Prediction of Performance during Sleep Deprivation and Alcohol Intoxication using a Quantitative Model of Work-Related Fatigue

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Shift work and particularly night work can cause fatigue with subsequent negative impacts on health, sleep, and alertness. To facilitate better management of work-related fatigue, we have developed, optimized and validated a computerized model that can predict changes in performance, vigilance, sleepiness, and tiredness. The present study is a laboratory-based validation that demonstrates the further utility of the model in predicting performance impairment resulting from sleep deprivation and alcohol intoxication. Twenty-two healthy volunteers (mean age=22.0 years) each completed three counter-balanced laboratory conditions: sleep deprivation, alcohol intoxication, and a placebo control condition. In each condition, subjects were woken at 0700 h and performance on a variety of tests was measured hourly from 0800 h. The tests at 0800 h were then used as a relative baseline to which all other performance data were expressed. The six measures of performance assessed were grammatical reasoning (response latency and accuracy), unpredictable tracking score, vigilance (response latency and accuracy), and simple sensory comparison score. Regression analyses indicated that the fatigue model predicted between 47 and 89% of the variance in actual performance measures. Thus, there were moderate to very strong significant relationships between work-related fatigue model predictions and neurobehavioral performance as measured under laboratory conditions.

CURRENT CLAIM: Following both sleep deprivation and alcohol intoxication, there are moderate to very strong relationships between work-related fatigue model predictions and objective neurobehavioral performance measures.

The Relative Effects of Sleep Deprivation and Alcohol on Performance

The relative performance impairment associated with SD has been compared qualitatively to impairment due to alcohol intoxication (Peeke et al., 1980; Krull et al., 1993; Roehrs et al., 1994). The observed declines in performance with either SD or alcohol intoxication are potentially dangerous and contribute to an increased risk of accidents and incidents at work (e.g., Gold et al., 1992; Smith et al., 1994; Dinges, 1995; Smith et al., 1998). Furthermore, previous research has quantitatively compared the levels of performance impairment associated with SD and alcohol intoxication and shown that the SD and fatigue associated with common shift schedules can produce impairment greater than what would be acceptable if it were due to alcohol intoxication (Dawson and Reid, 1997; Lamond and Dawson, 1999; Williamson and Feyer, 2000).

The specific changes observed in performance following SD include significant impairments to hand-eye coordination, decision making, memory, cognition, visual search performance, response speed, and response accuracy (Linde and Bergstrom, 1992; Fiorica et al., 1968; Babkoff et al., 1988). In addition to cognitive factors, affective components of behavior, such as motivation and mood, are also adversely affected with increasing duration of SD (Babkoff et al., 1988).

With moderate levels of both SD and alcohol intoxication, there is mild impairment on performance tasks, decreased alertness, and reduction in amplitude of EEG components (Goldberg, 1966; Wallgren and Barry, 1970; Naitoh et al., 1971; Kopell et al., 1972; Johnson and Naitoh, 1974). However, there are some differences between the autonomic effects of SD and alcohol intoxication. For example, alcohol increases heart rate but SD appears to have little or no effect (Koller et al., 1966). There are also differences in affect, with alcohol decreasing (Greenberg and Carpenter, 1956) and SD-increasing indicators of anxiety (Hord et al., 1975).

Given the evidence above that the general neurobehavioral impairments due to SD and alcohol are quantitatively similar, it is paradoxical that fatigue-related performance impairment has not been subject to similar levels of regulatory intervention as alcohol intoxication. Despite the dangers posed by work-related fatigue, few organizations or policy makers currently attempt to manage workplace fatigue in any systematic or quantitative manner. It thus seems appropriate to extend the scope of our previous modeling work to equate the impairment associated with SD and alcohol intoxication with work-related fatigue. If fatigue, sleep deprivation and alcohol intoxication...
can be compared quantitatively, then we can make more global predictions of impairment based on any one of these measures. Furthermore, being able to present work-related fatigue impairment as a function of SD and alcohol intoxication may improve our understanding of the relative risks associated with fatigue.

In this paper, we present further validations of an applied modeling approach that could be a valuable tool to improve shift work management. The model enables the quantification, comparison and prediction of work-related fatigue, which can be defined as fatigue associated with hours-of-work.

