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(eds.)

Shiftwork in the 21st Century
Challenges for Research and Practice

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Laboratory-based validations of a work-related fatigue model based on hours of work

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Introduction
The most common disorders associated with shiftwork, and particularly night work, are those of disturbed sleep and sleepiness (Akerstedt, 1988; Åkerstedt, Kecklund & Kutsson, 1991; Åkerstedt, 1995; Härmä, 1995; Kecklund, Åkerstedt & Lowden, 1997; Åkerstedt, 1998). The terms 'sleepiness' and 'fatigue' are often used interchangeably (Dinges, 1995) and are major risk factors associated with shiftwork (Gold, Rogacz, Bock, Tosteson, Baum, Speizer & Czeisler, 1992; Smith, Folkard, Tucker & Macdonald, 1998). This association is unquestionable (National Transportation Safety Board, 1990; Åkerstedt, 1995), however, many organisations do not manage work-related fatigue appropriately. The lack of fatigue management may reflect the absence of simple tools available for use within industry.

There are a number of validated models that have been used to predict sleepiness, alertness and other measures; however, these approaches generally require sleep onset and offset times as an input. Recording individual's sleep times may be possible within military and research environments but is prohibited by cost within most organisations. We have developed a simple work-related fatigue model that uses hours of work as the input. The model makes predictions of work-related fatigue based on:
- Time-of-day of work and non-work periods,
- Duration of work and non-work periods,
- Prior (seven-day) work and non-work history, and
- Biological limitations on recovery at different times of day.

Research suggests that commonly produced levels of fatigue and sleep deprivation can produce impairment greater than what would be acceptable if it were due to alcohol intoxication (Dawson & Reid, 1997). Therefore, the specific aim of this study was to further validate the previously published work-related fatigue model (Fletcher & Dawson, 1998) against performance impairment produced by sleep deprivation and alcohol intoxication. This validation also allowed predictions of impairment due to sleep deprivation and alcohol intoxication to be made from work-related fatigue scores.

Method
Subjects: Twenty-two volunteers with a mean (± SEM) age of 22.0 (± 0.58) years participated in the study. Subjects were required to complete a general health questionnaire and sleep diary prior to the study. Subjects who had sleep and/or other medical disorders, or were taking medication that was known to interact with alcohol, were excluded.

Procedure: The performance testing battery consisted of four tasks: grammatical reasoning (GRT), unpredictable tracking (TRK), vigilance (VIG) and simple sensory comparison (SSC). These tests were chosen so that changes in speed and accuracy could be measured across a range of tasks; from simple to complex.
Volunteers participated in three experimental sessions:  
1) sleep deprivation condition,  
2) placebo condition, and  
3) alcohol intoxication condition.  

The sessions were performed in a randomised cross-over fashion with at least one week between conditions. Subjects were required to arrive at the laboratory at 0200h on the night prior to each condition. Practice on the performance tests was carried out from approximately 2000h until the bedtime of 2300h. Subjects were woken at 0700h and baseline performance was tested at 0800h. Subjects were tested hourly from 0900h during each condition. Each testing session included each of the four performance tests.  

Work-related fatigue model: For each hour of the experiment, predictions of relative performance changes due to fatigue were determined using the work-related model. The hourly predictions of performance were used in the following analyses.  

Analyses: Scores on the performance tests were expressed relative to the average baseline (0800h) scores obtained before each condition. The relative scores within each interval were then averaged to determine the mean relative performance change across subjects. The analyses used hourly and/or blood alcohol concentration (BAC) intervals of 0.01%.  

Linear regressions were performed so that regression equations for the performance measures could be determined. The six measures were GRT mean response time, GRT error rate, TRK score, VIG score, VIG % correct and SSC % correct. Regression equations were determined for each measure with fatigue scores (FAT) and blood alcohol concentration (BAC).  

The fatigue score and blood alcohol concentration regression equations for each of the six measures were then solved simultaneously. These equations were solved so fatigue scores could be predicted using task scores and BAC. In addition, the equations were solved so that equivalent impairment due to alcohol intoxication could be predicted using task scores and fatigue predictions.

Results  

Performance: During the sleep deprivation condition, performance on four of the six measures significantly (p<0.001) decreased as hours-of-wakefulness increased. It was determined that for each hour of wakefulness, between the seventeenth and twenty-seventh hour, the relative decline in performance was 2.65% for GRT mean response time, 3.36% for TRK score, 1.98% for VIG score and 0.61% for VIG % correct. There was no significant change in GRT error rate or SSC accuracy across the seventeenth and twenty-seventh hours of sleep deprivation.  

The decline in performance observed in the alcohol intoxication condition was due to the effects of alcohol as no significant change was observed on any measure during the placebo alcohol condition. During the alcohol condition, it was observed that performance on five of the six measures significantly (p<0.001) 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 time, 0.68% for GRT error rate, 2.68% for TRK score, 2.05% for VIG score and 0.29% for VIG % correct. There was no significant change in SSC accuracy across the range of BAC.  

