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The link between fatigue and safety

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ABSTRACT

The objective of this review was to examine the evidence for the link between fatigue and safety, especially in transport and occupational settings. For the purposes of this review fatigue was defined as 'a biological drive for recuperative rest'. The review examined the relationship between three major causes of fatigue – sleep homeostasis factors, circadian influences and nature of task effects – and safety outcomes, first looking at accidents and injury and then at adverse effects on performance. The review demonstrated clear evidence for sleep homeostatic effects producing impaired performance and accidents. Nature of task effects, especially tasks requiring sustained attention and monotony, also produced significant performance decrements, but the effects on accidents and/or injury were unresolved because of a lack of studies. The evidence did not support a direct link between circadian-related fatigue influences and performance or safety outcomes and further research is needed to clarify the link. Undoubtedly, circadian variation plays some role in safety outcomes, but the evidence suggests that these effects reflect a combination of time of day and sleep-related factors. Similarly, although some measures of performance show a direct circadian component, others would appear to only do so in combination with sleep-related factors. The review highlighted gaps in the literature and opportunities for further research.

1. Introduction

Fatigue has been identified as a contributing factor for accidents, injuries and death in a wide range of settings, with the implications that tired people are less likely to produce safe performance and actions. These settings include transport operations such as road, aviation, rail and maritime, as well as other occupational settings (e.g., hospitals, emergency operations, law enforcement), particularly when irregular hours of work are involved. Almost everyone becomes fatigued at some time, either in their work or during their leisure time, and so may be at increased risk of accident or injury. Fatigue effects such as response slowing, failures in attention or failure to suppress inappropriate strategies have been identified in many high profile accidents (Mitler et al., 1988).

In many countries, fatigue is identified as a contributing factor in a significant proportion of road transport accidents (Horne and Reyner, 1995a; Lyznicki et al., 1998; Pierce, 1999; Philip et al., 2001; Dobbie, 2002). Estimates of the role of fatigue in crashes can vary considerably, depending upon the severity and circumstances of the crashes examined. Typical ranges cited are from 1 to 3% of all crashes (Lyznicki et al., 1998) to up to 20% of crashes occurring on major roads and motorways (Horne and Reyner, 1995b). There is general agreement that any percentages based on crash data underestimate the true magnitude of the problem, since the evidence for fatigue involvement in crashes is often questionable, being based on criteria that exclude other factors rather than identifying definite involvement of fatigue.

The objective of this paper is to review the scientific evidence for the link between fatigue, safety and performance outcomes. It will examine such questions as: what do we really know about the link between fatigue and safety? Is there evidence that we should be concerned about the effects of fatigue? Where are the gaps in our knowledge?

In any consideration of fatigue and its effects, the issue often passed over is the lack of a clearly defined and agreed upon definition of fatigue. Fatigue is a hypothetical construct which is inferred

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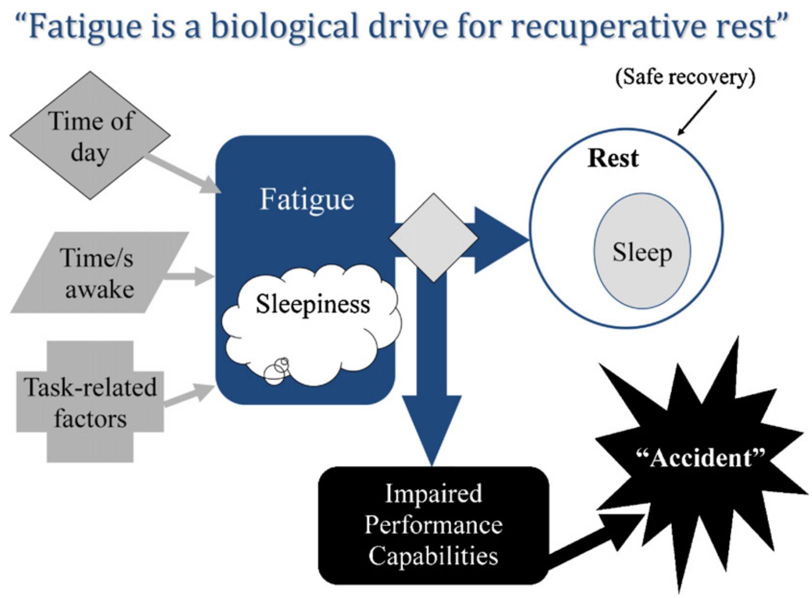

Fig. 1. Framework for examining the relationship between fatigue and safety.

because it produces measurable phenomena even though it may not be directly observable or objectively measurable. Fatigue, as a construct, links a range of factors that presumably cause fatigue with a number of safety-related outcomes. The link between experiences like a long period without sleep and crashes or accidents is through the projected effect of fatigue. Fatigue is the mechanism by which the link exists.

There is little agreement on a definition of fatigue (Desmond and Hancock, 2001; Noy et al., 2011). However, for the purposes of this review fatigue is simply defined as *"a biological drive for recuperative rest"*. This rest may or may not involve a period of sleep depending on the nature of the fatigue. We consider that fatigue may take several forms including sleepiness as well as mental, physical and/or muscular fatigue depending on the nature of its cause. In the context of modern transportation systems it seems probable that sleepiness and mental fatigue are the most important forms of fatigue. In this paper we look at the evidence that all forms of fatigue can result in reduced performance capabilities and safety due to slowed or incorrect responses and/or total failures to respond.

This review examines evidence for the link between factors that are purported to cause fatigue and adverse safety outcomes. It first looks at evidence for effects on clear safety outcomes including adverse incidents and accidents and second at the evidence for adverse effects on performance that may be precursors of safety outcomes. Fig. 1 describes the overall framework for this review. The result of the development of fatigue and sleepiness may be either a safe recovery or a decrease in performance capability which may lead to an adverse safety outcome. The review examines the effects of the main influences noted to increase fatigue which include circadian influences, sleep homeostasis factors of sleep loss and time since last sleep, and specific types of task characteristics. These are shown on the left-hand side of the model depicted in Fig. 1. The model conceptualizes the experience of fatigue and sleepiness as providing the drive for restorative rest and sleep (or safe recovery, as shown on the right-hand side of the model). To the extent that this drive remains unsatisfied, the capacity to perform is impaired and this in turn increases the risk of adverse safety outcomes. Increasing levels of fatigue and sleepiness decrease performance capacity with, of course, falling asleep having the most extreme effects on performance capacity.

This review examines safety outcomes such as accidents and injury and also attempts to summarize concisely the relevant literature on fatigue effects on performance including errors and slowed responding. It could be argued that the most definitive evidence for the effect of fatigue on safety will come from establishing temporal relationships between fatigue and outcomes like crashes, injuries and accidents. At the heart of this contention is the argument that evidence of changes in performance and behavior alone do not necessarily imply increased risk of adverse safety outcomes. Further, evidence from laboratory or even simulation studies has been critiqued as inadequately reflecting operational or real-world performance. Nevertheless, there is a large body of peer-reviewed and position papers on the link between fatigue, or the factors that cause it, and performance, which is based on the often implied rationale that decreases in performance functions are of importance as they signify increased risk of adverse safety outcomes.

Dinges and Kribbs (1991) formally stated the argument for this body of research and put forward the notion that performance is a critical probe of central nervous system capacity, primarily that performance changes are the functional consequences of the physiological effects of fatigue. Further, they argued that performance changes are a way of linking direct evidence of fatigue effects of sleep loss from laboratory studies with field studies where performance decrements are potentially more readily observable than infrequent adverse safety outcomes. Thus, the review includes performance effects as well as overt safety outcomes of fatigue. The review will focus mainly on the effects of fatigue on transport safety, especially motor vehicle safety, as well as on safety in occupational settings.

The review follows the framework shown in Fig. 1. It first covers the evidence for the effects of circadian, sleep homeostasis and task-related factors on fatigue and safety outcomes. It then examines the evidence for each of these influences on performance capacity. Finally, it summarizes the evidence for the link between performance and safety outcomes. In addition to reviewing the available evidence, the review identifies needs for further research.

2. Link between fatigue and safety outcomes

This section describes the evidence for the relationship between the causes of fatigue, including circadian, sleep homeostasis and task-related factors and adverse safety outcomes. It also reviews evidence from studies that have presumed the presence of fatigue irrespective of its specific causal mechanism.

2.1. Safety outcomes: circadian factors

It has long been recognized that one of the most prominent aspects of human circadian rhythmicity is the pronounced 24 h patterning of sleep and wakefulness. Both the probability of falling asleep and the subsequent sleep duration vary substantially over the 24 h day, and this appears to be largely due to the influence of the endogenous body clock (Czeisler et al., 1980; Zulley et al., 1981). Under normal (night sleep) conditions, both the probability of falling asleep and subjective ratings of sleepiness show a pronounced circadian rhythm, with maximum values occurring at about 06:00 (Lavie, 1986; Zulley, 1990; Åkerstedt and Folkard, 1995)

In light of this pattern in human sleep and wakefulness it is perhaps not surprising that a number of headline disasters and catastrophes have occurred at times when people are normally asleep. Both the Exxon Valdez and the Estonia ferry disasters occurred at night, and in both cases they were at least partially attributed to fatigue and human error. The same is true for a number of non-transport disasters such as Three Mile Island, Bhopal, Chernobyl, and the Rhine chemical spillage. Indeed, formal studies of road accident frequencies have shown that once traffic density is controlled for, the risk at night may be up to ten times as high as that during the day (e.g. Langlois et al., 1985; Horne and Reyner, 1995a,b). Similarly, an increased risk at night has been reported for fatal aircraft approach and landing accidents (Ashford, 1998), marine groundings (Folkard, 2000) and industrial injuries (Folkard and Tucker, 2003), once exposure has been controlled or corrected for. In short, the risk of a person being involved in an accident or injuring themselves would appear to be substantially increased at times when they would normally be asleep. In this review, "time of day" is distinguished from "circadian" on the basis of the quantitative measurement of the exposure. In studies where measures are infrequent, or limited to only part of the 24 h day, the term "time of day" is used, whereas if the measures are reasonably frequent and spread across the whole 24 h day then "circadian" is used.

Folkard (1997) reviewed several studies that examined the relationship between road transport safety and time of day. These studies either "corrected" their trends to take account of exposure (e.g. Hamelin, 1987) or traffic density (e.g. Langlois et al., 1985) or confined their attention to single vehicle (e.g. van Ouwerkerk, 1987) or "sleep-related" accidents (e.g. Lavie, 1991), in some cases omitting those in which alcohol may have played a role (e.g. Horne and Reyner, 1995a,b). Folkard (1997) performed a form of meta-analysis on the trends he reviewed and concluded that when "exposure" or traffic density was controlled for there was a pronounced circadian rhythm in the probability of an accident.

