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JAL Grigo, MRJ Baldock

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AUTHORS

JAL Grigo, MRJ Baldock

PERFORMING ORGANISATION

Centre for Automotive Safety Research
The University of Adelaide
South Australia 5005
AUSTRALIA

SPONSORED BY

Department for Transport, Energy and Infrastructure
GPO Box 1533
Adelaide SA 5001
AUSTRALIA

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ABSTRACT

This report provides a literature review of the topic of sleepiness and driving. Topics covered include the prevalence of sleepy driving, the difficulty of defining and measuring sleepiness-related crashes, the effects of sleepiness on laboratory measures related to driving performance, the effects of sleepiness on driving performance as measured by driving simulators or on-road studies, and issues related to the measurement of sleepiness (both subjectively-reported and objective measures). Recommendations for countermeasures and future research are made.

KEYWORDS

Sleepiness, fatigue, crash analysis, road safety

Summary

This review of sleepiness and driving demonstrates the need for further efforts to be made to research this complex issue and to develop effective countermeasures. The key findings of the review were the following:

- There is a high prevalence of driving while excessively sleepy. There are, however, a number of possible educational initiatives that could be useful for reducing the likelihood of people choosing to drive when sleepy.
- It is often difficult to determine if sleepiness is involved in a particular crash.
- It is difficult to measure sleepiness in a manner suitable for the development of in-vehicle or enforcement-related countermeasures. Although subjective measures of sleepiness can be useful in research, countermeasures are likely to require objective countermeasures. Current objective forms of sleepiness measurement, such as assessing brain waves or eye responses, require considerable improvement before they can be used for in-vehicle monitoring.
- Sleepiness affects a range of performance functions necessary for safe driving and so sleepiness can contribute to crash involvement without causing a driver to fall asleep at the wheel. It could be that countermeasure development is best directed at measuring performance (e.g. lane positioning). Such measures would not be sleepiness specific but could detect a variety of impairments.

Further research could also profitably be directed at these topics:

- Improved measurement of the effects of sleepiness on driving, including the use of better simulation and better outcome measures in simulator studies.
- On-road studies of the effects of sleepiness, including validation of the findings of simulator studies.
- Studies on particular populations susceptible to sleepy driving, such as shift workers, professional drivers, young or inexperienced drivers, carers, parents of young children, and those with sleep disorders.
- The effects of sleepiness on driving behaviour (e.g. risk taking).
- The relationships between sleepiness, medication and low doses of alcohol
- The effects of sleepiness when combined with driver distraction.

Contents

1 Introduction

Sleepiness is an issue commonly discussed in road safety literature (Nordbakke & Sagberg, 2007) but adequately defining sleepiness has proved to be a difficult task. The meaning of sleepiness has at times been confused with different, yet related, constructs such as fatigue. For example, fatigue has been described as a type of umbrella term encompassing the subjective feeling of sleepiness, tiredness, or exhaustion (Roads and Traffic Authority of New South Wales, 2001). Elsewhere, sleepiness has been used as synonym for fatigue for practical purposes, although with acknowledgement that there are differences between the two concepts (e.g., Hole, 2007).

Some researchers have emphasised the importance of distinguishing between the concepts but they have based these distinctions on differing grounds (Johns, 2000; MacLean, Davies, & Thiele, 2003; Philip et al., 2005). For the purpose of this review, the distinction between fatigue and sleepiness will be based on that presented by Philip et al. (2005). The distinction suggested by Philip et al. was that fatigue increases with sustained activity and can be eliminated with rest but not necessarily sleep, whilst sleepiness is the subjective need to sleep that cannot be eliminated through rest from activity alone (i.e., sleep is required). For consistency, the terms 'fatigue' or 'drowsiness' will not be used in this report, other than when referring to the findings of studies utilising those terms.

This report aims to review the measurement of sleepiness and its role in crashes. The review begins by investigating the prevalence of sleepiness in the driving population and then focuses on the relevance of this to crashes. The difficulties associated with determining if a crash is sleepiness-related and how this may lead to underestimates of the extent to which sleepiness is involved in crashes will be discussed. Studies looking into sleep apnoea will be presented to provide further evidence of the relationship between sleepiness and crashes. The review will then allude to how sleepiness may lead to crashes through a focus on research looking at sleepiness-related human performance decrements, and driving performance on simulators and on-road. Finally, the strengths and weaknesses of different measures of sleepiness will be discussed, with a particular focus on the relative merits of objective and subjective measures.