Theoretical Considerations of Quantitative Modeling of Shift Work and Fatigue

The current model, as applied in this paper, is based around a number of core components of fatigue, and predicts the work-related fatigue associated with actual or potential work rosters. Specifically, these components are the duration and timing of work and break periods, the prior work history, and the limitations of recovery sleep in humans. The development, basic validation and optimization of this model have been reported in detail in two previous publications from our group (Dawson and Fletcher, 2001; Fletcher and Dawson, 2001). However, the basic components of the model as used in the current validation study are briefly summarized.

At the broadest level, the model views hours-of-work as a time-varying function, with individuals existing in one of two states (where individuals are either working or not). From this perspective, the fatigue experienced by an individual at any specific time is a balance between two competing forces, that is those producing fatigue and those reversing the effects of fatigue, leading to recovery. Fatigue and recovery are likely to increase as a function of the duration of the work and non-work periods respectively, but are also dependent on the amounts and timing of wake (or sleep) periods in the previous week. For the purposes of our model, the duration, circadian timing, and recency of work periods are considered as fatiguing forces. Conversely, the duration, circadian timing, and recency of non-work periods are considered as forces of recovery.

Duration and Timing of Work Periods

Previous research has demonstrated that fatigue increases as a function of hours of prior wakefulness (Borbély, 1982; Daan et al., 1984), with a complex relationship in which there are significant linear (hours of prior wakefulness) and sinusoidal (circadian) components (Borbély, 1982; Folkard and Åkerstedt, 1991). On the basis of previously published literature (for example, Czeisler et al., 1980a; Zulley and Wever, 1982; Johnson et al., 1992), the model assumes that the circadian component of fatigue maps closely to the circadian core temperature rhythm, with a period of 24 hours and an arbitrary amplitude of 1.0 unit. Furthermore, fatigue accumulates sinusoidally during wakefulness at a maximum rate of 2.0 units per hour at 0500 h and a minimum value of 1.0 unit per hour at 1700 h, with proportional steps at each hour of the day.

In our model, the fatigue value of a work period therefore varies as a function of the duration (Rosa et al., 1989; Folkard, 1997) and circadian timing (Folkard and Åkerstedt, 1991; Folkard, 1997) of the work period. The increase in fatigue across a work period is therefore not linear but also dependent on the time of day that the work is occurring, with more fatigue accumulating when working during the subjective night than during the subjective day. Similarly, as the duration and quality of sleep (Czeisler et al., 1980a; Zulley et al., 1981; Strogatz, 1986; Monk, 1987) show a strong circadian component, the recovery value of non-work periods are also likely to vary as a function of their duration and timing. For example, the recovery value of a 12-hour break from work during subjective night is likely to be greater than the same length break taken during subjective day.

The amount of sleep that is predicted to occur within a specific recovery period is based on a statistical distribution of sleep, using sleep propensity curves derived from free-run and forced-desynchrony protocols (see for example, Czeisler et al., 1980a; Czeisler et al., 1980b). Given a specific work/non-work pattern, the amount of sleep achieved can be predicted with surprising accuracy. However, if sleep does not occur across a period in which it is likely to occur, then the actual work-related fatigue experienced by an individual would be higher than that predicted by our model.

Recency of Shifts

The model places a higher weighting on more recent work (or non-work) periods in determining the fatigue (or recovery) level than those that occurred further back in time. The model has a linear decay from a peak weighting value of 1 for the most recent hour to a value of 0 after seven days (or 168 hours). That is, over the period of a week, the value of work or non-work periods reduces linearly, and periods that occurred more than seven days prior do not contribute at all to the work-related fatigue score.

Saturation

The model also incorporates a saturation function that limits the total value of recovery that can be accumulated at any time. In practice, this saturation function prevents recovery from being ‘stored’ beyond full recovery. That is, individuals can only recover from fatigue that has been accumulated and cannot accrue recovery to offset against future fatigue. The saturation of recovery reflects the fact that sleep durations are finite, with individuals experiencing difficulty in extending sleep beyond 10-11 hours in length, irrespective of the amount of prior wakefulness (reviewed in Strogatz, 1986).