It was, however, noteworthy that the peak in accident risk occurred rather earlier than that in sleep propensity (namely between 02:00 and 03:00 rather than at 06:00). Indeed, other studies have also reported a rather earlier peak than would be expected (e.g. Kecklund and Åkerstedt, 1995; Bruno, 2004), even when attention was confined to accidents that were not due to speeding, where alcohol was below the legal limit (0.05%) and where the weather conditions were dry and good (Di Milia, 1998). There would appear to be only a single study that has shown a 06:00 peak in accidents classified as sleep-related by the police (Cabon et al., 1996), and that was for only one of the two data sets examined. Indeed, in his 1997 review Folkard reported that although the 24 h patterning in sleep propensity accounted for about 50% of the variability in the 24 h patterning of road accidents, there were significant differences between the two trends. By examining these differences he was able to demonstrate that there were three "residual peaks" in accident risk at 02:00, 14:00 and 21:00, and went on to suggest that these might reflect a "time-on-task" effect in risk (see Section 1.3.1).

Nevertheless, there may be a wide range of confounding factors that might obscure the link between circadian variations in sleepiness and transport accidents. These include not only potential differences in time awake and time-on-task, but also variations in the nature of the task being performed due to lighting conditions and traffic density. Thus the task of night-time driving in low density traffic is very different to that of daytime driving when traffic density is typically far higher. In addition, the proportion of alcohol-affected drivers involved in crashes peaks rather earlier in the night than sleepiness (Åkerstedt et al., 2008). These differences may be less marked in, for example, maritime operations when the vessel is under way rather than in close maneuvering situations, and it is notable that Folkard (1997) reported a rather later peak in collisions between ships at sea.

Folkard et al. (2006) argued that these factors are also present in many occupational and industrial situations. They reviewed three types of studies that allow a determination of the circadian rhythm in the risk of industrial or occupational injuries. Perhaps the most obvious way to assess this circadian rhythm in risk is to examine the trend in occupational injuries over the 24-h day and to correct for exposure. The first study to have done this was that of Åkerstedt (1995) who corrected the Swedish national occupational injury data for exposure on the basis of a time budget study of a representative sample of 1200 members of the population under consideration. More recently, similar US studies by Fathallah and Brogmus (1999) and Fortson (2004) corrected for exposure using data from the U.S. Bureau of Labor Statistics. Between them these three studies provided five trends in risk over the 24 h day, and there was considerable agreement between them in the nature of this trend, with the estimated peak occurring shortly after midnight at 00:28 (see Folkard et al., 2006 for further details).

However, Folkard et al. (2006) also identified a number of confounding factors that might have influenced the timing of this peak, namely:

- Time since waking;
- Time since starting work;
- The timing of rest breaks;
- Work quotas resulting in less work being performed in later hours at work;
- Occupational differences;
- Differences in the precise nature of the job being performed;
- Differences in the lighting conditions.

Folkard et al. (2006) argued that the effect of some of these confounding factors could be overcome by examining the trend in injuries over the course of the night shift in a specific industrial organisation. This follows from the fact that the occupation is clearly constant while both the lighting conditions and the nature of the work being performed are normally also fairly constant, although other confounders may still be present. 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 at a surgery in two munitions factories. He found that, far from increasing over the course of the night shift, as might be predicted from studies of sleepiness (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.

Several more recent studies have also provided hourly incident rates over the course of the night shift (typically from 22:00 to 06:00), namely those of Adams et al. (1981), Ong et al. (1987), Wagner (1988), Smith et al. (1994), Wharf (1995), Macdonald et al. (1997), Smith et al. (1997), Tucker et al. (2001). These studies showed a considerable agreement in the nature of the trend over the course of the night shift, with the estimated peak occurring shortly before midnight at 23:20 (see Folkard et al., 2006 for further details). It was notable that there was a slight increase in risk between 03:00 and 04:00, when sleepiness is high and performance low (e.g. Colquhoun, 1982; Folkard et al., 1995; Tucker et al., 1999), but that this effect was relatively small compared to the substantial decrease in risk over most of the night. This trend in risk over the night shift is clearly inconsistent with predictions from sleepiness or performance measures which would suggest that the maximum risk should occur in the early hours of the morning. Indeed, the trend in risk over the course of the night shift was significantly, but negatively, related to that in sleepiness (Folkard and Åkerstedt, 2004).

Folkard et al. (2006) argued that the least confounded estimate of the peak in risk could be obtained by examining the trend in the relative risk of incidents across the morning, afternoon and night shifts on 8-h shift systems where the work-pace is relatively constant. They reviewed five, mainly European, studies that appeared to meet this condition and where the incident rates were 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, while in the single American study (Levin et al., 1985) they were 08:00, 16:00 and 24:00. In two of the studies there were equal numbers of workers on each shift (Quaas and Tunsch, 1972; Smith et al., 1994), while in the others the original authors had corrected the data to take account of inequalities in the number of workers (Levin et al., 1985; Wanat, 1962; Wharf, 1995). Finally, two of the studies provided two separate estimates of the trend in risk.

The seven data sets showed a considerable agreement in the nature of the trend across the morning, afternoon and night shifts, with the estimated peak occurring at about midnight (00:04; see Folkard et al., 2006 for further details). Based on the pooled frequencies, risk increased in an approximately linear fashion, with an increased risk of 15.2% on the afternoon shift, and of 27.9% on the night shift, relative to that on the morning shift. However, it should be noted that although this trend over the three shifts arguably overcomes most of the various confounding factors listed above, it was confounded by differences in time since waking.

These three types of study thus appeared to vary substantially in terms of their potential confounding, but yielded very similar estimates of the time of the peak in the risk of injuries. In all three cases, the peak was estimated to occur at around midnight, although the amplitude of the rhythm increased with the number of potential confounders (see Folkard et al., 2006). This suggested that the major impact of the confounding factors was to increase the amplitude of the 24 h patterning in risk rather than the phase. Most importantly, the estimated peak in injury risk occurred substantially earlier than would be expected from considerations of sleepiness or sleep propensity.

In conclusion, there appears to be good evidence for a circadian rhythm in the risk of traffic accidents and industrial injuries, but in both cases the peak occurs earlier than would be expected if it was solely mediated by variations in sleepiness. The most obvious explanation for this discrepancy would appear to be that the trends in risk are confounded by differences in other factors that contribute to overall fatigue, such as time since waking. However, such an explanation is difficult to reconcile with the finding that self-ratings of sleepiness increase over most of the night shift while the risk of injuries decreases. Further, sleepiness ratings are typically higher on the morning shift than on the afternoon shift, but the reverse trend is found for the risk of incidents. One alternative explanation for this discrepancy is that risk is substantially more affected by factors such as time awake than are subjective ratings of sleepiness and sleep propensity. Another possible explanation is that there is a complex interaction between the circadian and homeostatic factors in determining the risk of injuries and accidents, similar to that which has been found for mood (Boivin et al., 1997) and performance on a frontal lobe task (Harrison et al., 2007; see Section 2.1). Clearly there is a strong need for further epidemiological studies in this area that systematically explore the reason(s) for these relatively consistent differences in the trends in risk and sleepiness.

2.2. Safety outcomes: homeostatic factors

Reduction in the quantity or quality of sleep, or extension of the time awake since sleep, produces a sleep debt and a homeostatic drive to sleep. Similar fatigue-related performance problems are produced by short-term severe sleep restriction (e.g., getting only 4 h sleep the previous night) and chronic partial sleep deprivation (e.g., shortening one's sleep by an hour over several nights) (Van Dongen and Maislin, 2003). However, from a safety perspective, chronic sleep restriction may pose the greater risk, since individuals who are chronically sleep-restricted may be less aware of their level of impairment and less likely to take appropriate precautionary measures.

The impact of sleep restriction on safety outcomes is difficult to study using routinely collected data, as sleep histories are usually lacking. Therefore most of the evidence available for an association with safety outcomes comes from epidemiological studies. The majority of relevant studies have focused on car or truck drivers and the risk of crashes or near misses. Although some studies have examined the safety effects of sleep loss in air and sea transport, as well as occupational settings such as hospitals, the main focus here will be on the effects of sleep restriction on motor vehicle transport safety.

The effects of sleep restriction and time since sleeping on safety incident risk are commonly confounded by circadian influences and time on task, and in some circumstances by mental and physical workload issues that contribute to fatigue. This is because drivers or others operating in the early hours of the morning or for very long periods of time are more likely to be sleep deprived and to have been awake for long periods than others. Therefore the best studies of sleep patterns and risk are those which have measured and controlled for the effects of time-of-day, time on task and other sources of fatigue, along with other major confounders.

2.2.1. Sleep restriction and traffic crashes: Non-commercial vehicle crash studies

A systematic review of research into the association between sleepiness and car crashes in 2001 (Connor et al., 2001) failed to identify any good quality studies that could quantify the safety effects of sleep deprivation, although much of the research suggested an association. Since then, two prospective case-control studies have been published which both show an increase in car crash risk associated with short sleep duration. Cummings et al. (2001) demonstrated a continuous U-shaped relationship between sleep duration in the last 48 h and the risk of crashing, with the lowest risk at approximately 15 h of sleep. When compared with drivers who had 12 h of sleep (the reference group), those with $\leq$9 h or $\geq$ 21 h in the last 48 h had a statistically significant increase in risk, although this was not adjusted for time of day, time-on-task variables or alcohol. With 9 h of sleep in the last 48 h, the risk of a crash was slightly more than double the risk with 12 h sleep. Connor et al. (2002) studied serious injury car crashes in a regional population and identified 5 h sleep in the last 24 h as a threshold for increased risk. They calculated the odds ratio associated with 5 or fewer hours of sleep, compared with more than 5 h, to be 2.7 (1.4–5.4) after adjustment for demographic variables, alcohol use, and time of day. In this study, the average trip length was about 20 min, and time on task was not a significant confounder. Neither of these two case-control studies found significant associations of car crash risk with measures of chronic partial sleep restriction, such as no "full" nights of sleep (>7 h) in the last week, or with elevated Epworth Sleepiness Scale scores.