Equating fatigue scores, sleep deprivation and alcohol intoxication: The above results outline the impacts of the sleep deprivation and alcohol intoxication conditions on a range of neuro-behavioural measures. By knowing the impacts of both conditions on performance, we can express the effects of sleep deprivation on these measures as a fatigue score or blood
alcohol equivalent. Similarly, we can express the effects of alcohol intoxication on the performance measures as a fatigue score or sleep deprivation equivalent.

**Linear regressions:** The linear regression equations for the four significantly affected measures were determined with both fatigue score and BAC as the dependent measure. Table 1 displays the regression equations for each of the four significantly affected measures with fatigue score as the dependent measure. Table 2 displays the regression equations for each of the four significantly affected measures with BAC as the dependent measure.

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_1$ GRG mean response</td>
<td>-12.335 + 0.398x_{Fat}</td>
</tr>
<tr>
<td>$Y_2$ TRK score</td>
<td>18.072 - 0.346x_{Fat}</td>
</tr>
<tr>
<td>$Y_3$ VIG score</td>
<td>-7.792 + 0.311x_{Fat}</td>
</tr>
<tr>
<td>$Y_4$ VIG % correct</td>
<td>1.344 - 0.068x_{Fat}</td>
</tr>
</tbody>
</table>

Table 1. Linear regression equations for the four significantly affected measures with fatigue score as the dependent measure. R² values are provided in the right column.

<table>
<thead>
<tr>
<th>Regression equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_1$ GRG mean response</td>
<td>-4.921 + 132.105x_{BAC}</td>
</tr>
<tr>
<td>$Y_2$ TRK score</td>
<td>5.589 - 201.51x_{BAC}</td>
</tr>
<tr>
<td>$Y_3$ VIG score</td>
<td>-1.654 + 205.463x_{BAC}</td>
</tr>
<tr>
<td>$Y_4$ VIG % correct</td>
<td>-0.586 - 25.291x_{BAC}</td>
</tr>
</tbody>
</table>

Table 2. Linear regression equations for the four significantly affected measures with blood alcohol concentration as the dependent measure. R² values are provided in the right column.

These regression equations were simultaneously solved for both fatigue score and BAC. Table 3 displays the BAC equivalent values of performance decline based on fatigue scores from 20 to 100. Table 4 displays the fatigue score equivalent values of performance decline based on BACs from 0.06 to 0.1%.

<table>
<thead>
<tr>
<th>Fatigue score</th>
<th>GRG mean response</th>
<th>TRK score</th>
<th>VIG Score</th>
<th>VIG % correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>40</td>
<td>0.06</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>50</td>
<td>0.09</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>0.06</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Predictions of blood alcohol concentrations that would be required to produce performance decrements at specific fatigue scores. Grey boxes represent areas beyond the limits of data measurement.
Table 4. Predictions of fatigue scores that would be required to produce performance decrements at specific blood alcohol concentrations. Grey boxes represent areas beyond the limits of data measurement.

<table>
<thead>
<tr>
<th>BAC (%)</th>
<th>GRG mean response</th>
<th>TRK score</th>
<th>VIG Score</th>
<th>VIG % correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>19</td>
<td>36</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>0.01</td>
<td>22</td>
<td>42</td>
<td>26</td>
<td>32</td>
</tr>
<tr>
<td>0.02</td>
<td>25</td>
<td>48</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>0.03</td>
<td>29</td>
<td>54</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>0.04</td>
<td>32</td>
<td>59</td>
<td>46</td>
<td>43</td>
</tr>
<tr>
<td>0.05</td>
<td>35</td>
<td>65</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>0.06</td>
<td>39</td>
<td>71</td>
<td>59</td>
<td>51</td>
</tr>
<tr>
<td>0.07</td>
<td>42</td>
<td>77</td>
<td>66</td>
<td>54</td>
</tr>
<tr>
<td>0.08</td>
<td>45</td>
<td>83</td>
<td>73</td>
<td>58</td>
</tr>
<tr>
<td>0.09</td>
<td>49</td>
<td></td>
<td>79</td>
<td>62</td>
</tr>
<tr>
<td>0.10</td>
<td>52</td>
<td></td>
<td></td>
<td>66</td>
</tr>
</tbody>
</table>

Discussion

The specific aim of this study was to further validate the work-related fatigue model against a range of performance measures. Performance impairment across a range of work-related fatigue scores was compared to impairment across sleep deprivation and alcohol intoxication. Detailed discussion relating to the effects of alcohol intoxication and sleep deprivation on performance will be limited except where it is related to work-related fatigue.

Alcohol intoxication (up to a maximum of 0.1% BAC) produced significant decrements in scores for grammatical reasoning (GRT mean response time and error rate), unpredictable tracking (TRK score) and vigilance (VIG score and % correct). Alcohol intoxication did not produce significant performance decrements in scores for simple sensory comparison (SSC % correct). It is not surprising that performance on the SSC task was not impaired, even at 0.1% BAC, because such tasks are generally included as negative controls.