2 Driving while sleepy: Prevalence and attitudes

Previous research investigating the attitudes of people towards sleepiness and driving suggests that most drivers acknowledge that there is an increased risk of being involved in a crash but that few drivers take appropriate precautions to prevent or combat sleepiness. For example, a study at rest stops along a highway in France showed although 50 percent of participants reported significant sleep restriction before commencing their trip, the drivers continued to drive regardless of their response to the survey (Philip et al., 1996). Although not directly measured, it is likely that those who reported sleep restriction had also been experiencing sleepiness while driving and therefore did not change their behaviour based on this, even after being explicitly questioned about their prior sleep.

This is also supported by more direct research into sleepiness and driving. Nordbakke and Sagberg (2007) conducted a national internet-based survey in Norway and found that 73 percent of drivers reported that they continue to drive despite feeling sleepy. Although many drivers realise that in order to prevent sleepiness while driving they should ensure sufficient sleep before their trip, it is uncommon for drivers to put this into practice (Nordbakke & Sagberg).

A relatively high prevalence of sleepiness while driving has also been found in the commercial vehicle industry. A study of long-haul bus drivers conducting 8-hour interstate trips in Brazil found 42 percent of drivers travelling during the day, and 38 percent of drivers travelling during the night, met the criteria for excessive sleepiness (Santos et al., 2004).

There are many factors likely to influence the prevalence of sleepy driving, such as driver knowledge and judgement of the seriousness of driving while sleepy, age-related factors, and motivational factors. For example, Jones, Rajaratnam, Dorrian, and Dawson (2010) utilised a mock jury in which they provided a group of Australian participants with a fatigue-related scenario. In the scenario a commercial truck driver reported feelings of exhaustion and sleep restriction before setting off on a trip where he fell asleep at the wheel leading to a crash killing two people. In this study, only one-third of the participants found the truck driver or the trucking company guilty, and many only gave the defendant half the maximum penalty (Jones et al., 2010). This finding suggests not only a lack of knowledge about the seriousness of driving while sleepy but also a tendency not to accept responsibility for the consequences of driving while sleepy, even if those consequences are severe (causing death). Although, to the authors' knowledge, there is no study directly comparing the attitudes of commercial and non-commercial vehicle drivers towards sleepy driving, commercial vehicle drivers may have a better understanding of the seriousness of this issue. In support of this suggestion, truck drivers in the USA have reported fatigue to be one of the most important safety issues at work (Hanowski, Wierwille, & Dingus, 2003).

Findings from previous research suggest that even if drivers consider a countermeasure to be efficient in reducing sleepiness, drivers are unlikely to use that measure, particularly if they are young (Nordbakke & Sagberg, 2007). Nordbakke and Sagberg also suggested that drivers may overestimate their capability to drive while sleepy, which may be due to a lack of understanding of the effects of sleepy driving. In addition, drivers who are highly motivated to continue driving may ignore their own subjective feelings of sleepiness or even turn off sleepiness alerting devices in order to reach their destination earlier (Nordbakke & Sagberg; Oken & Salinksky, 2007).

A number of researchers have reported a positive relationship between sleepiness and motor vehicle crashes (e.g., Bunn, Slavova, Struttmann & Browning, 2005; Connor et al., 2002; Connor, Whitlock, Norton & Jackson, 2001; Cummings, Koepsell, Moffat & Rivara, 2001; Gander, Marshall, James & Quesne, 2006; Horne & Reyner, 1995; Hutchens, Senserrick, Jamieson, Romer & Winston, 2008; Nordbakke & Sadberg, 2007; Pierce, 1999). Due to the relatively high prevalence of driving while sleepy in both commercial and non-commercial drivers, the consistently reported relationship between sleepiness and crashes is of great importance. In order to better understand the meaning and details of this relationship, sound methods of identifying sleepiness as a factor in crashes are required.

3 Sleepiness and crashes

3.1 The identification of sleepiness as a factor in crashes

Police data can be a useful starting point in studies investigating the factors involved in car crashes. This is because police attend a high volume of crashes and record information that is collected directly from the scene of the crash, within a very short time period of its occurrence. The quality of this data is also not likely to be heavily reduced by the memory difficulties or biases of crash-involved drivers. The police determine the main cause for each crash, including single vehicle crashes in which the driver is the sole occupant of the vehicle. Although there are advantages in utilising police data, police reports often allow police to state only one possible cause of the crash in their reports, despite many crashes involving multiple causal factors (Hole, 2007). Also, police officers may be required to only list sleepiness as a factor once it has been verified that the crash was not due to any other cause (Chipman & Jin, 2009; Garbarino, Nobili, Beelke, De Carli, & Ferrillo, 2001). This means that even if sleepiness were a major factor in a crash, it may not be listed on the crash report if evidence of other causal factors were present, such as high blood alcohol concentration (BAC) or high speed.