Fatigue Score

Given that the fatigue level of an individual can be viewed as the sum of the fatigue and recovery functions, it is possible to calculate the relative fatigue level for an individual on the basis of the shift history of work and non-work periods. By recording only an individual’s hours-of-work, we are thus able to determine the work-related fatigue level at any particular point in time.

By creating a stationary output function for the standard working week, a benchmarking approach is used to compare work-related fatigue scores produced across other shift schedules. We operationally define standard fatigue scores
(measured in arbitrary units) as those representing up to 100% of the maximum produced for a standard work week (0-40 units). Moderate fatigue scores represent a range between 40-80 units (100 to 200% of the maximum produced for a standard work week) and high fatigue scores (greater than 80 units) are 200% or more of the maximum produced for a standard work week. In the same way that the effects of fatigue on performance likely have a non-linear relationship, it is assumed that fatigue scores do not progress in a linear fashion. For example, a score of 80 most likely does not represent double the fatigue level experienced at a score of 40.

Model Validations

Our previous validations of the work-related fatigue model suggest that the outputs accurately reflect changes in measures such as objective performance, vigilance, objective and subjective sleepiness, and tiredness (Dawson and Fletcher, 2001; Fletcher and Dawson, 2001). However, a useful extension of such an approach is being able to equate the relative impairment observed in such measures with impairment due to specific levels of fatigue. Furthermore, it would also be useful to compare the relative impairment due to fatigue with impairment from other sources such as alcohol intoxication. Therefore, the aim of the present study was to assess and further validate the work-related fatigue model against performance impairment produced by sleep deprivation and alcohol intoxication in laboratory trials. In addition, this will allow predictions of performance impairment (due to the influences of either sleep deprivation or alcohol intoxication) to be made from calculated work-related fatigue scores.

METHODS

Subjects

Data for twenty-two healthy university students with a mean age of 22.0 years (SEM±0.58) were included in this study. The performance data for these subjects were included in a previous study comparing the performance impairment of sleep deprivation and alcohol intoxication (Lamond and Dawson, 1999). Subjects were screened for good general health and good sleep status prior to the study. Only social drinkers were included; abstinence or excessive drinking was grounds for exclusion. Subjects with a history of sleep research laboratory.

Four neurobehavioral performance tests were performed using a battery developed by Worksafe Australia. Detailed information on the specific battery of tests is given in Lamond and Dawson (1999), however they are discussed briefly hereafter. The tasks used in this study were a grammatical reasoning task (GRT) consisting of 32 presentations over 2-3 minutes, an unpredictable tracking task (TRK) of 3-minutes duration, a vigilance task (VIG) of 3.5-minutes duration, and a simple sensory comparison task (SSC) consisting of 24 stimuli presented over 1-2 minutes. Subjects were thoroughly trained on the tasks prior to commencement of each experimental condition, and all tasks were presented in counterbalanced order each time the battery was completed.

In each condition, subjects were woken at 0700 h and hourly testing was performed on all four tasks was measured from 0800 h. The results of the 0800 h tests were used as a baseline reference with which all subsequent test data were compared. In the sleep deprivation condition, subjects remained awake until performance testing was completed at 1400 h on the following day. In the alcohol intoxication condition, subjects consumed an alcoholic beverage at 30-minute intervals from 0900 h until their Blood Alcohol Concentration (BAC) reached approximately 0.10%. Both alcohol intoxication and placebo condition performance testing were completed by approximately 1600 h.

Work-related Fatigue Model

To allow comparison with the performance impairments produced by alcohol intoxication and sleep deprivation, for each hour of the experiment we also modeled work-related fatigue to predict relative performance changes. The generated hourly fatigue scores were then used in the following analyses as predictors of performance.

Analyses

Performance test scores were expressed relative to the average baseline (0800 h) scores obtained before each condition. The relative scores within each interval were then averaged across all subjects to determine the mean relative performance change. The analyses used hourly intervals and/or BAC intervals of 0.01%.

Both simple linear and polynomial regressions, each modeled with an intercept through zero, were then performed for all six recorded performance measures: GRT response latency, GRT error rate, TRK score, VIG response latency, VIG % correct, and SSC % correct. Without exception, second-order polynomial regressions returned higher correlation coefficients for all variables and thus accounted for more of the variance in the data. Therefore, polynomial regression data were used in the remaining analyses. Regression equations were determined for each of these measures with both fatigue scores (FAT) and blood alcohol concentration (BAC) as the dependent measure and are reported in the results.