These results are supported by another population-based case-control study (Stutts et al., 2003) that relied on post-crash telephone interviews to examine a range of possible risk factors for a sleep-related crash. The unadjusted odds of a driver being in a sleep-related (versus non-sleep-related) crash increased with each hour reduction in sleep the night (or day) before. For drivers who reported sleeping 6–7 h, the unadjusted odds of their crash being sleep-related was 2.6 (1.6–4.1) when compared to drivers sleeping 8 h; for those sleeping 5–6 h, it was 9.8 (5.5–17.5); 4–5 h, 12.2 (6.2–23.9); and less than <4 h, 19.9 (9.9–39.9). The odds of being in a sleep-related crash was also found to be associated with higher Epworth Sleepiness Scale scores, with unadjusted odds of 1.44 (1.08–1.92) for scores of 6–11 ("moderate sleepiness"), 3.03 (2.01, 4.55) for scores of 11–15 ("heavy sleepiness"), and 6.07 (2.38, 15.53) for scores of 16 or higher ("extreme sleepiness"). The study also showed that drivers who rated their overall sleep quality as fair or poor (compared to excellent), and who felt they did not get enough sleep on a routine basis, were at significantly higher odds for involvement in a sleep-related versus non-sleep related crash.

2.2.2. Sleep restriction and traffic crashes: Commercial vehicle crash studies

Direct evidence of the role of reduced sleep in commercial vehicles crashes was produced in the NTSB study of 107 single vehicle heavy truck crashes in which the driver survived (National Transportation Safety Board, 1995). Based on a review of the driver's 96 h duty-sleep history and characteristics of the crashes, 58% of the crashes were judged to have been due to driver fatigue. Sleep patterns over the preceding 96 h were studied, and using discriminant analysis the strongest predictors of a fatigue-related crash were the duration of the last sleep period, the total hours of sleep in the last 24 h, and split sleep patterns. Drivers in fatigue-related crashes were found to have an average of 5.5 h sleep in the last 24 h compared with 8.0 h for drivers in other crashes. A subsequent reanalysis of these crashes using principal components analysis and cluster analysis (Young and Hashemi, 1996) described two types of drivers involved in fatigue related crashes. There were drivers with regular sleep/work patterns who developed fatigue while on the job, and those with irregular sleep patterns who arrived at work already fatigued. That is, the contribution of different component causes of fatigue varied between drivers involved in fatigue-related crashes.

In 1997, Arnold et al. (1997) published a large survey of Australian truck drivers which found that the 20% of drivers who had less than 6 h of sleep before their index journey reported 40% of hazardous events. These were loosely defined as "fatigue-related events, such as nodding off, near misses or crashes". Recently, Hanowski et al. (2007) confirmed the importance of sleep restriction in a naturalistic study with a cohort of commercial vehicle drivers which clearly demonstrated a reduction in sleep hours compared with usual sleep in the period preceding safety-relevant critical incidents under normal driving conditions. From a sample of 82 drivers, 29 drivers contributed matched data to the analysis which found a statistically significant reduction from a mean of 6.70 h of sleep to 5.25 h of sleep in the period before a (video-verified) incident ($p = 0.0005$). Possible effects of alcohol and drug use were not controlled in this study, but the design meant that many stable individual characteristics did not confound the findings.

2.2.3. Sleep disorders and traffic crashes

The influence of sleep disorders on safety outcomes has also been studied in transportation (see Smolensky et al., 2011). Sleep disorders can disrupt both the quantity and quality of sleep, leading to both chronic and acute sleep loss. The most prevalent disorder in the general population is obstructive sleep apnea syndrome (OSAS), a condition in which an individual is repeatedly awakened during sleep as a result of brief periods of stopped (or obstructed) breathing.

There is a large body of literature describing and reviewing studies of OSAS and crash risk in both commercial and non-commercial drivers (American Medical Association, 1998; American Thoracic Society, 1994; Connor et al., 2001; Expert Panel on Driver Fatigue and Sleepiness, 1997). While concluding that there is an association, most studies have been unable to reliably quantify the size of any increased risk due to limitations of study design, other biases or lack of power. Most studies have been carried out in special populations, as the prevalence in the general population is sufficiently low to make population-based studies problematic. As the level of sleep deprivation associated with OSAS of a specified severity will vary between individuals, and severity is not measured in a standard way, it is not surprising that findings are heterogeneous even among the better designed studies.

A few studies stand out as being more robust, and suggest a significant increase in risk of crashing amongst drivers affected by untreated OSAS. Amongst car drivers these include a case-control study conducted in two emergency departments in Spain (Terán-Santos et al., 1999). The odds ratio for a crash resulting in driver injury associated with any sleep apnea was 7.2 (2.4–21.8), and for drivers with severe OSAS it was 8.1 (2.4–26.5), after adjustment for potential confounders. A good quality cross-sectional study from a sleep clinic in California (Wu and Yan-Go, 1996) produced a multivariable adjusted odds ratio of 2.6 (1.1–6.3) for the association of OSAS with self-reported crashes or near misses, and the Wisconsin Sleep Cohort Study based in a general population (Young et al., 1997) found an increased risk in men for verified crashes (OR = 4.2 for mild OSA and 3.4 for severe OSA) but no association in women. A more recent retrospective survey of drivers with confirmed OSAS and matched controls (Horstmann et al., 2000) found a small increase in risk of fatigue-related crashes amongst mild apneics and up to fifteen-fold risk in severe apneics. Importantly this study controlled for driving exposure. Mulgrew et al. (2008) demonstrated not only an association of severity of OSAS with crash risk, but also a disproportionately increased risk of crashes involving injury in drivers with OSAS.

Amongst truck drivers, Stoohs et al. (1994) found a doubling of risk of crashes identified from company records in truck drivers with sleep-disordered breathing, once average mileage was adjusted for. However, no association was found with severity of the condition. In a more recent and much larger survey study by Howard et al. (2004), the 16% of truck drivers that were found to have OSAS had a 30% increased risk of a self-reported crash in the last 3 years (OR 1.30 (1.0–1.69)).

Demonstrating the reversibility of an effect by removing or reducing the risk factor can contribute considerably to the establishment of causality of an association. In the OSAS study by Horstmann et al. (2000) a reduction in car crash incidence was demonstrated when patients were treated with nasal continuous positive airway pressure (CPAP) for their OSAS, with crash rates falling to background levels. Reductions in risk with CPAP therapy have also been shown in a number of other studies (e.g.Cassel et al., 1996; Engleman et al., 1996; Findley et al., 2000; George, 2001; Krieger et al., 1997).

2.2.4. Sleep homeostasis and safety outcomes in other settings

Shift work schedules can result in sleep restriction; this adds to the effect of circadian factors and extended work hours on the level of fatigue experienced by shift workers (described above). Sleep is shortened and disrupted prior to early morning shifts and following night shifts, or as a result of extended working hours, but these effects are often not separated from other influences on fatigue in shift work research. In a health care setting, differences in work schedules for junior doctors have been studied systematically (Barger et al., 2005; Lockley et al., 2006; Mountain et al., 2007) and the contribution of sleep restriction to the frequency of errors has been demonstrated by some. In a single-centre randomized cross-over trial of 20 interns working on two different schedules, Landrigan et al. (2004) and Lockley et al. (2004) showed 36% increase in serious medical errors and nearly six times increase in serious diagnostic errors on a traditional on-call schedule with 24-h or longer shifts, than on a modified schedule that restricted continuous duty to 16 h. Serious medication errors were 21% higher on the traditional schedule. Much of the difference between the groups was attributed to the verified differences in sleep duration, with interns sleeping 5.8 more hours per week on the modified schedule. While the lack of ability to blind such a study is a potential weakness, demonstrating the reversibility of sleep-related risk provides convincing evidence of a causal relationship with unsafe events.

Case studies and case series in many other settings concluded that sleep restriction and deprivation contributed to fatigue that "caused" safety-related incidents. While this kind of evidence is weak in terms of establishing a causal link between sleep loss and safety outcomes, and in establishing the magnitude of the effect, it nevertheless suggests that the relationship is causal. A wide range of studies fall into this category, including studies of the causes of "accidents" and other adverse safety outcomes (e.g., critical errors in hospitals, on-the-job injuries and fatalities) in other modes of transport (e.g., aviation, rail, maritime, commercial bus), and in other occupational settings. While a full review of this vast literature is beyond the scope of this paper, a few of the larger studies are reviewed briefly below.

Studies of fatigue in train drivers that involve safety outcomes are mostly case series and case reports, and generally lack detailed information about recent sleep patterns and other potential causes of fatigue. However, Kecklund et al. (1999) reported from the Swedish TRAIN study that of 79 safety-related incidents, 13 (17%) were judged to be fatigue-related and sleep restriction accounted for half of the fatigue-related crashes and about 9% of all incidents. Sleep restriction is also a recognized component of the fatigue that increases risk in seafaring and aviation (Allen et al., 2007; Gander et al., 2008; Hetherington et al., 2006; Phillips, 2000; Wadsworth et al., 2006).

Research into the association between sleep restriction and safety in industrial settings has recently been reviewed (Philip and Åkerstedt, 2006). The authors noted that impaired or shortened sleep is a major cause of accidents in industry as well as transport, but recognize the greater challenges of demonstrating this effect in industrial settings due to the more varied environment and less constant demand on vigilance and performance. Ulfberg et al. (2000) found that occupational accidents (not including driving) were much more commonly reported by OSAS patients than controls (OR = 6.3 (1.6–26) in men; 1.5 (1–11) in women), but work task and work hours were not controlled for. Self-perceived sleep debt was linked with both driving and non-driving accidents at work in a later study by this group (Carter et al., 2003). There have been a number of other studies of this nature, where exposure measures are self-reported and poorly defined, and confounders commonly not considered (Philip and Åkerstedt, 2006). These have found some positive results, but also inconsistencies such as a strong effect of insomnia on the risk of industrial accidents, without an increased risk of driving accidents (Leger et al., 2002). Lindberg et al. (2001) found that using Swedish government records, clinic patients with OSAS were 2–3 times more likely to have an occupational injury in a 10-year period than employed control subjects (cited in Young et al., 2002), but there has been no large population based study of OSAS and occupational accidents.

Finally, a study of fatal occupational injuries using data from a 20-year longitudinal Swedish health survey found that workers who reported having difficulties sleeping in the past two weeks were significantly more likely to die from a work-related injury (RR = 1.89 (1.22–2.94)) (Åkerstedt et al., 2002). Although the authors concluded that self-reported disturbed sleep was a predictor of accidents at work, they were unable to directly link reported sleeping difficulties to the time of death, and also lacked information on potential confounding variables, such as factors contributing to workers' sleeping difficulties.

In conclusion, there is considerable evidence from motor vehicle crash studies that sleep restriction is associated with increased risk of crash involvement. Evidence for a causal association is strongest with respect to acute, severe sleep loss, but has also been shown with respect to chronic partial sleep restriction. Since most of the research has been conducted in uncontrolled "real world" conditions with highly variable contextual factors and substantial measurement error, it is not possible to estimate reliably the magnitude of risk associated with sleep restriction. No crash studies have linked time since last sleep, another homeostatic measure, to an increase in crash risk.