It has also been suggested that police officers vary greatly in their awareness of sleepiness and may lack the time and specific knowledge required to consistently identify sleep-related vehicle crashes (Garbarino, Nobili, Beelke, De Carli, & Ferrillo, 2001; Horne & Reyner, 1995; Mortazavi, Eskandarian, & Sayed, 2009). Crash investigators may not have sufficient understanding to collect the data required to investigate sleepiness as a possible factor in the crash (Gander, Marshall, James & Quesne, 2006). Therefore, even if sleepiness were a factor in a crash it may be overlooked, especially when other more obvious causes are present. Unfortunately, due to the nature of sleepiness, being subtle and insidious, it is often difficult for police or witnesses to identify (Chipman & Jin, 2009; Gander, Marshall, James & Quesne; Garbarino, Nobili, Beelke, De Carli, & Ferrillo, 2001; Knipling & Wang, 1994) and is unlikely to be reported by the driver due to fear of prosecution (Hole, 2007; Mortazavi, Eskandarian, & Sayed). Additionally, police reports do not include information on sleepiness-related risk factors such as prior sleep restriction or length of time driving before the crash (Fell & Black, 1997). The inclusion of such information in police data forms would allow sleepiness to be considered as a possible factor by independent researchers at a later date.

Therefore, although police data is a useful starting point in investigating sleepiness as a risk factor for crashes, there is likely to be a substantial under-representation of sleepiness-related factors in police reports. It is unlikely police services have the resources to increase the volume of data recorded at the scene of a crash, and, although specific training may reduce the number of sleepiness-related crashes which are overlooked, the reporting constraints are likely to continue to limit the benefits of this. Therefore, it may be more useful for researchers to design criteria that can accurately identify a sleepiness-related crash and/or identify sleepiness as a factor within the police data, even when the crash may not have been identified as sleepiness-related by police at the crash scene.

Various approaches have been taken to determine a sleepiness-related crash. Checklists of symptoms likely to precede a sleepiness related crash have been developed, including those such as 'difficulty keeping eyes open', 'entering a dreamlike state', 'more frequent eye blinks', 'difficult to concentrate on driving', 'changing position, moving' and 'yawning' (Nordbakke & Sagberg, 2007). The study by Nordbakke and Sagberg found differences in symptoms retrospectively reported by car drivers who had fallen asleep at the wheel compared to those who had just been afraid of doing so. Specifically, the researchers found those who had fallen asleep at the wheel were significantly more likely to report difficulty keeping eyes open and entering a dreamlike state of consciousness and significantly less likely to report yawning (Norbakke & Sagberg). However there was still a considerable proportion of those who had fallen asleep who also reported yawning, and of those who had just been afraid of falling asleep who reported difficulty keeping their eyes open and entering a dreamlike state of consciousness. The study could have benefited from comparing results to a control group of drivers who had not fallen asleep or been afraid to fall asleep, especially because falling asleep at the wheel is not the only danger when driving while sleepy. With further validation it is possible that symptom checklists could be used retrospectively to determine the likelihood that sleepiness was involved in a crash, but the sensitivity, and specificity of this type of measure is questionable and replication is also required.

Another factor that may be useful to take into account when trying to determine if sleepiness was likely to be involved in a crash is the circadian rhythm. Studies of sleepiness, driving and the circadian rhythm provide support for the relationship between sleepiness and crash risk. The circadian rhythm is a recurring systematic change in a biologically driven event, such as sleepiness, that cycles within an approximately 24-hour period (Webb, 1982). Sleepiness is one of the most dramatic subjectively-experienced changes related to the rhythm (Conroy & Mills, 1970). Given the relationship between the circadian rhythm and sleepiness, if driving while sleepy influences crash risk, it can be hypothesised that at times where people tend to be most sleepy during a typical day according to the circadian rhythm, there will also be an increase in crashes during those times. This relationship has indeed been found in various studies, with a peak in crashes occurring in the early morning and mid-afternoon (approximately 2-5am and 2-4pm respectively) (Chipman & Jin, 2009; Horne & Reyner, 1995; Connor et al., 2002). However, due to differences in internal circadian rhythm, individuals may not experience a peak in sleepiness at the same time, making it less valid to identify an individual crash as sleepiness-related based on time of day. It would be optimal if the individual's internal phase prior to the crash is considered. However, this would be difficult as currently the best non-intrusive measure of circadian phase is assessed using measurements of body temperature (Kantermann, Juda, Vetter & Roenneberg, 2010). This information is currently not recorded during driving and may also be influenced by other factors present in the environment (Kantermann et al., 2010).