In order that fatigue scores could be predicted using task scores and BAC, the fatigue score and blood alcohol concentration regression equations for each of the six measures needed to be solved simultaneously. This was also done so that equivalent impairment due to alcohol intoxication could be predicted using task scores and fatigue predictions.
Finally, time-series regressions were performed between the hourly performance on each test and the predictions derived from the work-related fatigue model. Time series analysis was performed to assess whether the circadian phase of performance as predicted by the model was consistent with the actual performance phase as observed in the collected data. Statistical analysis between the regressions at a phase lag of zero and at the phase lag at maximum correlation would normally be performed to assess whether the phase differences make a statistical difference to the relationship, however this was not achievable as the duration of data collection was insufficient (i.e., <1.4 cycles).

**RESULTS**

**Performance Measures**

During the sleep deprivation condition, it was observed that performance on four of the six measures significantly decreased as hours-of-wakefulness increased. It was observed that during each hour of wakefulness, between the seventeenth and twenty-seventh hour, the mean relative decline in performance was 2.69% for GRT mean response latency, 3.36% for TRK score, 1.98% for VIG mean response latency, and 0.61% for VIG % correct (all \( p < 0.001 \)). There was no significant change in GRT error rate or SSC accuracy between seventeen to twenty-seven hours of sleep deprivation. Figures 1 and 2 show the comparative effects of alcohol intoxication and sleep deprivation on mean relative performance for all six recorded performance measures, split into two arbitrary groups. These figures also indicate the amount of sleep deprivation required to produce performance impairment comparable to that observed at BACs of 0.05 and 0.10% for each performance measure.

The decline in performance observed in the alcohol intoxication condition was due solely to the effects of alcohol, as no significant change was observed on any measure during the placebo condition. During the alcohol condition, it was observed that performance on five of the six measures significantly decreased as BAC increased. It was determined that for each 0.01% increase in BAC, the relative decline in performance was 2.37% for GRT mean response latency, 0.68% for GRT error rate, 2.68% for TRK score, 2.05% for VIG mean response latency, and 0.29% for VIG % correct (all \( p < 0.001 \)). There was no significant change in SSC accuracy across the range of BACs.

Figure 3 illustrates the associations between relative values for each of the significantly affected performance measures, and the predicted fatigue scores based on hours of wakefulness used in subsequent regression analyses. Note that performance data for GRT error rate, TRK score, and VIG error rate

![Figure 1](image1.png)  
**Figure 1.** Mean relative performance levels for the first group of measures on the alcohol intoxication (left) and SD condition (right). The equivalent performance decrements at 0.05% and 0.10% BAC are indicated on the right hand axis. Error bars indicate ±1 standard error of the mean (SEM).

![Figure 2](image2.png)  
**Figure 2.** Mean relative performance levels for the second group of measures on the alcohol intoxication (left) and SD condition (right). The equivalent performance decrements at 0.05% and 0.10% BAC are indicated on the right hand axis. Error bars indicate ±1 standard error of the mean (SEM).
subsequently produced negative correlation coefficients (R), as predicted fatigue scores increased as relative performance values decreased, and vice-versa.

Regression Analyses
The regression equations for performance measures were determined separately, with either fatigue score or BAC as the dependent measure. Table 1 displays the regression equations for each of the six measures with fatigue score as the dependent measure. Table 2 displays the regression equations for each of the measures with BAC as the dependent measure.

The best-fit polynomial regression equations were then simultaneously solved for both fatigue score and BAC. It was found that solving polynomial equations in some cases produced a complex number (i.e., square root of a negative number) with no straightforward mathematical solution. Below, we report numerical solutions for each statistically significant performance measure where these were available from solved polynomial regressions. Table 3 displays the BAC equivalent values (rounded to 2 decimal places) of performance decline based on fatigue scores from 10 to 100.

Time-series Analysis
Time-series analyses revealed that the circadian rhythms in performance measures that were predicted by the work-related fatigue model and those observed in the collected data differed by between one and four hours. In all six measures, the work-related fatigue model predicted that the performance minimum occurred earlier than what was measured in the laboratory.