Evidence gathered from other forms of transport, and from studies in occupational settings examining outcomes other than crashes, offers additional support linking homeostatic risk factors to negative safety outcomes. However, with the exception of recent studies of resident work hours carried out in hospital settings, and studies directed at OSA patients, most of these do not provide conclusive evidence linking lack of good quality sleep to adverse safety outcomes.

2.3. Safety outcomes: task-related factors

2.3.1. Safety outcomes: Time-on-task factors

Time-on-task is considered to induce workplace fatigue (mental including cognitive and affective, and physical) and is often examined as a surrogate exposure measure in evaluating the association with "accident" and injury risk in industrial and occupational settings. Time-on-task can be defined in various ways, and is often referred to as time on duty, time into the work shift, or driving time. The following are examples of time-on-task and how they may increase the risk of adverse safety events:

- A machinist working in a plant awakes at 6:00 a.m., arrives at work at 7:00, works through both the rest break and lunch to finish up a product for shipment.
- A cross-country truck driver is on the 12th hour of continuous driving without an over-night stay at a rest-stop.
- An air-traffic controller is in the third hour of work during the heavy flight traffic holiday periods.

In each of these illustrative scenarios, time-on-task is either modified or potentially confounded by the starting time for a workday or task (for example, prolonged driving), time since awaking, amount of time doing the task, duty time, and time since last break. It has been documented that time-on-task contributes as an important factor related to the risk of an "accident" or work injury; however few studies have been properly designed or made statistical adjustments for controlling for potential confounders such as the impact of work breaks, circadian rhythms, time-of-day or shift scheduling.

The distribution of time into the work shift of injuries and accidents is fairly well characterized and is most frequently reported to peak in the first half of the workday (Macdonald et al., 1997; Folkard, 1997) with a second peak occurring after prolonged work (Oginski et al., 2000; Hanecke et al., 1998). With respect to time into the work shift or time-on-task as related to the occurrence of an injury, a study of 2,425 accident records indicated a peak in accidents during the second and third hours into the shift (Macdonald et al., 1997). Adverse safety events such as crashes have a tendency to peak at certain times relative to the time-of-day and time-on-task: for example a meta-analysis of transportation accidents reported that 2–4 h into the time-on-task is the peak risk period for these events (Folkard, 1997).

Consistent with transportation injuries, a case-crossover study of traumatic hand injury (Lombardi et al., 2003) which included 1166 workers distributed primarily among machine trades (32.8%), service workers (14.9%), and construction (14.8%) reported that the largest percentage (54.6%) of hand injuries occurred in the 4-h morning period from 08:00 to 12:00, with a peak during 10:00–11:00 (14.9%). Also, with regards to time to injury since the start of the work shift, 11.4% of all injuries occurred within the first 60 min of the workday. After the first hour, 16% of injuries occurred within each of the next three hourly periods, so that overall, injuries were greatest from the beginning of the work shift up until the end of the fourth hour (59.9%).

A recent review of injury and accident data from four studies (three of which were large national based populations) in relation to successive hours on duty (Folkard and Lombardi, 2006) found that apart from a slightly heightened risk from the second to fifth hour, overall trends in risk increased in an approximately exponential fashion with time on shift, after correcting for “exposure”. The increased risk during the second to fifth hour has also been reported in a number of other studies. The review also demonstrated a drop in relative risk between 5 and 6 h into the shift but risk increased exponentially over the remainder of the work shift. It was hypothesized that the decrease in risk after the fifth hour represents a beneficial effect of rest breaks (see following section for further details). In contrast, the increased risk during the second to fifth hour has been argued to reflect a decrease in controlled, effortful processing that has been insufficiently compensated for by increased automated processing with time-on-task (Folkard, 1997).

2.3.1.1. The impact of rest breaks on time-on-task. Few studies have examined the critical issue of the impact of rest breaks on reducing the adverse effect of increased time-on-task. Tucker et al. (2003) reported a fairly linear increase in risk between successive breaks. However, in a more recent reanalysis of two studies, Tucker et al. (2006) found an initial increase in risk from the first to the second half-hour following a break, but little evidence for a consistent linear increase over subsequent half-hour periods. In the first study (Smith et al., 1994), on-duty injury data from two similar production engineering companies were recorded for a workforce of approximately 4250 shift workers that included 4645 incidents over a 12 months period. With respect to continuous time-on-task between breaks, the results suggested that there was an initial increase in risk from the first to the second half-hour on task. However, a variety of trends was observed in the subsequent half-hours with the trends differing dependent upon the degree of work pacing.

The second study used data from a multi-center, interview-based, case-crossover study designed to assess risk factors for acute traumatic occupational hand injuries (Lombardi et al., 2003; Sorock et al., 2003). The analyses focused on the effects of a break for workers who either reported having a break in the 90 min leading up to the injury, or whose injury occurred within 90 min of the start of their shift. Work shift start time and time of injury were available for 1163 subjects, and the elapsed time since the end of the break or the start of the shift was calculated for each subject. A total of 407 injuries was reported as having occurred within 90 min of the last break or since the start of the shift. There was a statistically significant effect of elapsed time-on-task; where injury risk was lower in the first half-hour, relative to risk in the subsequent half-hours, but remained relatively constant between the second and third half-hour. Gender was also examined in this study and the pattern was the same for men and women. Tucker et al. (2006) concluded that rest breaks are an effective means of offsetting the accumulation of risk as a function of time-on-task during industrial shift work; however it was suggested that the beneficial effects of rest breaks may be relatively short-lived in at least some work environments.

2.3.1.2. Time of day and time-on-task. In relation to the association between time-on-task and accident or injury risk, an important question is whether this risk is independent of time of day (or other factors confounded with time of day, such as traffic density or task cycles). The importance of a potential interaction among these two factors cannot be overstated, since each factor can increase or decrease the effect of the other.

In one large study involving 80 drivers who had completed more than 200,000 miles of highway driving following one of four driving schedules, a number of performance and alertness parameters were examined (Mitler et al., 1997; FMCSA, 1996). The authors reported that driver alertness was more consistently related to time of day than to cumulative time-on-task (i.e., time-on-duty).

In comparison, in several other studies where continuous time-on-task between breaks was examined for workers from industrial environments, accident risk was reported to be independent of time of day as the increase in risk was consistently observed across all shifts (Tucker et al., 2006; Wharf, 1995). One explanation proposed by Tucker et al., is that this may be due to the monotony of the task. Gillberg and Åkerstedt (1997) offered a similar explanation for the findings of their study of sleep loss and performance. In that study, although performance was affected early in the task, the decrease in rate across time on task was similar across the duration of the experiment.

In summary, the research to-date suggests that injuries and accidents peak in the first half of the workday, with a second peak occurring after prolonged work. With respect to continuous time-on-task between breaks, there is an initial increase in risk from the first to the second half-hour on task. These trends differ by factors such as work pacing and timing of rest-breaks. Also, with respect to the interaction among time of day and time-on-task, more research is needed since the results appear to be inconsistent across studies.

2.3.2. Safety outcomes: workload related factors

The nature of work tasks, such as monotony, boredom, and lack of stimulation, can also contribute to physical and mental fatigue and may increase safety risk. Carskadon and Dement (1987) suggested that rather than causing fatigue, monotony “unmasks” underlying sleepiness and referred to this as latent sleepiness becoming manifest in low-stimulus situations.

In the context of traffic safety, the monotony of driving at night and motorway driving are of particular concern, especially for long trips. The term “highway hypnosis” or “white line fever” is often used by drivers to describe the loss of conscious awareness that can result from the sameness of a long stretch of roadway. Relevant research on the topic is restricted to descriptive studies. In the U.S., 55% of drowsy driver crashes identified by police occur on high-speed roadways, and 52% occur at nighttime between the hours of 10PM and 6AM (Stutts et al., 2005). Surveys by Horne and Reyner (1995a, b) found a higher proportion of fatigue-related crashes on motorways (20%) than for accidents in general (16%). An audit of traffic crashes in the UK (Flatley et al., 2004) identified 17%

of crashes as being sleep-related, but that this proportion varied from 3 to 30% depending on the type of road. The finding that higher traffic density was associated with a higher number of sleep related crashes in city driving but protective on motorways suggested that lack of stimulation was increasing risk. Artificial lighting on motorways decreased sleep-related crashes a little, but longer daylight in the summer did not.

In reports of a case series of train crashes (Edkins and Pollock, 1997) and prospectively collected data on critical incidents in trains (Kogi and Ohta, 1975), the authors emphasized the contribution of monotony to crash causation. Keckl und et al. (1999) compared the nature of train drivers' work to motorway driving.

Apart from monotony, other characteristics of the work environment and task may contribute to physical or mental fatigue and increase safety risks, but again there is little direct evidence. In the GAZEL cohort of 20,000 French drivers, Chiron et al. (2008) measured a range of work characteristics and found two indicators of self-reported work fatigue associated with the occurrence of at-work crashes, after adjusting for health status, location of residence, type of family, transport mode and mileage. These were "nervously tiring work" for males (RR = 1.6, (1.1, 2.3)), and sustained standing for females (RR = 3.0, (1. 8.4)). "Nervously tiring work" was not specifically defined but was contrasted with "physically tiring work", implying a high mental workload. With respect to crashes while commuting, a self-reported uncomfortable position at work was a risk factor among women (RR = 1.9, (1.1, 3.3)). These occupational factors were not linked to road crashes in private trips.

In conclusion, the literature with respect to the effects of workload on driver alertness and safety is limited to descriptive analyses of crash data, along with case series investigations of safety incidents in other transport arenas, most notably rail. There is some limited evidence that specific work characteristics can affect safety, related to mental and muscular fatigue rather than to sleepiness. We found no controlled studies documenting boredom and monotony as causal factors in fatigue crashes, either as independent risk factors or in combination with known causes of sleepiness, such as sleep deprivation or circadian troughs.

2.4. Safety outcomes: evidence from measures of fatigue

Evidence of the link between fatigue and safety is also available from studies that attempt to focus on fatigue directly rather than on the factors that cause fatigue as discussed in the previous sections. Some studies use a single global measure of fatigue, which may or may not be tied to any specific fatigue cause(s). These overall measures may be subjective (i.e. self-reported fatigue or sleepiness) or may combine measures of causal factors to construct a composite fatigue measure or index. Sometimes an overall assessment of fatigue is derived from the nature of the crash or other adverse safety event (e.g., a crash where there is no evidence of any avoidance maneuver being taken by the driver), or from directly observed signs of driver fatigue. The next sections examine the evidence of the fatigue-safety link from studies using these different approaches.