Sleep deprivation up to 28 hours produced significant decrements in scores for GRT response time, TRK and vigilance (VIG score and % correct). Sleep deprivation up to 28 hours did not produce significant decrements in GRT error rate or SSC % correct. It is not particularly surprising that that accuracy on the GRT did not significantly decline in response to 28 hours of sleep deprivation because subjects were instructed to concentrate primarily on accuracy. Furthermore, it has been established that speed is more likely than accuracy to decline on tasks such as the GRT (Broadbent, 1953).

The regression ($R^2$) values between predicted fatigue scores and the four significantly affected measures range from 0.4 to 0.7 (see Table 1). The highest correlation exists between the fatigue predictions and the vigilance score where over 70% of the variance is accounted for by the predictions. Next highest is the relationship between fatigue predictions and grammatical reasoning response times where over 60% of the variance is accounted for by the predictions. For vigilance accuracy, over 50% of the variance is accounted for by the fatigue predictions. Finally, 40% of the variance in tracking score is accounted for by fatigue predictions. Thus, the fatigue scores are strongly related to the observed performance impairment, particularly for vigilance scores ($R^2>0.7$) and grammatical reasoning response times ($R^2>0.6$).

The linear regression ($R^2$) values between BAC and the four significantly affected measures range from 0.5 to 0.94 (see Table 2). The highest correlation exists between BAC and the vigilance score where 94% of the variance is accounted for by BAC. Next highest is
the relationship between BAC and vigilance accuracy where over 75% of the variance is accounted for by BAC. For tracking score, nearly 70% of the variance is accounted for by BAC. Finally, over 50% of the variance in grammatical reasoning response time is accounted for by fatigue predictions. Thus, the fatigue scores are strongly related to the observed performance impairment, particularly for vigilance scores ($R^2 > 0.9$) and grammatical reasoning response times ($R^2 > 0.7$).

This data shows that for one out of the four affected measures, the work-related fatigue scores had a stronger relationship with performance than BAC. However, for three out of the four affected measures, the work-related fatigue scores had a weaker relationship than BAC. Taken together, these results suggest that BAC levels account for a greater proportion of the variance in the performance data than the fatigue scores. However, this does not negate the fact that fatigue scores were moderately to strongly related to the performance measure data.

The two sets of regressions outlined in tables one and two above were determined using fatigue scores or blood alcohol concentrations as the dependent measure. The regression equations from each of the significantly affected performance measures were then solved simultaneously. This allows the performance impairment at various fatigue scores to be equated to comparable levels of impairment due to alcohol intoxication.

Table 3 displays the BAC required to obtain performance decrements equivalent to the impairment observed at specific fatigue scores. The results in table 3 are derived from the output of the simultaneous equations when they are solved using BAC as the dependent measure. Performance decrements equivalent to those observed in the 0.05-0.08% BAC range occur at fatigue scores between 40 and 80 points. For vigilance score, the most highly correlated measure for work-related fatigue, performance decrements equivalent to those observed in the 0.05-0.08% range occur at fatigue scores between 50 and 70 points.

Table 4 displays the fatigue scores required to obtain performance decrements equivalent to the impairment observed at specific BAC. The results in table 4 are derived from the output of the simultaneously solved equations when they are solved using fatigue score as the dependent measure. Performance decrements equivalent to those observed in the 50-80 range of fatigue scores occur between 0.03-0.1% BAC. For vigilance score, the most highly correlated measure for BAC, performance decrements equivalent to those observed in the 50-80 fatigue point range occur between 0.05 and 0.09% BAC.

It is worth noting that the predictions for 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 = 0.1%) of BAC for GRT mean response times, GRT error rate and VIG % correct. However, based on the actual data for TRK score and VIG score, the performance at 80 points is predicted to be equivalent to performance decrement seen at 0.08 and 0.09% respectively.

Of these two measures, vigilance score is the measure that correlates most strongly with the fatigue predictions. In fact, vigilance score is the most highly correlated measure of all ($R^2 = 0.713$ and 0.942 for sleep deprivation and alcohol intoxication respectively). We can therefore investigate the relationship between vigilance score and fatigue score to get the best possible prediction of performance impairment. Using regression equations for vigilance score, it is predicted that the equivalent BAC impairment at 80 fatigue points is 0.09% BAC. However, this simply suggests that the previously reported relationships between fatigue scores and performance measures may be conservative.

Based on the estimates that have been determined using linear regressions, the relationships between fatigue scores and performance measures do seem quite strong ($R^2$ values between 0.39 and 0.71). The strongest relationship, which is between fatigue scores
and vigilance score ($R^2 = 0.713$), best illustrates the relative impairment due to fatigue. The results illustrate that a fatigue score of 80 is associated with impairment comparable to what would be observed in an individual with a BAC greater than 0.08%.

If an individual registered such a BAC whilst working or operating a motor vehicle, it is unlikely that they would be permitted to continue. However, a significant proportion of the rosters employed in 24-hour operations produce work-related fatigue scores greater than 80. Therefore, the same level of impairment that would not be acceptable if it were due to alcohol seems to be allowed when it is due to 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 used in this article direct us toward the question 'how tired is too tired?' Results of such studies give us some indication of what levels of fatigue should be accepted, however, further validation is required before this question can be answered unequivocally.

References