Anund and Patten (2010) recently published a report in which they provided suggestions to improve the chances of accurately identifying the involvement of sleepiness in a given crash. The researchers argued that factors such as the circadian rhythm should be taken into account (Anund & Patten). Other indicators that Anund and Patten suggested to be most useful for sleepiness identification were those related to sleep history (i.e., number of hours slept, number of waking hours during the last 24 hours), lifestyle factors (i.e., shift work, coming home from night shift), and the presence of a sleep disorder. These indicators seem to be a worthy set of criteria but it would be a difficult task to make a clear decision regarding the presence or absence of sleepiness based only on these indicators. With results from these criteria a researcher could determine the *likelihood* that sleepiness was involved in a crash, but none of the criteria on their own or collectively can provide a definite answer for a specific crash.

Two other noteworthy sets of criteria for sleep-related crashes were those compiled by Horne and Reyner (1995) and the RTA, NSW Centre for Road Safety (2008). According to the NSW crash criteria, in order for a crash to be considered fatigue-related there must have been at least one fatigued driver in the crash (RTA, NSW Centre for Road Safety, 2008). In order to be considered a fatigued driver, the driver must have been described by police as being asleep, drowsy or fatigued, and/or the driver must have operated the vehicle in a way suggesting reduced alertness due to fatigue, where no other relevant factor was involved (RTA, NSW Centre for Road Safety, 2008). Examples of this are head-on collisions on a straight road where the vehicle was not overtaking, situations where the vehicle left a straight section of road, or, left the road on a curve where the vehicle was not travelling at an unreasonably high speed (RTA, NSW Centre for Road Safety, 2008).

The criteria for a sleepiness related crash compiled by Horne and Reyner (1995) are similar to the above in that they rule out other crash causes. In Horne and Reyner's criteria, the driver must have recorded a BAC below the legal limit, and must not have been speeding or following the vehicle in front too closely. Additionally, the vehicle must have been free of mechanical defect, and either collided with the back of a vehicle or left the road with no sign of prior braking. Finally, at the scene the police officers must have suspected sleepiness as a main cause of the crash and there must have been good weather conditions and visibility, including the ability for the driver to have seen the point of run off, or point of impact, for several seconds before the crash occurred (Horne & Reyner).

Although the above sets of criteria for sleepiness-related crashes are likely to underestimate the involvement of sleepiness to a degree, because they again must rule out other causes before the crash is attributed to sleepiness, they are an improvement on studies that solely use the crash causes listed by police, or retrospective self-reports by crash participants of sleepiness symptoms. This is because they rely on more objective measures than self-report data, minimising possible biases, and may allow for sleepiness-related crashes to be identified even when police have not specified sleepiness as a cause. Additionally, these crash criteria can be applied prospectively in case-control studies, which can provide stronger evidence of the relationship between sleepiness and crashes.

3.2 The extent to which sleepiness is involved in crashes

Estimates of the extent to which sleepiness is involved in crashes have proved difficult to formulate. Figures vary largely across the literature, and so estimates from various studies will be presented, followed by an evaluation of what is likely to be most accurate.

Australian crash statistics demonstrate that sleepiness while driving is a serious issue. In the Northern Territory, fatigue was listed as a factor in nearly five percent of fatal crashes between 1998 and 2003 (Northern Territory Department of Infrastructure, Planning and Environment, 2004) and Tasmanian statistics are quite similar, quoting a figure of 4.5 percent (Department of Infrastructure, Energy and Resources, 2008). However, these figures are likely to underestimate the contribution of sleep-related factors in crashes. The New South Wales Road Traffic Authority (RTA) directly addressed some of the issues associated with under-reporting of fatigue-related crashes in police databases before analysing their data and found fatigue was involved in 20 percent and 16 percent of all fatal crashes in 2007 and 2008 respectively (Roads and Traffic Authority, NSW Centre for Road Safety, 2007; Roads and Traffic Authority, NSW Centre for Road Safety, 2008). Crash statistics from Queensland support these higher estimates. In the Christmas to New Year period of 2008 to 2009, 25 percent of fatalities involved fatigue (Department of Transport and Main Roads, 2009), while in the financial year of 2007 to 2008, the corresponding figure was 17.5 percent (Queensland Transport, 2008).