2.4.1. Self-reported fatigue or sleepiness

Self reported measures of fatigue or sleepiness are based on the participant's recognition of manifestations of fatigue. However, there is considerable variability in individual abilities to recognize fatigue (Horne and Baulk, 2004; Kaplan et al., 2007), and in most studies there is potential for recall bias to affect estimation of fatigue once an incident has occurred. Both acute sleepiness (which may be measured using the Stanford Sleepiness Scale or the Karolinska Sleepiness Scale, for example) and chronic daytime sleepiness (often measured with the Epworth Sleepiness Scale (ESS)) have been used as exposure measures in studies of safety-related events, as well as less validated instruments.

Since acute sleepiness is a transient exposure it is difficult to measure reliably in epidemiological studies. Acute sleepiness has been estimated with retrospective measures over a short and specific recall period in two prospective case-control studies where it has been a strong predictor of crash risk (Connor et al., 2002; Cummings et al., 2001), but may be affected by recall bias. In a prospective cohort study, the French GAZEL cohort of car drivers (Nabi et al., 2006) collected baseline data on self-reported frequency of driving while sleepy and then identified serious road traffic crashes in the following three years. Compared with drivers who reported not driving while sleepy in the last 12 months, those who did so a few times a year had an odds ratio of 1.5 (1.2–2.0), and those who did so once a month or more had three-fold risk (OR = 2.9 (1.3–6.3)), after adjustment for many potential confounders and without being affected by recall bias. These studies suggest that drivers who are aware of being sleepy have a higher average crash risk than those who are not, even though it is unlikely to be a reliable reflection of level of fatigue in everyone.

More commonly, participants in studies are asked about usual or chronic daytime sleepiness. In driver studies, the association of the Epworth Sleepiness Scale with crash risk has been inconsistent. Descriptive studies have found a positive association between ESS and the risk of a crash in car drivers (e.g. Maycock, 1996; Stutts et al., 2003) and in truck drivers (e.g. de Pinho et al., 2006). In a survey of 2342 randomly selected Australian commercial vehicle drivers (Howard et al., 2004), 24% of drivers had excessive sleepiness, and increasing sleepiness was related to an increased crash risk. The sleepiest 5% of drivers on the Epworth Sleepiness Scale and Functional Outcomes of Sleep Questionnaire had around twice the risk of a crash, adjusted for established risk factors. In the Stutts et al. (2003) study cited earlier, an Epworth score of 11–15 (described as heavy sleepiness) was associated with an almost three-fold greater odds of involvement in a sleep-related versus non-sleep-related crash, while an Epworth score of 16 or greater (extreme daytime sleepiness) was associated with a nearly six-fold increase in odds for involvement in a sleep-related crash. In contrast, the case-control studies of Connor et al. (2002), Cummings et al. (2001) and Terán-Santos et al. (1999) found no significant association between ESS and crash risk in car drivers, although findings for other sleep-related exposures were positive.

Evidence from workplace studies also suggests a link between self-reported daytime sleepiness and accident risk. In a study of 532 workers in eight industrial plants in Israel, excessive daytime sleepiness (defined as Epworth Sleepiness Score >10) was found to double the risk of occupational injuries (Melamed and Oksenberg, 2002). More than 90% of those with Excessive Daytime Sleepiness (EDS) reported being affected for more than two years. Data on injuries were extracted from company records and included minor injuries that did not require time off work. The Swedish study by Lindberg et al. (2001) reported a similar doubling of risk for workers who reported both snoring and EDS.

2.4.2. Model-based indices of fatigue or sleepiness

Other measures that combine different causes of fatigue include model-based predictors of fatigue where the inputs are data on both homeostatic and circadian factors. These include the "Sleep-Wake Predictor" which models level of sleepiness based on hours of sleep, time since waking, and time-of-day. This measure is associated with significantly increased risk of serious injury car crashes (Åkerstedt et al., 2008). Predictive models are covered in detail in Dawson et al. (2011).

2.4.3. Direct observation

Recently, video and other in-vehicle technologies have made it possible to conduct "naturalistic driving" studies that allow for more direct assessment of the relative risk associated with various levels of driving behavior and performance. In the U.S., volunteer drivers drove 100 instrumented vehicles (either their own or a vehicle loaned to them by the project) over a period of 12–13 months, yielding 43,000 h of driving data, including video of their faces as well as of the forward roadway (Klauer et al., 2006a,b). Determination of driver drowsiness was based on a review of the driver face video, observing signs of slackness in the facial muscles, limited overall body movements, and reductions in eye scanning behaviors (indicative of moderate drowsiness), along with extended eye lid closure and difficulties keeping the head in a lifted position (severe drowsiness). During the 12–13 month study period, the 241 primary and secondary drivers who participated in the study were involved in 69 eligible crashes (including non-police-reported events) and 761 near-crashes. Analysis of the data revealed that the odds of being involved in a crash or near crash were nearly three times higher when the driver was drowsy, compared to not being drowsy (OR = 2.9). The estimated population attributed risk, or PAR, for driving while drowsy, taking into account the prevalence of the behavior in the driving population, was 22–24% of all crash and near crash events

2.4.4. In-depth crash investigations

In-depth crash investigations represent another area of research where determinations of driver fatigue are based on a consensus of factors and circumstances. In standard police crash investigations, relatively little information is available to the investigating officers; however, in in-depth crash investigations, considerably more data is often gathered and analyzed. An example of this type of study is the Large Truck Crash Causation Study (Craft, 2007). The study involved collection of over 1000 variables on 1123 large trucks involved in 963 serious injury crashes occurring in 17 U.S. States. Drowsiness was cited as a causative factor in 13% of the crashes, and was associated with an 8-fold increase in crash risk.

In conclusion, studies linking estimates of fatigue using a range of measures and safety outcomes have consistently demonstrated higher crash or accident risk with higher frequency of experiencing sleepiness.

3. Link between the causes of fatigue and performance outcomes

This section looks at the evidence for the relationship between the same causes of fatigue as in the first section and adverse effects on performance which may mediate or intervene between these factors that increase fatigue and adverse safety outcomes.

Why should fatigue affect performance? Current theories of the effects of fatigue on performance are based on the concept of the regulation of effort and that fatigue states are associated with a loss of task-directed effort. For example, the Compensatory Control model which was developed to explain the adaptive effects of stressors on performance (Hockey et al., 1998) has been extended to explain the effects of fatigue. According to compensatory control theory, fatigue-inducing conditions like sleep loss affect the way that effort is regulated. Sleep loss produces fatigue and as a result both decreases the operator resources available to the task and increases the effort required to perform the task. Performance effects due to fatigue are mainly on secondary task activities, since primary task activities are protected (Hockey et al., 1998). Similarly, task-induced fatigue states due to high workload or long duration, monotonous tasks for example, are associated with loss of task-directed effort and poorer performance as a result (Matthews and Desmond, 2002).

Not all performance functions may be sensitive to fatigue. Dinges and Kribbs argue that studies need to be looking at the right kind of indicators and have made a strong case for use of the psychomotor vigilance task and a set of specific measures of response lapsing and slowing (Dinges and Powell, 1985; Dinges and Kribbs, 1991; Kribbs and Dinges, 1994). Matthews and Desmond argue that fatigue effects need to be evaluated across a broad range of performance indicators in order to determine which performance functions are affected. Studies that cover a range of measures show variation in the effects of fatigue on task performance. Where previously it was argued that fatigue effects occur mostly in complex cognitive tasks (Bonnet, 1994; Pilcher and Huffcutt, 1996), recent studies have demonstrated effects on simple tasks rather than complex tasks (e.g., Williamson et al., 2001; Pilcher et al., 2008). Many studies have emphasized that sustained or prolonged tasks are most vulnerable to fatigue, but fatigue-related performance decrements have also been shown in short duration tasks (Gillberg and Åkerstedt, 1998).

Much of the evidence of fatigue effects on performance comes from laboratory and simulator studies of performance. The obvious advantage of these studies is the level of control over many of the variables that confound studies in the field. The disadvantages are that laboratory and simulator studies are alleged to be more vulnerable to fatigue effects since real life circumstances involve more inherent stimulation (Åkerstedt et al., 2005). This has been found in comparisons of the effects of sleep deprivation on car driving performance (Philip et al., 2005) and motorcycle performance (Bougard et al., 2008) in the laboratory and on-road.

Furthermore while simulators are more like the real-world, the consequences of performance decrements are not the same as in the real world, and the implications of performing poorly are not as great. Individuals consequently may not exert the same degree of effort to overcome fatigue effects in laboratory or simulator studies, which could explain why performance decrements are found more often in simulator studies than in the field (Philip et al., 2005).

Performance on real world tasks may be less affected by fatigue due to greater compensatory effort because of the risk of negative consequences (e.g., crashes), or because real-world tasks are often inherently more interesting and engaging than simulator or laboratory task (Hockey et al., 1998). It is also possible that real world effects will be on secondary aspects of the task such as response variability rather than overall reaction speed or concentrating on one aspect of the task (such as keeping the car on the road) at the expense of other aspects (such as paying attention to road signs). This would help to explain the comparative infrequency of safety-related outcomes in fatigued individuals.

Individual differences may also play a significant role in the relationship between fatigue and performance. A review by Van Dongen et al. (2005) highlighted the very large contribution of individual variability (up to 92% variance) to the prediction of performance effects during sleep deprivation, and provided evidence of considerable within-individual consistency in cognitive performance during sleep deprivation. The authors suggested that individual responses to sleep loss may be a characteristic trait of each individual.

Galliaud et al. (2008) tested the trait hypothesis by dividing study participants into vulnerable and resistant groups on the basis of their response to sleep deprivation and their relationship between EEG-confirmed sleep pressure and reaction time performance. Although EEG changes over increasing sleep loss did not differ between the two groups, only the vulnerable group showed deterioration in reaction speed: the resistant group showed little performance deterioration. Individual differences clearly are an area of further research needed to understand the link between causes of fatigue and performance effects.

3.1. Performance outcomes: circadian factors

There have been two narrative reviews of circadian rhythms and performance (Colquhoun, 1982; Carrier and Monk, 2000).

Colquhoun concluded that there was evidence for an underlying circadian rhythm in performance, but that the dimensions of the performance rhythm are affected by a wide range of influences – including task-related, individual characteristics and situational characteristics including the level of fatigue – such that time on task and sleep deprivation affect the shape of the performance rhythm. Carrier and Monk's review supported this overall conclusion but argued that:

- Time-of-day effects depend on the type of performance function being measured.
- Time-of-day effects inevitably interact with homeostatic effects, making it difficult to analyse the contributions of each to changes in alertness and performance. In forced desynchrony studies which separate time-of-day and sleep homeostasis effects by imposing a wake–sleep schedule that is shorter or longer than the 24-h natural period a wide range of performance functions have been shown to exhibit rhythms that correlate with body temperature. Performance and temperature minima occur close in time.
- The influence of hours since waking is at least as strong as circadian influences on performance, and the differences in performance functions or tasks are more likely due to sleep homeostasis factors.