Table 1

<table>
<thead>
<tr>
<th>Measure</th>
<th>Regression Equation</th>
<th>R²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y₁ GRT Mean Response</td>
<td>-0.012 xₚ + 0.01 xₚ²</td>
<td>0.68</td>
<td>&lt;0.0001</td>
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<tr>
<td>Y₂ GRT Error Rate</td>
<td>-0.07 xₚ + 0.0004 xₚ²</td>
<td>0.89</td>
<td>&lt;0.0001</td>
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<tr>
<td>Y₃ TRK Score</td>
<td>0.5 xₚ + 0.008 xₚ²</td>
<td>0.47</td>
<td>0.0004</td>
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<tr>
<td>Y₄ VIG Mean Response</td>
<td>-0.04 xₚ + 0.003 xₚ²</td>
<td>0.84</td>
<td>&lt;0.0001</td>
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<tr>
<td>Y₅ VIG % Correct</td>
<td>-0.01 xₚ + 0.0004 xₚ²</td>
<td>0.74</td>
<td>&lt;0.0001</td>
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<tr>
<td>Y₆ SSC % Correct</td>
<td>-0.05 xₚ + 0.0002 xₚ²</td>
<td>0.55</td>
<td>&lt;0.0001</td>
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Table 2

<table>
<thead>
<tr>
<th>Measure</th>
<th>Regression Equation</th>
<th>R²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y₁ GRT Mean Response</td>
<td>-165.0 x₈ + 2705.6 x₈²</td>
<td>0.74</td>
<td>&lt;0.0001</td>
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<tr>
<td>Y₂ GRT Error Rate</td>
<td>-41.1 x₈ + 221.4 x₈²</td>
<td>0.80</td>
<td>0.0003</td>
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<td>Y₃ TRK Score</td>
<td>27.7 x₈ - 1816.2 x₈²</td>
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<td>0.0008</td>
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<tr>
<td>Y₄ VIG Mean Response</td>
<td>110.4 x₈ + 853.9 x₈²</td>
<td>0.98</td>
<td>&lt;0.0001</td>
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<td>Y₅ VIG % Correct</td>
<td>53.9 x₈ + 243.0 x₈²</td>
<td>0.96</td>
<td>&lt;0.0001</td>
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<tr>
<td>Y₆ SSC % Correct</td>
<td>101.8 x₈ + 444.2 x₈²</td>
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<td>0.21</td>
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</table>

Polynomial regression equations, R² and significance (p) values for performance measures with fatigue score (xₚ) as the dependent measure.

Polynomial regression equations, R² and significance (p) values for performance measures with fatigue score (x₂) as the dependent measure.
The aim of this study was to further validate a model of work-related fatigue against performance measures recorded during sleep deprivation (SD) and alcohol intoxication. By knowing the impact of both SD and alcohol on performance, we were able to express the effects of sleep deprivation on performance as a fatigue score or blood alcohol equivalent. Similarly, we could express the effects of alcohol intoxication on the performance measures as a fatigue score or sleep deprivation equivalent.

The amount of variability in performance measures accounted for by fatigue scores ranged between 47 and 89%, with the strongest correlation existing between predicted fatigue and the GRT error rate. Next highest was the relationship between fatigue predictions and vigilance response latency (84% of the variance was predicted). For vigilance accuracy, 74% of the variance was accounted for by the fatigue predictions. Finally, 55% of the variance in simple sensory comparison and 47% of the variance in tracking score was accounted for by fatigue predictions. The variability accounted for by blood alcohol concentrations (BAC) was somewhat higher within the significantly affected measures, ranging between 74 and 98%. The highest correlation existed between BAC and the vigilance response latency (98%), followed by vigilance accuracy (96%), grammatical reasoning error rate (80%), tracking score (76%), and grammatical reasoning response latency (74%).

These data show that, for only one out of the five measures significantly predicted by both fatigue score and BAC, the work-related fatigue scores had a stronger relationship with the performance data than did BAC. It is therefore clear that BAC levels account for a greater proportion of the variance in the performance data than the fatigue scores. Nevertheless, predicted fatigue scores still related moderately to strongly with the measured performance measure data and supports the practicality of the model in predicting performance impairment due to SD.

