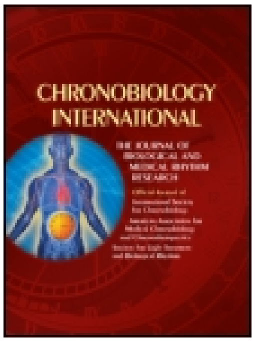

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ESTIMATING THE CIRCADIAN RHYTHM IN THE RISK OF OCCUPATIONAL INJURIES AND ACCIDENTS

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The authors recently published a prototypic Risk Index (RI) to estimate the risk of critical errors associated with shift systems. This RI was based on published trends in the relative risk of injuries and accidents, and a simple additive model was proposed to estimate the risk for a given shift system. However, extending the RI to irregular work schedules requires an estimation of the phase and amplitude of the circadian rhythm in risk. This paper integrates the published evidence on three independent sources of data that allow such estimations to be made: the trend in risk over a 24 h day, over the course of the night shift, and across the three different (8 h) shifts. Despite potential confounders, maximum risk (i.e., acrophase = peak time) estimates across these three trends showed a remarkable consistency, with all three estimates occurring at about midnight, although the amplitude estimates varied considerably. The best estimate of the amplitude of the circadian rhythm in risk would appear to be that based on trend over the three (8 h) shifts, as this trend is the least confounded. The estimated acrophase (peak time) in risk appeared earlier than would be predicted from consideration of the circadian rhythm in alertness, fatigue, or performance on simple interpolated tasks, such as reaction time or performance on the Psychomotor Vigilance Test.

Keywords Accidents, Occupational injuries, Workplace safety, Work schedules, Mathematical models, Shift work, Circadian rhythm, Risk

INTRODUCTION

Workplace safety is a priority in many industries, particularly so in situations where there is a high public health and/or environmental risk,

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such as in transportation or nuclear power. A number of authors have produced models based on alertness, fatigue, or performance to predict the likelihood of human error on different work schedules; many of these models were published in the proceedings of the Fatigue and Performance Modelling Workshop (2004). These models have generated considerable interest in the safety community, as they provide a potentially simple mechanism for assessing the relative safety of different work schedules. However, while some models account for trends in the various measures of alertness and performance reasonably well, they do not account for some relatively consistent trends in the relative risk of accidents and injuries, referred to collectively here as *incidents* (Folkard and Åkerstedt, 2004; Folkard and Lombardi, 2006; Folkard and Tucker, 2003). This is despite the fact that these trends were obtained in studies where the a priori risk appeared to be constant or was corrected for. Hence, the trends obtained could reasonably be assumed to reflect variations in the likelihood of the individual operators making errors related to their particular work schedule.

Recent papers have proposed a prototypic Risk Index (RI) to estimate the risk of critical errors associated with shift systems (Folkard and Lombardi, 2004, 2006). This RI integrates published trends in the relative risk of injuries and accidents associated with three different (8 h) shifts, successive day or night shifts, the length of the shift, and the interval between successive rest breaks during the course of a shift. A simple additive model based on these trends (and linear extrapolation where necessary) was used to estimate the risk for any given shift system. In principle, the RI is similar to other models of fatigue that have been proposed, such as the UK government health and safety executive's fatigue index (FI). It shares with them the distinct advantage that it considers features of shift systems in combination with one another. This contrasts with work hour limitations or regulations (e.g., the European Union's Working Time Directive) that consider features of shift systems independently from one another. Further, the RI has two distinct advantages over the other "combined-feature" models: it is based directly on trends in the risk of injuries and "accidents" and thus has a high face validity, and the output is an estimate of the relative risk associated with the shift system rather than an arbitrary fatigue value, thus allowing informed decisions to be made as to the shift system's acceptability.

The prototypic version of the RI (Folkard and Lombardi, 2004, 2006) can be used to provide risk estimates for most types of shift system, and the derived estimates are typically positively correlated with the fatigue values derived from the FI. However, in its current form, the RI is based on "normal" shift start times for Europe (namely, 06:00, 14:00, and 22:00 h) and cannot be used for operations with irregular work schedules in, for example, transportation. To extend it to irregular work schedules requires an estimation of the phase and amplitude of the circadian rhythm in risk. This paper integrates the published evidence on three independent sources of data that allow such estimations to be made—the trend in the risk of occupational injuries over the 24 h day, the trend in risk over the course of the night shift, and the risk across the three different (8 h) shifts.