Certainly the research since the 2000 review has not challenged these conclusions to any significant extent. A number of recent studies have attributed performance decrements to circadian influences, but due to lack of appropriate controls in many of the studies, the changes can be accounted for by other influences. For example, Contardi et al. (2004) found evidence of circadian variation in a range of measures in a driving simulator task, but these effects were confounded by sleep deprivation as no sleep occurred from the start of testing at 10am for over 24 h. Another driving simulator study (Moller et al., 2006) also showed circadian fluctuations which could also be accounted for by time awake effects as all decrements occurred at or near the end of testing.

Stronger evidence of circadian effects can be seen in a simulator study of motorcycle riding performance that showed worse performance at 6:00 a.m. (close to the circadian trough) than at 6:00 pm when riders were rested, but not when sleep deprived (Bougard et al., 2008). This apparent circadian pattern cannot be due to sleep deprivation or time awake which would have produced the opposite effects, although testing with other combinations of time-of-day and sleep deprivation is needed to confirm the performance link with circadian changes.

Generally there is strong evidence that sleep homeostasis effects must be accounted for in interpreting circadian influences on performance. Studies by Macchi et al. (2002) and Graw et al. (2004) showed that if sleep deprivation effects are reduced by strategic napping, the circadian effects either disappear or are greatly reduced. Further, a study by Williamson and Friswell (2008) which started a period of 28 h of sleep deprivation for two rested groups at 6:00 am or 12:00 am found that adverse circadian effects on performance only occurred in combination with high levels of sleep loss. Circadian influences alone had no adverse effects on performance on any test.

There is also evidence that task type interacts with circadian influences (Folkard and Monk, 1985). Early studies demonstrated that memory varied with circadian rhythm such that long term memory performance was better if material was learned at night compared to the morning, and even better if night learning was followed by a period of sleep (Hockey et al., 1972). Anderson et al. (1991), however, found that memory performance also depends on diurnal type, with performance declining over the day for morning-type individuals but improving for evening-types. Studies of short term memory effects, on the other hand, have shown mixed relationships with circadian rhythms. Davies et al. (1984) showed that the short term memory component of a successive discrimination vigilance task was performed better in the morning than the afternoon, even though the vigilance decrement did not show a circadian effect. In contrast, Wyatt et al. (1999) found that short term memory declined with time since waking, but not with time-of-day. Clearly, further research is needed to clarify the relationship between circadian influences and memory processes.

Recent work has focused on circadian changes in executive control processes. Diurnal changes have been found for measures that required active inhibition of responding but not for aspects of the task that are automatic and predictable (Manly et al., 2002). However this study again suffered from potential confounding due to time awake influences. A follow-up study using the same performance measures by Harrison et al. (2007) used a forced desynchrony protocol in which continuous time awake and time asleep periods were imposed in a 2–1 ratio for 28 h over seven 24-h days. The authors failed to find performance effects of circadian or time-of-day influences alone, but the combination of time awake and circadian influences produced poorer inhibition of responses. Again, speed of response and automatic, predictable response showed no circadian effect. These studies call into question the independent effects of circadian influences, at least for tasks involving attentional control.

In conclusion, the comparative paucity of evidence and inconsistency of the findings available on circadian effects on performance indicate that further research is needed to clarify this relationship. It seems that there is evidence for a circadian component in some performance measures that, in general, is similar to body temperature. Other measures show no main circadian effect, but do show an interaction with time since waking. A number of recent studies that have used methodologies like strategic napping and forced desynchrony that attempt to separate sleep homeostasis and circadian influences have failed to show time-of-day effects on performance. It is possible that the heart of this problem lies in variations in the circadian effects on different performance measures.

3.2. Performance outcomes: homeostatic factors

Reviews of the relationship between sleep deprivation and performance have concluded consistently that there is clear evidence for the link. An early narrative review (Krueger, 1989) concluded that total sleep loss or fragmented sleep resulted in poorer reaction time, decreased vigilance, perceptual and cognitive distortions and affect changes. Further, a critical narrative review by Dinges and Kribbs (1991) of the nature of the effects of sleep deprivation on performance refined these conclusions. Dinges and Kribbs reviewed the history of the evidence on performance decrements due to sleepiness. They argued that fatigue effects on performance could be characterised:

- primarily by performance variability especially in lapses in performance as well as memory problems, accelerated vigilance decrement and shifts in optimum performance;
- performance decrements occurring especially during self-paced tasks (contrary to Bonnet who concluded the opposite);
- visual functions affected first (e.g. RT);
- decrements in short term and long duration tasks, especially for sustained attention tasks and in simple rather than complex tasks.
- Dinges and Kribbs argued strongly for the importance of the evidence of performance effects due to sleep loss.

A third narrative review by Bonnet (1994) also highlighted the critical nature of the sleep loss-related performance effects. Consistent with the previous reviews, Bonnet concluded that behavioral effects due to partial and total sleep deprivation in humans were consistent and well-defined, including greater performance decrements for tasks that have long duration, do not provide knowledge of results, are externally paced or fast paced, are less well-practiced and involve immediate recall.

A systematic meta-analytic review was conducted by Pilcher and Huffcutt (1996). This meta-analysis included 19 papers published on the performance effects of short and long total sleep deprivation (defined as 45 h loss of sleep or less, and more than 45 h sleep loss) and partial sleep deprivation (less than 5 h sleep). The review compared short and long duration cognitive (≤6 min and ≥10 min) and motor (≤3 min and ≥6 min) performance tasks as well as mood effects. The meta-analysis showed that the performance of sleep deprived groups was poorer than that of non-sleep deprived controls, but there was considerable variation in the effect size between studies and no attempt was made to take account of the variability between effect size estimates (Balkin et al., 2004).

More recent studies have continued to confirm the link between sleep deprivation and performance decrements in laboratory (Belenky et al., 2003), simulator (Fairclough and Graham, 1999; Lenne et al., 1997) and occupational and other real-world settings (Drory, 1985; Philip et al., 2003a).

One group of studies examined the comparative importance of sleep deprivation effects on performance against an established benchmark of alcohol consumption. In the laboratory (Dawson and Reid, 1997; Lamond and Dawson, 1999; Williamson and Feyer, 2000; Falleti et al., 2003; Roehrs et al., 2003), in a driving simulator (Fairclough and Graham, 1999; Arnedt et al., 2001), and on a closed track (Powell et al., 2001), performance while sleep deprived was at least as poor as performance while at the legal limit for alcohol consumption for driving (either 0.05% or 0.08% blood alcohol concentration). The importance of these studies is that they all demonstrated effects on subjective fatigue and performance and consistently showed that the magnitudes of these effects were at a level judged to compromise road safety.

3.2.1. Sleep homeostasis effects on specific performance functions

Some of the recent studies provide further understanding of the types of performance functions most affected by sleep deprivation. The simple reaction time test is the most widely used performance measure in studies of sleep loss, usually in the form of the Psychomotor Vigilance test (PVT) (Dinges and Powell, 1985). A number of authors maintain that simple reaction time and the PVT in particular are most sensitive to the effects of sleep loss and fatigue (Gillberg et al., 1994; Dinges et al., 1997; Balkin et al., 2000; Dorrian et al., 2005; Philip et al., 2001) and that variability of response (lapses in responding, patterns of the longest responses, etc.) is the most sensitive measure of simple reaction time performance (Dinges and Kribbs, 1991). The PVT test has also been the focus of studies attempting to reveal the underlying causes of performance changes due to sleep loss. For example, there is evidence that PVT performance varies with objective measures of sleepiness (Mean Sleep Latency Test), suggesting that these outcomes may share a common origin (Franzen et al., 2008). Drummond et al. (2005) used functional magnetic resonance imaging to examine the brain regions involved in extreme reaction times on the PVT under well-rested and sleep deprivation (36 h) conditions. This study demonstrated that slow reaction times under sleep deprivation conditions occurred when neural activity involved brain regions identified as the ‘default mode’ or the baseline working state of the brain, which occurs when the person is not actively cognitively involved. Poor performance on the PVT was consequently attributed to disengagement from the task and inattention. PVT performance correlated well with a number of driving performance measures taken in a simulator, but the relationship deteriorated with increasing time without sleep (Baulk et al., 2008).

Despite the concentration on the PVT, a few studies have compared the effects of sleep loss on a range of performance functions. Williamson et al. (2001) compared 28 h of time awake with varying doses of alcohol using a range of eight performance tests and found that while alcohol impaired performance on all tests, sleep loss had effects on simple tests involving monotony, passive concentration and difficult visual discrimination. A similar study of 24 h of wakefulness also using a broad range of cognitive performance tests showed a greater effect on the speed of simple detection responses than for any other performance measures (Falleti et al., 2003). A study of the effects of three nights of sleep restricted to only 4 h (Stenuit and Kerkhofs, 2008) also showed impairment in speed of execution rather than accuracy, again, predominantly for simple tests.

These findings together with those from the studies using the PVT reinforce the effort compensation hypothesis that simple, unstimulating tasks that demand attention are most vulnerable to the effects of sleep loss due to its de-arousing nature (Dinges and Kribbs, 1991). According to this hypothesis, more complex cognitive tasks are spared, as their greater interest and activating effects produce compensatory efforts to maintain performance.

Harrison and Horne (2000) challenged the applicability of this latter interpretation in the real world on the basis that some complex cognitive tasks, especially those involving the prefrontal cortex, are also vulnerable to the effects of sleep loss. Research findings since this review have tended to be supportive (Nilsson et al., 2005; Thomas et al., 2000). Research on the effects of 35 h of sleep deprivation by Drummond and coworkers, for example, showed that verbal learning (Drummond et al., 2000), serial subtraction (Drummond et al., 1999) and divided attention (the first two tasks combined in a dual task, Drummond and Brown, 2001) were impaired in sleep deprived compared to rested conditions. Functional Magnetic resonance imaging (fMRI) conducted at the same time as task performance demonstrated task-dependent activation of the prefrontal cortex and parietal lobes, with increased activity during verbal learning and divided attention, but decreased activity for the serial subtraction task. This led the authors to conclude that cerebral responses are adaptive to the cognitive demands of the task. Further work has demonstrated that this compensatory response is facilitated by task difficulty (Drummond et al., 2004). Notably, even though 35 h of sleep deprivation did not affect performance on this task (logical reasoning), the cerebral response varied directly with task difficulty, suggesting that maintenance of cognitive function during sleep loss is achieved by compensatory changes in cortical activation. Recent work by Killgore and colleagues provided further evidence of the importance of the prefrontal cortex. They used odor identification accuracy as a measure of orbitofrontal cortex function and showed significant decrements in odor identification after 24 h of wakefulness (Killgore and McBride, 2006) and that individuals with higher odor identification abilities were more resistant to cognitive decrements over 77 h of sleep deprivation (Killgore et al., 2008).