Findings from previous research suggest that the increase in risk caused by sleepiness is likely to be involved in both non-injury (e.g., Maycock, 1996) and more severe crashes (e.g., Knipling & Wang, 1994). A systematic review found that sleepiness is involved in more fatal crashes compared to all crashes combined (Connor, Whitlock, Norton, & Jackson, 2001). An analysis of NSW statistics revealed that 0.8 percent of all crashes are fatal and 44 percent involve injury, but that for fatigue related crashes, 1.5 percent are fatal, and 43 percent involve injury (Roads and Traffic Authority, NSW Centre for Road Safety, 2008).

Sleepiness-related crashes are of concern in both rural and metropolitan areas, with police reports in NSW showing that 42 percent of sleep-related crashes occur in a city (Fell & Black, 1997). Sleepiness is also involved in a considerable proportion of both truck and car crashes. Previous research demonstrates that fatigue is a factor in 15 percent of commercial vehicle fatalities (Bunn, Slavova, Struttmann, & Browning, 2005) and 17.6 percent of truck crashes (Gander, Marshall, James, &

Quesne, 2006). A large scale study by Dingus et al. (2006) found that drowsiness was involved in 14 percent of all car crashes and was the strongest contributing factor in crashes involving driver impairment.

In terms of relative risk, Connor et al. (2002) found that when car drivers reported sleepiness they had eight times the risk of having a crash. A case-control study conducted on rural highways in Washington State found that drivers had a 14 times higher crash risk if they reported feeling like they were falling asleep while driving (Cummings, Koepsell, Moffat & Rivara, 2001).

As shown, sleepiness is involved in a considerable proportion of crashes in both rural and metropolitan areas, in commercial and non-commercial endeavours, and is over-represented in fatal crashes. Although estimates of the proportion of crashes involving sleepiness are difficult to formulate, which can be seen in the large variability in study findings, it is probable that the higher estimates are more accurate. This is because studies that take into account the issues associated with police-reported data and consider the difficulties in determining a sleepiness-related crash seem to produce larger estimates. For example, the NSW study that considered these issues, via methods mentioned earlier in this review, found fatigue to be involved in 16 percent of fatal crashes in 2008 (Roads and Traffic Authority, NSW Centre for Road Safety, 2008). Similarly, Horne and Reyner (1995) addressed these issues and found in two studies in two different regions that 16 percent or 23 percent of all crashes were sleep-related. The greater estimate for the second study is likely to be due in part to the researchers briefing police about identification of sleep-related crashes. Another group of researchers found that 3.2 percent police-reported crashes were sleep-related but when they analysed the data for all crashes, including those not ascribed as sleep-related by police, using a indirect measurement of sleep propensity, they estimated that 21.9 percent of crashes were actually related to sleepiness (Garbarino, Nobili, Beelke, De Carli, & Ferrillo, 2001). Finally, an independent study suggested 41-71 percent of fatigue-related truck crashes in New Zealand were not accurately identified as such because of police reporting constraints (Gander, Marshall, James, & Quesne, 2006). Therefore, apart from the likelihood that sleepiness is often under-represented in crash statistics, there is a need for researchers to be aware of the difficulties associated with sleepiness-related outcome measures when reporting statistics and attempting to identify relationships.

3.3 Effects of driving while sleepy: Insights from sleep apnoea research

In addition to the evidence presented in the preceding review, investigations into the relationship between sleep apnoea and motor vehicle crashes provide further support for the relationship between sleepiness and crash risk. Sleep apnoea is defined by the DSM-IV TR as a type of breathing related sleep disorder (American Psychiatric Association, 2000). The disorder causes sleep disruption leading to excessive sleepiness (American Psychiatric Association). Patients with sleep apnoea commonly experience and report excessive sleepiness, and, when extreme, this sleepiness caused by the disorder may lead to drivers falling asleep at the wheel (American Psychiatric Association; Teran-Santos, Jimenez-Gomez, Cordero-Guevara & Burgos-Santander, 1999; Lloberes et al., 2000).

Lloberes et al. (2000) found patients with sleep apnoea retrospectively reported a significantly greater number of motor vehicle crashes compared to non-apnoeic, non-snoring controls. A study utilising a case-control design also found a strong relationship between sleep apnoea and elevated crash risk (Teran-Santos, Jimenez-Gomez, Cordero-Guevara & Burgos-Santander, 1999).