ESTIMATION OF THE TRENDS

Method

The trends considered here were based on published data from two sources:

- Literature searches conducted in December 2004 and January 2005 using PsycINFO, SIGLE, and Google search engines with the following terms: work hours, shift work, time of day, or work schedule, combined with accident, injury, safety, or risk; and
- The substantial collection of reprints and papers held by the first author.

The literature searches resulted in over 1500 "hits," though most of those that appeared to be relevant were general "review" or "advice" documents, often supplied by commercial consultancies or by governmental organizations. The major exceptions were a number of articles of which the first author was already aware.

Two types of analyses performed using SPSS version 12.0.1 for Windows were used to evaluate the trends. First, non-parametric Kruskal-Wallis or Friedman analyses were based on the relative risks calculated for each of the data sets. Non-parametric analyses were chosen in view of the facts that relative risk values are not likely to be normally distributed and the variances are not likely to be equal. These analyses give equal weight to each study, despite the differences in the total number of incidents reported, and essentially determine whether the trends reported in the various studies are similar. The main disadvantage of this type of analysis is that it would give undue weight to an atypical trend reported in a study based on only a small number of incidents.

Secondly, for those trends where the frequency values did not have to be corrected for exposure, a chi-square analysis was based on the summed frequency of incidents, giving equal weight to injuries and "accidents." These summed frequencies were also used to estimate 95% confidence intervals based on a Poisson distribution. This second form of analysis essentially weights the studies according to the number of incidents reported, but suffers from the disadvantages of using chi-square with large data sets and giving undue weight to a study reporting an atypical trend if it were based on a large number of incidents. In the present paper, both analytic methods were used to overcome the shortcomings associated with each method by itself. Thus, if the results of both analyses resulted in similar conclusions, the conclusions are likely to be independent of the assumptions underlying each analysis.

Estimating the Trend Across the 24 h Day

One way to assess the circadian rhythm in risk is to examine the trend in occupational injuries over the 24 h day and correct for exposure. The first study to have done this was that by Akerstedt (1995), who corrected the Swedish national occupational injury data for exposure on the basis of a time budget study of a representative sample of 1,200 members of the population under consideration. More recently, studies by Fathallah and Brogmus (1999) and Fortson (2004) have corrected for exposure using data from the United States Bureau of Labor Statistics. These three studies report corrected hourly data across the 24 h day in five different measures: lost time injuries of one day or more ($n \approx 160{,}000$; Akerstedt, 1995), all compensation claims ($n > 600{,}000$; Fathallah and Brogmus, 1999), low back disorder compensation claims ($n \approx 72{,}000$; Fathallah and Brogmus 1999), laceration compensation claims ($n = 42{,}902$; Fortson, 2004), and fall compensation claims ($n = 29{,}074$; Fortson, 2004).

In order to make comparisons across these five data sets, the corrected frequency of incidents for each hour of the day in each study was expressed relative to the 24 h mean for that study, yielding a series of 24 relative risk values for each study. A non-parametric Kruskal-Wallis analysis based on the relative risk values for the five data sets yielded a highly significant main effect of hour of the day ($\chi^2 = 96.32$, df = 23, $p < 0.001$). Note that in this case it was not appropriate to base a chi-square test on the summed frequencies, as each of the trends had to correct for exposure and thus combining raw frequency scores would be biased.