In the present study, performance impairment at various fatigue scores was equated to comparable levels of impairment due to alcohol intoxication. Discussion of the effects of alcohol intoxication and sleep deprivation on performance was discussed in a previous paper from our group (Lamond and Dawson, 1999) and is therefore limited here except where specifically related to assessment of work-related fatigue. Specifically, performance decrements equivalent to those observed in the 0.05-0.10% BAC range occurred at fatigue scores between 10 and 90 points. For vigilance score, the most highly correlated measure for work-related fatigue, performance decrements equivalent to those observed in the 0.05-0.10% range occurred at fatigue scores between 60 and 90 points. From the perspective of the fatigue scores, performance decrements equivalent to those observed in the 50-80 range of fatigue scores occurred between 0.01-0.09% BAC. For vigilance response latency, the most measure with best-fit against BAC, performance decrements equivalent to those observed in the 50-80 fatigue point range occurred between 0.04-0.09% BAC.

### Table 3

<table>
<thead>
<tr>
<th>Fatigue Score</th>
<th>GRT Mean Response</th>
<th>GRT Error Rate</th>
<th>TRK Score</th>
<th>VIG Mean Response</th>
<th>VIG % Correct</th>
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<td>10</td>
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<td>80</td>
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<tr>
<td>90</td>
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<td>100</td>
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</table>

Blood alcohol concentrations predicted to produce equivalent decrements in performance measures to those observed at the indicated fatigued scores. Gray cells represent complex solutions (square root of negative value), nonsensical values (i.e., performance at BAC <0%) or predicted values that are outside the limits of data measurement (i.e., performance at BAC >0.11%).

### Table 4

<table>
<thead>
<tr>
<th>BAC (%)</th>
<th>GRT Mean Response</th>
<th>GRT Error Rate</th>
<th>TRK Score</th>
<th>VIG Mean Response</th>
<th>VIG % Correct</th>
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<td>0.00</td>
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</table>

Fatigue scores predicted to produce equivalent decrements in performance measures to those observed at the indicated blood alcohol concentration. Gray cells represent complex solutions (square root of negative value) or values that exceed the limits of data measurement (i.e., performance at fatigue score <10).

### Table 5

<table>
<thead>
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<th>Lag Maximum (hrs)</th>
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<tr>
<td>GRT Mean Response</td>
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<tr>
<td>GRT Error Rate</td>
<td>1</td>
</tr>
<tr>
<td>TRK Score</td>
<td>3</td>
</tr>
<tr>
<td>VIG Mean Response</td>
<td>1</td>
</tr>
<tr>
<td>VIG % Correct</td>
<td>3</td>
</tr>
<tr>
<td>SSC % Correct</td>
<td>4</td>
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</table>

Time-series analysis results for all performance measures. Lag maximum is the time difference between a correlation at a time of zero hours, R(0) and at a time of best correlation, R(max).
These findings can be compared with a previous validation between outputs of the current work-related fatigue model and conditions of sleep deprivation and alcohol intoxication (data from Dawson and Reid, 1997; cited in Fletcher and Dawson, 2001). This previous validation observed changes in neurobehavioral performance, as determined by the OSPAT tracking performance assessment task, across 28 hours of sleep deprivation and alcohol intoxication up to 0.10% BAC in a separate group of volunteers to the present study. The OSPAT test determines a performance score based on changes in hand-eye co-ordination, reaction time and vigilance measures. This validation of work-related fatigue against performance predicted that a fatigue score of 80 points produced impairment on the OSPAT test equivalent to a BAC greater than 0.05%. The current validation suggest that the performance impairment observed at 80 points is equivalent to impairment measured at slightly higher BAC levels, above 0.08% on the measures that were significantly affected in this study.

It is worth noting that the predicted BAC equivalents at 80 fatigue points are interpolated from the fatigue score data predictions for three of the measures. That is, the BAC predicted to produce impairment equivalent to that observed at 80 fatigue points is actually higher than the testing limit (BAC=0.10%) of BAC for GRT mean response times, GRT error rate and VIG % correct. However, based on the actual data for TRK score and VIG response latency, the performance at 80 points is predicted to be equivalent to the performance decrement seen at around 0.08 and 0.09% respectively. Of these two measures, vigilance response correlates most strongly with the fatigue predictions. In fact, vigilance response was perhaps the most utilitarian measure of all, with very strong correlations (R^2=0.84 and 0.98 for sleep deprivation and alcohol intoxication, respectively) and the broadest range of predictive values (see Tables 3 and 4).