Memory lapses have been identified as a significant contributor to many accidents (e.g., Reason, 1990; Shorrock, 2005), although studies of memory function under sleep loss conditions have shown mixed findings. Drake et al. (2001) found that probed-recall memory was sensitive to rapid (0 time in bed for one night) and intermediate (4 h time in bed for two nights) but not slow (6 h time in bed for four nights) accumulation of 8 h sleep loss. Smith et al. (2002) using a high and low memory load task demonstrated that speed and accuracy of performance deterioration commenced as early as 1 h after usual bedtime. Turner et al. (2007) showed decreased memory span and attention in a verbal working memory task under conditions of 42 h of total sleep deprivation. In contrast, visuo-spatial working memory with delayed free recall was not affected by one night without sleep (Nilsson et al., 2005) whereas supervisory control of executive functioning was affected in this study. Further research is needed to clarify the effects of sleep loss on memory function.

Response inhibition or supervisory control has been the focus of a few recent studies, and while all showed a significant impairment in performance with increasing sleep deprivation, the nature of the performance effect differed. Two studies using very similar types of tasks (sustained attention to response, Harrison et al., 2007; "Go-NoGo" task, Drummond et al., 2006) showed increasing difficulty in withholding responses with increasing time awake. A further study using a more complex choice reaction time task in which time to prepare for the response was varied (Jennings et al., 2003) showed that sleep deprivation specifically impaired the development of optimal preparatory strategies for responding when under time pressure, but did not impair the ability to inhibit responses. The authors suggested that this performance effect may be interpreted in terms of the decreasing ability to apply effort following sleep deprivation being incompatible with the effort required for strategic planning. While intriguing, further research is needed to understand the effects of sleep loss on supervisory control.

A few studies have conducted systematic evaluations of sleep deprivation effects on real world performance, especially on-road and in medical settings. For example, Philip et al. (2003a) compared simple reaction time performance after only 2 h sleep at regular intervals during a drive on the highway and found significant performance impairment in sleep deprived drivers. Extending working and on-call hours for medical residents produced significant decrements in attention, vigilance and driving simulator performance equivalent to impairments seen following 0.04–0.05g% blood alcohol concentration (Arnedt et al., 2005). In another study of the effect of on-call scheduling, residents on-call showed slower reaction time and more lapses compared to residents not on call, but there was no difference in these measures pre and post call (Saxena and George, 2005). In an aviation study of one night of sleep loss (Wilson et al., 2007), performance on an air vehicle task showed significant decrements in the last two test sessions. These studies demonstrate both that there are effects of sleep deprivation in real world settings and that these effects can be evaluated in context.

In conclusion, the number of research reports and the consistency of findings provide very strong evidence that fatigue-inducing conditions like sleep loss produce impairments in performance. Furthermore, the current neurological evidence indicates that the performance decrements associated with sleep loss are due to actual changes in cerebral function. The evidence on the type of performance functions most at risk is not as clear. Simple monotonous and un-stimulating tasks are certainly vulnerable to impairment from sleep loss, but the evidence is less clear on more complex tasks. This may be due to their complexity making it difficult to determine exactly what aspect of performance function is affected. There is some evidence that task complexity and familiarity interact in determining which performance functions are most at risk from sleep loss.

In addition, the nature and characteristics of sleep loss that produce performance decrements is not entirely clear. Sleep loss and performance studies have used varying amounts and patterning of sleep loss. Many of the studies that found a relationship between sleep loss and performance impairment used total sleep deprivation of varying degrees. There are a number of studies however that demonstrated performance decrements with modest sleep loss of 2–3 h per night (Vgontzas et al., 2004; Dinges et al., 1997). Furthermore there is also evidence that rapid sleep deprivation of one night with no sleep has a larger effect on performance than a series of nights of reduced sleep (Drake et al., 2001). Again, the exact dose–response relationships between sleep loss and performance impairments need further study.

3.3. Performance outcomes: task-related factors

A number of task-related dimensions have been linked with fatigue and performance decrements. Time on task is the most often identified, however workload-related dimensions, particularly un-stimulating or monotonous tasks, have also been identified as being important for fatigue-related performance effects. The evidence for each of these dimensions is described in the next section.

3.3.1. Performance outcomes: time on task factors

Krueger (1989) reviewed the effect of needing to sustain task performance over time and argued that continuous performance of cognitive tasks for prolonged periods produces predictable performance decrements. Krueger also emphasized the interaction of effects of sleep loss, circadian rhythms and workload on continuous work operations. A related review of the effects of work shift duration, specifically comparing 8 and 12 h shifts on fatigue, performance and safety concluded that there was no clear evidence of adverse effects of extended work shifts on any of these outcomes (Smith et al., 1998). This review, however, looked at shift duration effects at a gross level. The studies reviewed included an extremely diverse range of occupations and types of tasks, and as the authors pointed out, the effects depended at least partly on the nature of the job or task. Evidence from the human performance literature supports this contention.

Tasks requiring vigilance or sustained attention have historically been one of the well-researched fatigue-prone tasks and have attracted renewed interest in recent years due to increasing emphasis on jobs requiring sustained attention particularly due to automation (Warm et al., 2008). The decline in performance over time, or the vigilance decrement, has been observed in a range of laboratory and occupational tasks including monitoring, surveillance, inspection and quality control (e.g., Dorrian et al., 2007; Pigeau et al., 1995; Mackie et al., 1994). Driving has been identified as a particularly at-risk vigilance task. One on-road study tested drivers who took a break at a rest stop during long-distance trips and compared their reaction time performance on a driving simulator with a matched control group of non-traveling community residents (Philip et al., 2003b). Fatigue, measured by duration of sleep in the past 24 h, distinguished drivers and controls and, most importantly, duration of driving before testing was the major determinant of performance decrements.

There is currently considerable debate on the nature of the relationship between time on task and performance. Traditionally, the effect of fatigue on vigilance tasks has been attributed to lack of arousal caused by little stimulation from the task, which results in decreased attention, missed signals and lapses in performance (Manly et al., 1999). More recently, a resource theory explanation was advanced for the time on task effect. This theory is based on the observation that vigilance performance decrements occurring in tasks that apparently require little effort are, in reality, associated with high ratings of mental workload and effort and this experience causes fatigue. Pattyn et al. (2008) characterised the two views as the boredom (under-arousal) or cognitive fatigue (resource demands) hypotheses and found evidence for the boredom hypothesis. The results of other recent studies have supported the cognitive fatigue hypothesis (Smit et al., 2004; Helton and Warm, 2008), and so supported resource theory. Further research is needed to resolve the mechanism of time on task effects.

Some research has addressed the question of the safe duration for continuous, prolonged tasks: for example, how long tasks like driving can be performed before fatigue effects on performance appear. Looking at simulated driving, Thiffault and Bergeron (2003) found that performance decrements shown as more frequent, large steering wheel movements occurred as early as 20–25 min into a 40 min drive. This finding is supported by a laboratory study using a continuous visual tracking task (Peiris et al., 2006) which showed that the first EEG-confirmed behavioral microsleeps occurred around 22 min into the 60 min test session on average in non-sleep deprived participants. In contrast, in a study of simulated highway driving, Ting et al. (2008) found substantial increases in sleepiness scores and decreases in a range of driving performance measures over a 90 min drive, and especially in the last 10 min period, which led the authors to suggest that the optimum duration for safe highway driving is 80 min. All of these studies showed performance effects with time on task in rested individuals. Clearly, however, there is considerable variation in estimated safe task duration, and further research is needed to resolve it, especially for tasks like driving. There is no doubt, however that this research will need to take into account other factors like the nature of the task and interactions with the circadian rhythm of performance.

3.3.2. Performance outcomes: workload factors

Unstimulating or monotonous tasks have been identified as particularly vulnerable to fatigue-related performance decrements. In many cases, these sorts of tasks are vigilance tasks, involving sustained attention. In driving simulation studies, fatigue effects on driving performance occur especially under less stimulating conditions. For example, Matthews and Desmond (2002) showed that during simulated driving increasing task-related fatigue produced performance deterioration, but only on straight or monotonous sections of the road and not on curves. Oron-Gilad and Ronen (2007) found similar results of a differential effect of road type, but their results highlighted the fact that the driving task itself produced fatigue.

The effects of monotony have also been shown in non-driving tasks. Peiris et al. (2006) demonstrated the performance decrements in a monotonous continuous visual tracking task. In fact, Richter et al. (1998) attributed the higher fatigue and larger performance effects found in a vigilance task compared to a driving simulator to the greater monotony of the vigilance task. In addition, the robust effects of monotony were shown in a study of time on task effects using a visual vigilance task every 3 h during 64 h of sleep deprivation (Gillberg and Åkerstedt, 1998), since time on task effects were larger than those due to sleep loss and commenced from the beginning of the study.

Not only have studies demonstrated that fatigue due to time on task produces deterioration in performance, recent work suggests that interventions that reduce fatigue and improve arousal will also improve performance (Gershon et al., 2008; Oron-Gilad et al., 2008). Implementing interactive secondary cognitive tasks during simulated driving under monotonous conditions significantly improved simulated driving performance and reduced perceived effort and sleepiness ratings. It is notable, however, that the type of secondary task was highly important. Two tasks, working memory and choice reaction time, had adverse effects on fatigue and performance, while a trivia or general knowledge task reduced performance decrements and increased alertness (Oron-Gilad et al., 2008). Work on vigilance performance by sonar operators also demonstrated that performance could be improved by employing feedback and signal injection to reduce the amount of focused attentional effort required (Mackie et al., 1994). The observations that monotonous time on task effects on performance can be overcome by strategically adding activities or modifying the task provides further evidence of the causal link between these task characteristics and performance decrements.

In summary, the research shows that the nature of the task being performed can have adverse effects on performance. Two characteristics in particular have been identified as increasing the likelihood of performance deficits: sustained attention and unstimulating or monotonous tasks. Often these two characteristics occur together. Encouraging evidence is emerging on the use of secondary cognitive tasks to overcome fatigue and performance effects of long duration and un-stimulating tasks.

4. Link between performance and safety outcomes

Including performance outcomes in a review of the link between fatigue and safety makes the implicit assumption that performance effects are an indirect mechanism or a precursor to adverse safety outcomes. Certainly, this was the argument used in most of the performance studies included in this review. The question is, whether this assumption can be supported. Is there evidence that the effects of fatigue on performance really do increase the likelihood that under the same conditions, accidents and injuries are more likely to occur?