The average trend across the five data sets is double-plotted in Figure 1 to illustrate the rhythmic nature. Clearly the mean relative risk values varied substantially over the 24 h day, being highest at night and lowest during the day. However, as Fortson (2004) recognized, this 24 h pattern reflects both variations in the likelihood of individuals making the sort of errors that result in incidents, but also a number of confounding factors, such as:

- There are systematic differences within and between industries where production may vary, or when more intense work is performed at the

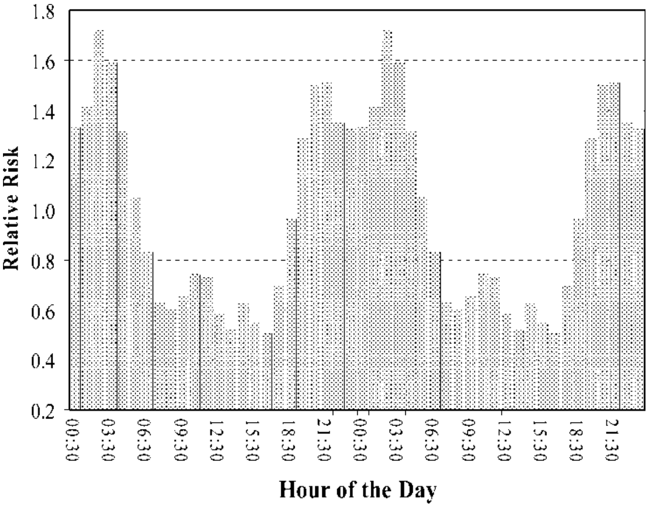

FIGURE 1 The relative risk across the course of the 24 h day (double-plotted).

beginning or end of a workday. For example, longer production runs during the night shift leading to lower exposure to potential injury risk factors.

- The pronounced 24 h natural light/dark cycle will result in jobs being intrinsically less safe at night for many workers.
- At night, workers will, on average, have been awake for longer than at most points during the day.
- The frequency and/or pattern of rest breaks may differ over the 24 h day.
- The reporting of an injury may vary systematically over the 24 h day.

Estimating the Trend Over the Course of the Night Shift

The effect of some of these confounding factors can be overcome by examining the trend in injuries over the course of a shift in a specific industrial organization, as the occupation is clearly constant while both the lighting conditions and the nature of the work being performed are normally also fairly constant. Vernon (1923) reported an early study in this area in which he examined the trend over the night shift in the frequency of cuts treated by surgery in two munitions factories (n = 666). He found that, far from increasing over the course of the night shift—as might be predicted from studies of fatigue (e.g., Folkard et al., 1995; Tucker et al., 1999)—the injury rates actually decreased substantially over at least the first few hours of the night shift. He also reported an indirect measure of productivity (i.e., the power consumed by the plant) and noted that although this roughly paralleled risk during the day shift, it failed to do so at night. From this observation, Vernon concluded that while productivity may have been the major determinant of risk on the day shift, some other factor must have determined risk at night. He failed to indicate what he thought this other factor might have been, but given the decreasing trend in risk from the start of the night shift, it is difficult to account for it simply in terms of fatigue.

Several more recent studies have also provided hourly incident rates over the course of the night shift (typically from 22 : 00 to 06 : 00 h), such as those by Adams et al. (1981, n = 829), Ong et al. (1987, n = 150), Wagner (1988, n = 775), Smith et al. (1994, n = 902; 1997, n = 657), Wharf (1995, n = 777), Macdonald et al. (1997, n = 774), and Tucker et al. (2001, n = 274). In order to compare across the studies, the frequency of incidents for each hour was expressed relative to that for the first hour in each study. A non-parametric, repeated-measures Friedman analysis based on these relative risk values for the nine data sets yielded a significant effect of hour on shift ($\chi^2 = 20.44$, df = 7, $p < 0.005$). A chi-square test was then based on the summed frequencies across the nine data sets for each hour of the shift, which also yielded a highly significant effect of hour on shift ($\chi^2 = 120.516$, df = 7, $p < 0.001$).