The variations in correlations reflect the fact that different tasks are differentially sensitive to the effects of SD and alcohol. Underlining this fact is the observation that SSC % correct was not significantly affected even at a BAC of 0.10%. Across the range of experimental conditions in this study therefore, this measure was completely insensitive to the effects of moderate alcohol intoxication. GRT latencies and error rates were significantly impaired by mild levels of SD, with a modeled fatigue score of only around 30-40 equivalent to BAC impairment around 0.07-0.10% (see Table 3). On the other hand, vigilance latency and error rates were particularly sensitive measures as reflected by a much broader spread in predictions of performance impairment. Using solved regression equations for vigilance response, it was predicted that the equivalent BAC impairment at 80 fatigue points would be approximately 0.09% BAC.

While it is clear that the relationships between performance measures and fatigue scores were moderate to very strong, this was particularly the case for vigilance score. However, the basic time series analyses that were performed indicate that the relationships could be strengthened further. This is because the outputs generated by the fatigue model predict a performance trough earlier than in the actual performance data. An explanation for this potential phase mismatch is discussed hereafter.

We know from the literature that many aspects of human performance and alertness map closely to the circadian rhythm of core body temperature (Monk et al., 1983; Folkard and Monk, 1985; Monk and Moline, 1989; Johnson et al., 1992; Monk and Carrier, 1998). Furthermore, it has also been documented that factors such as age (Monk et al., 1995; Campbell and Murphy, 1998) or sleep/wake pattern (Moore-Ede et al., 1982; Wilkinson, 1982) can have a significant impact on when core body temperature and thus performance measures will peak and trough. Therefore, it is not surprising that the performance troughs in our young adult subjects occur later than the work-related fatigue model would predict. The work-related fatigue model is constructed using generalized principles that include a predicted “normal” performance trough at 0400 to 0600 h. However, because the subject population in this study is quite young (average age of 22 years), this trough may be delayed. As shown in Table 5, the performance troughs on the six measures occur between one to four hours later than the model would predict. Whether or not this phase difference impacts significantly on the results cannot be determined, as the measurement period of the study was too short to allow statistical analysis across the entire cycle of performance. However, it is likely that the reported relationships between fatigue scores and performance measures may have been overly conservative, hence increasing the utility of the present model in normally entrained individuals, as any inherent error would underestimate the fatigue experienced by a particular work schedule.

Based on the polynomial regression between fatigue and vigilance response (R^2=0.84), a fatigue score of 80 is comparable with the impairment that would be observed in an individual with a BAC of 0.09% or greater. If an individual registered such a BAC while working or operating a motor vehicle, they would clearly not be permitted to continue. However, a significant proportion of the rosters employed in 24-hour operations produce work-related fatigue scores greater than 80 (for examples, see Dawson and Fletcher, 2001). Therefore, the same level of performance impairment that would be unacceptable if it were due to alcohol regularly occurs due to work-related fatigue. The specific impact of any roster on work-related fatigue will obviously depend on a number of factors including number of consecutive night shifts and duration of break periods (Knauth, 1998). However, as a general rule it is difficult but not impossible to avoid fatigue scores greater than 80 points when employees are required to work in 24-hour operations.

Comparisons such as those conducted in this manuscript can lead to questions like, “How tired is too tired?” in relation to work safety. Results of the present and previous studies give us some indication of what levels of fatigue should be accepted, however, in order to better answer this question we are conducting further validations of simulator and field-based shift work data against fatigue-model predictions. Finally, while focusing here on work-related fatigue, we also acknowledge the additional impacts of non-work-related fatigue on fatigue in general. That is, the impacts of individual differences in family and social arrangements, coping strategies, and employee support services or lifestyle education and training competency.
Such issues can make very significant differences to the impact of any roster on fatigue. With further validations and increasing understanding of non-work issues, models such as the one used in the present validation should provide increasing accuracy and utility in the future.

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