Two independent reviews of the relationship between sleep apnoea and crash involvement also arrived at the conclusion that both commercial and non-commercial drivers are at increased risk of crash due to their disorder (Tregear, Reston, Schoelles, & Phillips, 2009; Charlton et al., 2004). The review conducted by Charlton et al. suggested that the reason for this relationship is likely to be excessive sleepiness, but Tregear et al. suggested that other factors, such as body mass index, may be more important in determining the crash risk of individuals with sleep apnoea. Pierce (1999) argued that within sleep apnoea patients the increased risk may instead be independent of their excessive sleepiness symptoms. However, as noted by Tregear et al., it may be that current measures of sleepiness do not have enough sensitivity to show the relationship between sleepiness and crash risk for sleep apnoea patients, as their scores tend to cluster at the high end of the scale, reducing variability in scores and, hence, the statistical power of the analyses. Individuals with sleep apnoea are at increased risk of a crash but it is clear that this population may have different challenges compared to a non-apneic population, and that this should be taken into account when considering research in this area.

3.4 Summary

Overall, it is likely that studies using detailed and carefully considered sleepiness-related crash criteria as the outcome measure are more reliable and valid in estimating the relationship between sleepiness and motor vehicle crashes. The importance of this is apparent when the current estimates are considered. Studies using other methods are likely to underestimate the relationship between sleepiness and crashes and therefore provide a misrepresentation of the importance of addressing the issue of sleepy drivers.

4 Sleepiness and driving performance

The chief mechanisms by which sleepiness is thought to lead to crashes are falling asleep at the wheel and decrements in driving performance. By measuring the effects of different levels of sleepiness on driving performance it may be possible to determine the key factors likely to lead to a sleepiness-related crash. To understand how sleepiness may lead to driving performance decrements and in turn crashes, three avenues of research are particularly useful. These are studies that investigate the relationship between sleepiness and cognitive or psychomotor performance, studies utilising a driving simulator, and the relatively small collection of on-road studies. The paucity of on-road studies is due to the ethical concerns surrounding the safety risks of such research.

4.1 Sleepiness and performance decrements

Total sleep deprivation is often used in studies investigating the influence of sleepiness on cognitive or psychomotor performance. Using this method, Franzen, Siegle and Buysse (2008) deprived participants of one night of sleep and found, compared to a control group, that both subjective and objective sleepiness increased with sleep deprivation. Longer reaction times and greater lapses (reaction times greater than 500ms) were also found in the sleep deprived group (Franzen et al.).

The slowing of reactions with increasing sleepiness has also been found in research utilising chronic partial sleep deprivation (Belenky et al., 2003; Swann et al., 2006). This finding is important because it has previously been argued that, compared to total sleep deprivation, chronic partial sleep deprivation is more commonly experienced in everyday life (Belenky et al., 2003; Goel, Rao, Durmer & Dingus, 2009). Therefore, studies investigating chronic partial sleep deprivation rather than total sleep deprivation are likely to have greater external validity. Although both types of research have pointed to longer reaction times, the difference between chronic partial sleep deprivation and total sleep deprivation is important because recovery from chronic partial sleep deprivation is slower than that of short-term total sleep restriction and so the negative effects that this has on performance last longer (Belenky et al, 2003). According to Andreassi (2000) sleep physiology changes after sleep deprivation. Specifically, when a person who has been chronically sleep deprived is allowed to recover from their sleep debt, the proportion of non-rapid eye movement (NREM) and rapid eye movement (REM) sleep during their recovery will be different to that before sleep deprivation. In the recovery sleep, NREM sleep is overcompensated for and the proportion of REM sleep is reduced (Andreassi, 2000). This is an important finding because REM sleep may be more important than NREM sleep for the restoration of mental activities relevant to driving, such as attention (Zerouali, Jemel & Godbout, 2010). Together this suggests that chronic partial sleep deprivation is not only more common in everyday life, but also likely to take longer to recover from, particularly in relation to capacities important for safe driving.

Although there is a general consensus in the literature that sleepiness increases reaction times (Drummond, Paulus & Tapert, 2006; Franzen et al.; Lim & Dinges, 2010; Philip et al., 2004; Swann, Yelland, Redman & Rajaratnam, 2006; Urrila, Stenuit, Huhdankoski, Kerkhofs & Porkka-Heiskanen, 2007), currently it is unclear if the relationship between sleepiness and reaction time is influenced by age. Some researchers have reported no age difference (Urrila et al., 2007) while others have suggested older people are more resistant to the effects of sleepiness (Philip et al., 2004).

