task.

4.2.2.4 Non-Decision Time. In the diffusion model, the non-decision time parameter estimates the time needed for all non-decision processes including sensory and motor transport times. Lower numbers indicate faster transport times.

Figure 9 plots diffusion model non-decision time estimates vs. time for the Modafinil and No Modafinil groups. Scores during the test period are not significantly different from baseline for either group.

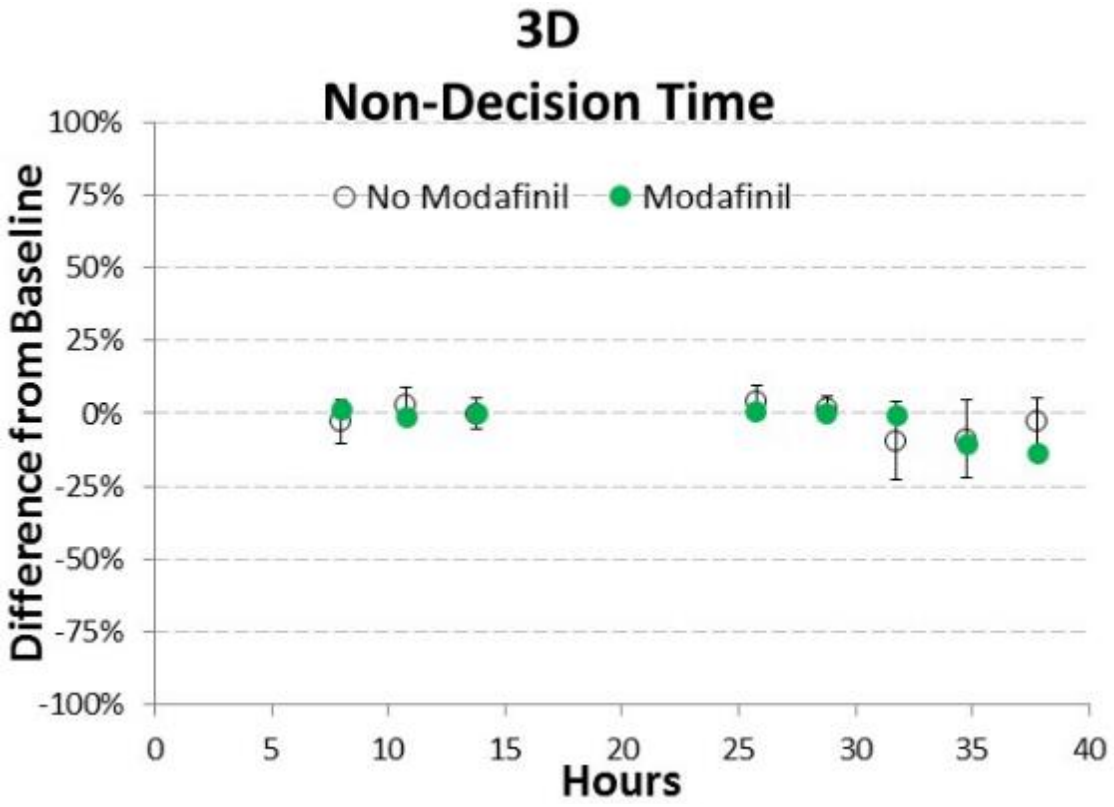

Figure 9. Diffusion model non-decision time parameter for Modafinil and No Modafinil groups as a function of measurement time for the 3D task.

5.0 DISCUSSION

One important goal of this study was to determine if there was a differential effect of fatigue for 2D vs. 3D (stereoscopic) location tasks. Whereas the 2D contrast sensitivity scores in the test session did not differ significantly from baseline performance for either of the Modafinil or No Modafinil groups, the 3D tests showed clear performance losses in the test sessions, particularly for the No Modafinil diffusion model metrics. However, because the diffusion model analysis of the 3D task utilized both response accuracy and speed, whereas the 2D task limited the analysis to accuracy, a direct comparison of these results should be interpreted with caution. It is well established that metrics that use speed and accuracy are generally more sensitive to group or treatment differences than an accuracy metric alone [19]. A diffusion model analysis of both 3D and 2D tasks would provide a more definitive answer.

In the diffusion model, decision time is directly proportional to the amount of information needed to make a decision (boundary separation) and inversely proportional to the rate at which information is accumulated (drift rate). Note that decision time is not equivalent to reaction time because reaction time includes non-decision time (sensory and motor transport time). In the current study, the 3D task boundary separation was 21% above baseline and drift rate was approximately 49% below baseline (at maximum impairment). Therefore, the decision time at maximum impairment was approximately (100+21) / (100-49) = 2.4 times longer than baseline decision time. Ratcliff and Van Dongen used a diffusion model to examine the effect of sleep deprivation (36 hours) on performance in a PVT. They found that boundary separation was approximately 61% above baseline and drift rate was approximately 43% below baseline in the sleep-deprived condition. This finding is similar to the current study in that sleep deprivation lowers information accrual rate (sensitivity) and increases boundary separation for the amount of information required to make a decision. In the Ratcliff study, decision time in the sleep-deprived state was approximately (100+60) / (100-43) = 2.8 times longer than the baseline decision time, which is slightly longer than the estimate obtained in this study (2.4).

This research shows that Modafinil is a significant fatigue countermeasure when performing a stereoscopic depth discrimination task. This study was part of a larger, parent study [14] that also found that Modafinil generally increased performance in the fatigued sessions for a wide range of cognitive tasks.

Although the parent study was originally designed to compare the effect of combining caffeine with Modafinil, the small number of observers in each condition reduced the statistical power such that a comparison between the groups was difficult to interpret. Because of the small number of observers, we collapsed the data into Modafinil and No Modafinil groups; therefore, we cannot report on any interaction between caffeine and Modafinil. The parent study, which had the same statistical power restrictions, tentatively concluded that “the combination of caffeine with modafinil does not appear to improve or inhibit performance above that with modafinil alone” [14, p. 44].

6.0 CONCLUSION

Fatigue due to sleep deprivation has a strong influence on stereo depth localization when pharmaceutical countermeasures are not used. The magnitude of the performance loss is nearly equivalent to that measured using the PVT, which is the “gold standard” of fatigue metrics due to its high sensitivity. This research suggests that sleep deprivation fatigue could reduce the performance of boom operators using RVS stereoscopic displays, which is a potential safety risk. Additional research should examine the effect of fatigue and other challenges in an operational environment, such as hypoxia, on RVS air refueling to better quantify the potential risks.

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LIST OF ABBREVIATIONS AND ACRONYMS

2D	two-dimensional
3D	three-dimensional
D	diopter
PVT	psychomotor vigilance test
RVS	remote vision system
VA	vergence-accommodation