Using these summed values, risk rose by about 20% from the first to second hour, but then decreased substantially and in an approximately linear fashion to reach a minimum at the end of the shift (see Figure 2). It is notable that there was a slight increase in risk between 03 : 00 and 04 : 00 h, when performance and alertness are thought to be at their lowest ebb, but this effect was relatively small compared to the substantial decrease in risk over most of the night. This trend in risk over the night

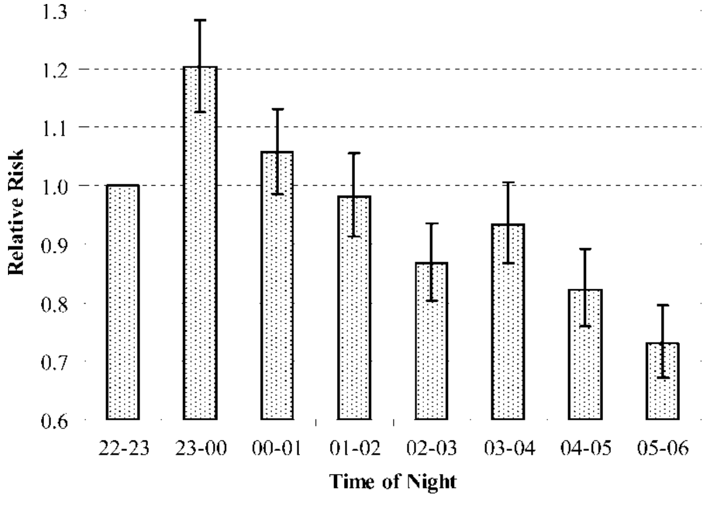

FIGURE 2 The relative risk across the course of the night shift. (Error bars are 95% CIs.)

shift is clearly inconsistent with predictions from fatigue or performance measures, which would suggest that the maximum risk should occur in the early hours of the morning.

There remain, however, some problems in using this trend in risk over the course of the night shift to assess the circadian rhythm in risk. The data points only cover one-third of the 24 h day and are thus of limited value in estimating the entire circadian rhythm. Perhaps more importantly, this trend is still potentially confounded by some of the factors previously described. Thus, many industrial companies use work quotas such that the effective average workload (and hence risk) may reduce over the course of a shift. In addition, the trend totally confounds variations due to circadian influences with those due to the effects of time on task and the timing of breaks.

Estimating the Trend Across the Three Shifts

As with estimating the trend over the course of the night shift, some of the confounding factors can also be overcome by examining the trend in the relative risk of incidents in the morning, afternoon, and night shifts of 8 h shift systems, where the work pace is relatively constant. There are five studies that are based on relatively large numbers of incidents that appear to meet this condition and where the incident rates are reported separately for the morning, afternoon, and night shifts. In the four European studies, the shift change times were 06 : 00, 14 : 00, and 22 : 00 h, while in the American study (Levin et al., 1985), they were 08 : 00, 16 : 00, and 24 : 00 h. It should be noted that the studies for this trend differed from one another in terms of their location, industry, and both the numbers of incidents reported and the size of the population in which they occurred. They also likely differed in terms of the criteria used in determining whether an incident was recorded. Direct comparisons between studies may be biased; however, valid comparisons within each study can be made.

In two of the studies, there were equal numbers of shift workers on each shift (Quaas and Tunsch, 1972; Smith et al., 1994), while in the others the original authors had to correct the data to take account of inequalities in the number of workers (Levin et al., 1985; Wanat, 1962; Wharf, 1995). Further, Smith, Folkard and Poole (1994) reported two separate sets of data for different work areas, and Quaas and Tunsch (1972) reported injuries and “accidents” separately, giving a total of seven data sets across the three shifts. These seven data sets comprise underground coal minors’ injuries (Wanat, 1962; n = 3,699), metal plant workers incidents (Quaas and Tunsch, 1972; injuries n = 1,415; accidents n = 688), paint manufacturers’ injuries (Levin et al., 1985; n = 119), engineering workers' injuries (Smith et al., 1994; site 1 n = 2,461; site 2 n = 2,139) and industrial coal minors' injuries (Wharf, 1995; n = 1,970).