In addition to longer reaction times, Drummond, Paulus and Tapert (2006) found sleep deprivation can lead to increased errors of commission (i.e., difficulty inhibiting a response when that response is inappropriate), specifically in motor responses. The researchers utilised a Go-NoGo task where the participant must respond with a button press as quickly and accurately as possible to a shape displayed on a screen. The participants were told which shapes to respond to and which not to respond to, with the latter being either the same size or shape as the stimuli requiring a button press

(Drummond, Paulus & Tapert, 2006). Participants completed this task after a normal night of sleep, after both one and two consecutive nights of sleep deprivation, and after both one and two sleep recovery nights (Drummond, Paulus & Tapert, 2006).

Although not directly evaluated in these studies, the errors of commission and longer reaction times due to sleepiness could both lead to an increase in crash risk. Errors of commission could lead to inappropriate reactions (such as swerving) to events on the road that would otherwise not have lead to a crash. Longer reaction times could affect the driver's ability to respond to a hazard in time to avoid a crash.

Other factors likely to influence driving performance include attention, the ability to detect change, to obtain and process important information, and to be aware of the body's position and movements through space. This is because rapidly noticing changes on the road, detecting hazards, quickly and accurately processing important information and solving problems should intuitively be important in crash avoidance. Accurate knowledge of one's orientation in relation to surroundings is also likely to be important when driving (Quarck, Ventre, Etard & Denise, 2006). Research suggests all of these factors are likely to deteriorate with increasing sleepiness (Gradisar, Terrill, Johnston, Douglas, 2008; Kendall, Russo & Killgore, 2006; Lim & Dingus, 2010; Quarck et al., 2006; Smith et al., 2009; Zerouali, Jemel & Godbout, 2010).

For example, Smith et al. found that, at higher levels of sleepiness, inexperienced drivers were slower at responding to hazards. Also, Gradisar et al. (2008) found adolescents reporting less than eight hours sleep per night had poorer performance on working memory tasks than those reporting eight to nine hours sleep per night. In support of this finding, a meta-analysis of the effects of short term sleep deprivation on cognition by Lim and Dinges (2010) revealed significant deterioration in simple and complex attention, working memory, cognitive processing speed, and short-term memory associated with sleep deprivation.

Kendall, Russo and Killgore (2010) also reported impairments in cognitive processing and visual attention after participants had remained awake for 40 hours. Visual attention was measured by exposing participants to brief flashes of light while they were performing a continuous serial addition task. The participants were more likely to effectively 'not see' the flashes of light when they were sleep deprived (Kendall et al.). This type of visual attention is likely to be important and characteristic of situations experienced on the road. While concentrating on the driving task, sleepy drivers may be less likely to see sudden changes in their visual field, such as brake lights on a car in front. Deficits in attention due to sleep deprivation have been reported using auditory oddball tasks. Auditory oddball tasks involve repeatedly presenting an auditory tone of the same frequency to a participant. Another tone, with differing frequency or duration, is also presented amongst the standard tones. The brain's physiological response to this change is recorded using an EEG in the form of an event related potential (ERP). The task can be used to measure both automatic and selective attention (Zerouali, Jemel & Godbout, 2010). In the automatic attention condition, Zerouali et al. (2010) asked participants to focus on random digits presented on a screen while ignoring the tones. In order to ensure participants were focusing on the digits they were required to press a mouse button indicating which digit was of a greater value. The auditory and visual stimuli were desynchronised in order to prevent the contamination of visual stimuli on the auditory response (Zerouali et al.). In the selective attention condition, Zerouali et al. instructed participants to ignore the visually presented digits and to focus on the tones, using a mouse to report any change in the tone frequency or duration. Zerouali et al. (2010) found sleep deprivation was related to increases in a type of event related potential related to selective attention and speculated that this was a mechanism of the brain to recruit more resources in order to compensate for the effects of sleep loss. Zerouali et al. also found reductions in another type of event related potential representing impairment in ability to automatically detect change following sleep deprivation.

Quarck et al. (2006) measured the vestibular-ocular-reflex in participants after normal sleep and after 26 to 29 hours of sleep deprivation. The vestibular-ocular-reflex involves stimulation of the vestibular system, usually via the semi-circular canals of the inner ear, which provides feedback on the position and movements of the body or head (Quarck et al.; Stern, Ray & Quigley, 2001). In order to stimulate the semi-circular canals participants can be seated in chairs that move in various directions, shifting the body's position in space (Quarck et al.). The vestibular-ocular-reflex involves involuntary ocular responses to this vestibular stimulation. Specifically, nystagmus will appear, which involves the eyes oscillating with a slow phase in the opposite direction to the chair rotation and then a rapid phase back in the direction of movement (Quarck et al.; Stern, Ray & Quigley, 2001). Changes in the vestibular-ocular-reflex are therefore relevant to vestibular functioning. The eye movements in relation to the chair movements can be measured using an electrooculogram (EOG) or infrared eye tracking systems (Quarck et al.; Stern, Ray & Quigley, 2001) Quark et al. found changes in the vestibular-ocular-reflex were related to sleep deprivation and suggested that sleep deprivation may therefore have an impact on driving ability through its influence on perception of one's body in space.