Answering this question requires stepping out of the fatigue literature and locating studies that have examined whether performance failures such as errors or delayed responding make accidents or injury more likely. Also, if fatigue is involved, we need to determine whether it is associated with expected specific performance deficits including attentional failures and errors involving lapses or slowed reaction time. Reviewing the research on the link between performance or behavior and safety outcomes reveals three main types of evidence.

One type of evidence comes from studies of self-reported cognitive failures and accident or injury outcomes. Two studies have demonstrated a relationship between reported accidents and minor injuries and reporting of cognitive failures (Wadsworth et al., 2003; Wallace and Vodanovich, 2003). A number of studies have identified links between driver behavior using the Driver Behaviour Questionnaire (DBQ) and traffic accidents, but the results have been equivocal with respect to the involvement of fatigue. Parker et al. (1995) showed that driving violations predicted traffic accidents, but driving lapses characteristic of fatigue (e.g., having no clear recollection of the road just traveled on) did not. On the other hand, a recent study using the DBQ as well as a number of other individual difference measures showed that driver errors were associated with problems of attention regulation and inattention (Wickens et al., 2008), which is consistent with fatigue effects. It should be noted that all of these studies involved self-reported performance and safety outcomes, and the size of the relationships found were modest, at best. This type of evidence alone is insufficient to conclude that performance failures predict adverse safety outcomes.

The second type of evidence comes from studies of performance-related functions and their association with accidents or injury. This group of studies provides stronger evidence as they involve measured performance and objective outcomes rather than self-reported performance deficits and safety outcomes although none of the studies focused directly on fatigue-related effects. A meta-analysis on the information processing predictors of vehicle accidents (Arthur et al., 1991) found moderate relationships between cognitive performance and crashes measured by archival data for professional drivers, although the analysis was weakened by the comparatively small number of studies included and gross groupings of predictor variables. A more recent systematic review of the cognitive performance predictors of crash risk for older drivers (Anstey et al., 2005) showed poorer measured performance to be associated with higher crashes based on state records.

Unfortunately, in studies linking cognitive test performance and crashes, testing has been conducted a variable time before the crashes occurred and it is not known how stable the performance characteristics are. Current state characteristics may not be relevant to safety outcomes at another time, whereas trait or ongoing characteristics are more likely to be so. As fatigue is most likely to be a current state characteristic, it is important to establish that the performance decrements and safety outcomes are contemporaneous and are not just associated within individuals over time.

The third type of evidence does not suffer from the temporality problem, as these studies involve analysis of the causes of accident or injury reports, so performance deficits and safety outcomes are not separated in time. Most of these studies have implicated behavior and error in particular as primary causes of accidents and injury. For example, an analysis of the causes of all occupational fatalities in Australia over a three year period linked directly performance and safety by showing that error, especially error in skilled behavior, was the most frequent antecedent to the fatal accident and most often occurred just prior to the accident event (Williamson and Feyer, 1990; Feyer and Williamson, 1991; Feyer, Williamson and Cairns, 1997). Work by Salminen and Tallberg (1996) on work-related fatalities and serious injuries produced very similar results, and a study by Döös et al. (2004) also highlighted the importance of error either as risk-creating or risk-triggering precursors of injury accidents. Although it was not possible to determine the role of fatigue in these studies, the predominance of skill-based error including lapses is consistent with the identified effects of fatigue on performance. Some specific evidence on the role of fatigue in the performance-safety outcome link is available from a study by Hobbs and Williamson (2003). This study was an in-depth analysis of the causes of 619 safety critical incidents reported by licensed aircraft maintenance personnel. Again error was a dominant cause, especially memory lapses, and fatigue (determined by self-report) was associated in around 12% of occurrences. Importantly, when fatigue was involved, the odds of memory lapses increased 2.4 times and of perceptual errors by 3.2 times, which is consistent with expected performance effects. Importantly, fatigue was not associated with error types that would not be expected: violations, rule-based and knowledge-based errors.

Drawing these three lines of evidence together, a consistent picture emerges that confirms the assumption that performance decrements play a causal role in accidents and injury. The picture can be seen in studies using self-report, retrospective performance measurement and descriptive accident analysis methodologies. Furthermore, while overall evidence on the involvement of fatigue is limited, it is notable that the types of performance effects that occur due to fatigue do lead to adverse safety outcomes.

5. Conclusions

This review provides evidence of a link between fatigue and safety outcomes. Factors that cause fatigue have been demonstrated to have adverse effects on performance as well as safety outcomes. This review was restricted to three main input types that are thought to cause fatigue: circadian, sleep homeostasis and task-related influences. Across multiple studies, sleep-related factors, including sleep deprivation and time since waking, show impairments in performance and increased accidents and injuries. Furthermore, performance effects correlate well with neurological evidence of changes in cortical function, providing converging evidence to reinforce the link between sleep homeostasis factors and performance.

The evidence for the effects of task-related inputs to fatigue and performance is also quite strong. It demonstrates clearly that performance impairments occur in tasks requiring sustained or continuous attention, especially monotonous tasks. For safety outcomes, however, the question remains open as there have been a limited number of studies. The performance research suggests that accident and injury risk is higher when tasks are unstimulating and prolonged and that monotony and low-stimulus situations may not only unmask underlying sleepiness, but may also actually cause fatigue in rested individuals. As this type of task characterizes most work in transport operations and in many other occupations, there is undoubtedly a critical need to test the relationship between long duration tasks and monotonous tasks and safety outcomes.

The link between circadian influences and performance and safety outcomes is rather less clear. The performance studies produced inconsistent findings, and safety outcome evidence reveals a diurnal pattern, but one that is inconsistent with circadian changes that are expected to affect fatigue. This review focused on independent circadian rhythm effects and concluded that much of the research evidence supporting a role for circadian effects is likely to be confounded by homeostatic influences. Some evidence points to a potential combined effect of circadian and other fatigue-related causes, but more research is needed to understand the role of circadian factors and fatigue-related effects on safety.

This review highlighted a number of research needs. There is clearly a strong need for further epidemiological studies of the link between circadian influences and safety and performance outcomes that systematically explore time of day effects unconfounded by other sleep-related factors like time awake. Better information is also needed on the effects of circadian influences on specific performance functions like memory. Gaps remain in our understanding of the effects of homeostatic sleep processes on safety. These include identification of high risk population subgroups and high risk conditions for the effect of sleep deprivation on safety, identification of the important individual and contextual effect modifiers of this relationship, and further research on recovery times, especially the amount and patterning of sleep required to return to baseline risk.

More research is needed on the performance effects of fatigue to confirm which performance functions are most sensitive and therefore vulnerable to fatigue and which types of tasks are most at risk. Current research shows that tasks involving sustained attention and lack of stimulation or monotony in particular increase the likelihood of performance deficits. While research on sustained attention or vigilance tasks has a long history, further work is needed to define better the mechanism of the performance effects. Research is also needed to determine safe task duration, especially for monotonous tasks, and on the interaction of workload effects with known homeostatic and/or circadian causes of fatigue. Commercial motor vehicle sector operators may provide the best population for these studies due to their occupational exposure to long stretches of monotonous high-speed roadways which can be studied while controlling for other known causes of sleepiness and fatigue, such as hours slept and total time spent driving. Encouraging evidence is emerging from recent studies of the use of secondary cognitive tasks to overcome fatigue and performance effects of long duration and unstimulating tasks. This work needs further follow-up to determine which types of tasks are most successful at enhancing performance without distraction and interference with the primary task, such as driving (Williamson, 2008). Gander et al. (2011) and Balkin et al. (2011) contain an extensive discussion of fatigue countermeasures.

A number of research needs were identified relating to methodological issues. Most of the research on safety outcomes is based on epidemiological studies using non-standard measures of a range of fatigue-related exposures and cross-sectional or retrospective designs. Stronger research designs are needed including larger scale empirical studies using test tracks and driving simulators to objectively measure the effects of various levels of acute and chronic sleep loss, sleep inertia, and circadian disruption on driving performance and safety. Also needed are large prospective studies with careful measurement of sleep patterns, work and circadian influences, safety outcomes and potential confounding variables, and randomized controlled trials of interventions that reduce fatigue-related exposures. An example of such a study design is the large scale prospective naturalistic driving study conducted in the US (Dingus et al., 2006), that is currently planned to be extended.

However, in order to assess the independent effects of sleep loss, circadian misalignment, sleep inertia, and specific sleep disorders on motor vehicle crash/near-crash involvement, much more detailed data collection and monitoring of subjects will be required.

The review also highlighted the need for better measures, including the development of an objective measure of driver fatigue that can be applied at the scene of a crash investigation and a review of the use of subjective fatigue ratings. While most studies demonstrate relationships between fatigue ratings and causal factors like restricted sleep, long duration tasks or circadian effects, many fail to find significant relationships between such fatigue ratings and performance or safety outcomes (Belz et al., 2004; Dorrian et al., 2000, 2003; Leproult et al., 2003; Moller et al., 2006; Philip et al., 2003a,b). There are several potential methodological limitations related to using self-rated fatigue scales (or any self-reports) that could lead to the finding of no association with safety outcomes for some studies. These issues include the use of non-validated scales which may lead to random misclassification of exposure, systematic or differential information biases in reporting fatigue. For example, among occupations that always report being alert in their ratings, it would be unlikely to find any association with injuries or accidents.

One strength of this review is that it combined varying types of evidence to examine the effects of fatigue on safety-related outcomes. It included both performance effects, like error and slowed responding which signal increased safety risk, as well as the direct safety outcomes of accidents and injuries. Well-designed laboratory or simulator studies of performance provide good evidence of direct effects of fatigue-related causes due to the control they afford over a wide range of potential confounders and most importantly, the temporality of exposure and effect. Well designed epidemiological studies with appropriate control for confounders and other extraneous variables provide evidence of strong associations between fatigue and safety outcomes. When these sources of evidence concur, our conclusions are better supported (e.g., a causal link between fatigue-related sleep homeostasis factors and safety outcomes).

Many argue that fatigue is an increasing health and safety problem in our daily lives (Mitler et al., 1988; National Academy of Science, 2006) due to the so-called 24-h society with round-the-clock operations. Expectations of live global communication result in decreasing emphasis on the need for sleep, and the nature of work has changed to comprise more sustained attention and monitoring tasks. The results of this review indicate a clear need for further research to address some important unanswered questions about the link between fatigue and safety. In doing so, some significant methodological challenges will need to be overcome. Nevertheless there is compelling evidence that fatigue compromises safety, and that fatigue and its causes need to be managed carefully.

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