In comparing across the studies, the frequency of incidents for each shift was expressed relative to that for the morning shift in each study. A non-parametric Kruskal-Wallis analysis based on these relative risk values for the seven data sets yielded a highly significant main effect of shift ($\chi^2 = 16.08$, df = 2, $p < 0.001$). The chi-square test based on the summed frequencies across the seven data sets for the three shifts also yielded a highly significant effect of shift [$\chi^2 = 124.08$, df = 2, $p < 0.001$]. Based on these pooled frequencies, risk increased in an approximately linear fashion, with an increased risk of 15.2% on the afternoon shift and 27.9% on the night shift relative to that on the morning shift (see Figure 3). However, it should be noted that although this trend over the three shifts arguably overcomes the various confounding factors discussed above, it provides only three, equally spaced data points to cover the 24 h day and is thus of limited resolution in estimating the circadian rhythm in risk.

ESTIMATING THE CIRCADIAN RHYTHM IN RISK

In order to estimate the phase and amplitude of the circadian rhythm in risk from the estimated trends across the 24 h day, the night shift, and the three shifts described above, group cosine curves were fitted to the relative risk estimates using a least-squares technique. The 5, 9, and 7 (respectively) sets of relative risk estimates contributing to the overall curves shown in Figures 1–3 were treated as coming from separate "days." Thus, the group cosinor analyses were based on 120, 72, and 21

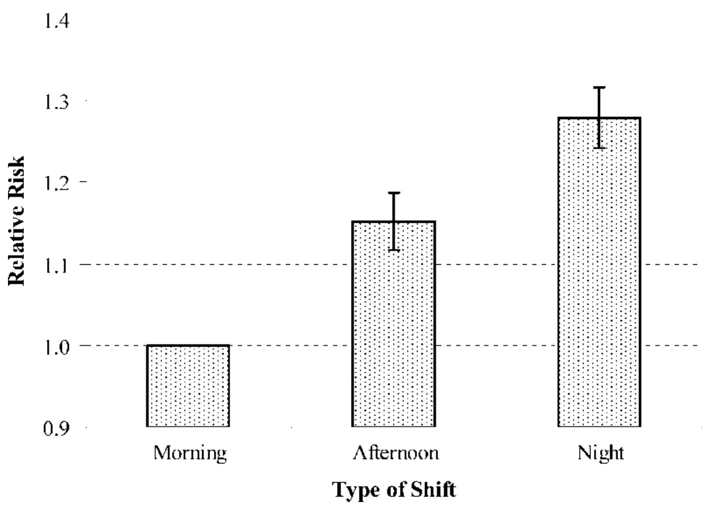

FIGURE 3 The relative risk across the three shifts. (Error bars are 95% CIs.)

relative risk estimates, respectively. The hourly risk values for the trends over the 24 h day and across the night shift were assumed to reflect the risk at the middle of the hourly bin from which they were obtained (i.e., 00 : 30, 01 : 30, etc). Likewise, the risk values for the trend across the three shifts were taken as reflecting the risk at the midpoint of the shift (i.e., 10 : 00, 18 : 00, and 02 : 00 h).

Statistically significant fits were obtained for all three sets of risk estimates, although the fit for the trend over the night shift was considerably less reliable ($p = 0.032$) than that for the 24 h day and three shift data ($p < 0.001$ in both cases). The estimated acrophases (i.e., times of maximum risk) for the three sets of risk data were extremely similar to one another, ranging from 23 : 20 h for the trends over the night shift to 00 : 28 h for the trends over the 24 h day. However, the 95% confidence intervals for the acrophase estimate based on the trend over the night shift were considerably larger than those for the other two trends, as shown in Table 1.

The estimates of the amplitude of the circadian rhythm in risk showed far greater differences across the three trends. The largest estimated amplitude (0.510) was found for the trends over the 24 h day, and the smallest (0.155) for the trends across the three shifts (see Table 1), with that for the trend across the night shift falling approximately in the middle. The smaller amplitude obtained for the trend across the three shifts might reflect, in part, the use of single, mid-shift, values, although this would account for only a small portion of the difference in amplitude observed. Taken together, these acrophase and amplitude estimates suggest that the various confounding factors discussed previously served to increase the amplitude estimate for the trends over the 24 h day, and to a lesser extent that for the trends over the night shift, while having little effect on the acrophase estimates.

DISCUSSION AND CONCLUSIONS

The aim in this paper was to estimate the circadian rhythm in the risk of occupational injuries and accidents. Three independent sets of data were identified that provide trends that can be used to make this assessment: the pattern over the 24 h day, the trend over the night shift, and

TABLE 1 Results of the Group Cosinor Analyses for the 24 h Day, Night Shift, and Three Shift Trends

Trend	Acrophase	Amplitude	*p*
24 h day	00 : 28 h (±0 : 36)	0.510 (±0.079)	<0.001
Night shift	23 : 20 h (±2 : 36)	0.324 (±0.302)	=0.0321
Three shifts	00 : 04 h (±1 : 12)	0.155 (±0.048)	<0.001

95% confidence intervals are shown in parentheses.

the trend over the three (8 h) shifts used to provide 24 h cover. All three trends would appear to be relatively consistent and statistically reliable across the studies identified. However, they would appear to differ in the extent to which they may be confounded.

Despite this potential confounding, maximum risk (i.e., acrophase) estimates across the three trends showed a remarkable consistency, with all three estimates occurring at about midnight. This was despite the intrinsic differences between the three data sets in their time resolution and in whether they were predominantly based on European (trend across the three shifts) or American (trend across the 24 h day) data. This latter point is important in view of the somewhat later normal shift start times in America (08 : 00, 16 : 00, and 24 : 00 h) compared to Europe (06 : 00, 14 : 00, and 22 : 00 h), and suggests that the timing of the estimated acrophases were indeed due to an endogenous circadian rhythm in risk rather than to "warm up" or "fatigue" effects.

It is also noteworthy that the acrophases occurred rather earlier than would be predicted from consideration of the circadian rhythm in alertness, fatigue, or performance on simple interpolated tasks, such as reaction time or performance on the Psychomotor Vigilance Test. The results reported in this paper cannot explain the reason for this discrepancy, although it would appear to be important from both practical and theoretical perspectives. Thus, from a practical viewpoint, it would seem that mathematical models based on alertness, fatigue, or performance on interpolated task may be of limited value in predicting the risk of errors resulting in occupational injuries or accidents. Whether this limitation of the mathematical models also applies to measures of productivity clearly warrants further investigation. From a theoretical perspective, there is also a clear need for further research to elucidate the nature of the relationship, if any, between fatigue and risk. Such research might elucidate whether current methods for estimating fatigue fail to do so successfully and hence fail to relate to risk, or whether risk is strongly influenced by factors other than fatigue.

The amplitude of the circadian rhythm in risk varied across the three trends, with that based on the 24 h day data being more than three times as large as that based on the trend across the three (8 h) shifts. It would appear that the various confounding factors identified with respect to the trend based on the 24 h day, and to a lesser extent that based on the trend over the night shift, served to increase the estimated amplitude of the circadian rhythm while having little, if any, effect on the estimated acrophase. This pattern of results is similar to that found for the effect of masking factors, such as activity, on estimates of the circadian rhythm in core body temperature in entrained individuals (Folkard, 1989). In both cases, the masking or confounding factors appear to be roughly in phase with the endogenous ones such that their effect is simply to increase the amplitude of the circadian rhythm without affecting its phase. The best estimate of the amplitude of the circadian rhythm in risk would appear to be that based on trend over the three (8 h) shifts, as this trend is the least confounded. The authors have accordingly used this amplitude estimate and an acrophase of midnight in the most recent version of the Risk Index designed to cope with all rotating work schedules, whether they be regular or irregular and whatever the start time of the various periods of work (Risk Index calculator and report both available at Spencer et al., 2006).

However, the revised Risk Index clearly needs to be validated for irregular work schedules and rotating work schedules that differ from the largely weekly, forward-rotating shift systems on which it is based. Further, the revised Risk Index might provide reasonably accurate estimates for permanent shift systems if the individuals involved showed little circadian adjustment, as is normally the case. However, it clearly could not cope with the minority of individuals who show circadian adjustment to their permanent work schedule. Indeed, the authors are currently considering whether it might prove feasible to develop a version of the Risk Index for permanent shift systems, although this would clearly necessitate some form of assessment of whether each individual shows circadian adjustment to their schedule.

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