Other researchers have compared the effects of sleepiness on cognitive and psychomotor performance with the effects of alcohol. Lamond and Dawson (1999) utilised a sensory comparison task, a tracking task, a vigilance task, and grammatical reasoning task to compare participants in three conditions: alcohol intoxication, sustained wakefulness (28 hours), or placebo. Performance on the simple sensory comparison task was not influenced by either sustained wakefulness or alcohol intoxication but performance on the tracking and vigilance tasks deteriorated both with alcohol intoxication and sustained wakefulness (Lamond & Dawson). The researchers reported that moderate levels of sleepiness in participants produced by 20 to 25 hours of sustained wakefulness lead to performance decrements equivalent to those participants with a BAC of 0.10g/100ml.

The findings of this study were supported by subsequent research comparing the effects of BAC and sleepiness on psychomotor performance (Maruff, Falleti, Collie, Darby & McStephen, 2005). Maruff et al. suggested that they had improved on the methodology used by Lamond and Dawson because they took into account group variability in performance. Despite this, the researchers similarly found sustained wakefulness, in this case 24 hours, produced greater psychomotor performance decrements than a BAC of 0.05g/100ml. Maruff et al. found, in addition to an increase in magnitude of performance deterioration, that there was also an increase in variability of response with sustained wakefulness.

From the above discussion it is clear that sleep-related factors influence human performance. These influences impact on a range of processes, from one's ability to accurately and effectively perceive the environment, to the processing of and response to this information. Although the above studies did not directly measure driving performance, the ability to safely navigate on the road and respond to hazards is likely to be influenced by impairments in these processes. Therefore, it is probable that sleepiness influences driving performance through its influence on sensation/perception, information processing, and response. Furthermore, studies comparing the effects of increasing BAC to the effects of increasing sleepiness suggest the changes in these processes may have a substantial influence on road safety. It should be borne in mind, however, that high BACs may alter driving behaviour (chosen actions, including risk taking) in addition to driving performance (ability to safely drive). Although sleepiness may affect cognitive and psychomotor processes in a similar way to alcohol, the influence sleepiness has on driving behaviour requires further research.

4.2 Sleepiness and performance in a driving simulator

Studies using driving simulators have an advantage over the studies mentioned in the previous section as they can provide information on the effects of sleepiness on the performance of driving tasks rather than simply factors which are likely to affect performance on these tasks. In comparison to on-road studies, driving simulators also provide researchers with more control over possible confounding factors such as traffic flow, lighting, temperature, monotony and so on. They are also useful in that they avoid potential ethical concerns associated with on-road driving studies.

Within the driving simulation studies there are large differences in experimental methods and measures used to gather data. Despite this, when taken together, research on driving simulators supports the contention that sleepiness has a detrimental effect on driving performance (e.g., Akerstedt, Peters, Anund & Kecklund, 2005; Biggs et al., 2007; Contardi, Pizza, Sancisi, Mondini & Cirignotta, 2004; Ingre, Akerstedt, Peters, Anund & Kecklund, 2006; Mortazavi, Eskandarian & Sayed, 2009; Pizza, Contardi, Ferlisi, Mondini & Cirignotta, 2008).

Biggs et al. restricted participants' sleep to either nine or four hours and then tested the participants' performance on a driving simulator in two 30 minute testing sessions spaced 30 minutes apart. Subjective sleepiness was rated every five minutes in response to a tone during the driving tasks. The researchers found those participants who had been restricted to four hours of sleep rated their sleepiness as higher and drifted and crossed lane markings more often on the driving simulator task.

Similar findings were found by Ting, Hwang, Doong and Jeng (2008). These researchers allowed participants to drive for 90 minutes in a driving simulator and measured subjective sleepiness before and after the simulated driving session (Ting et al., 2008). The participants reported greater sleepiness after, compared to before, the simulation. Increased time driving was found to be related to participants crossing the edge line more often, increased lateral deviation of their vehicle within the lane, and increased variation in speed (Ting et al.). These findings suggest that, with increasing sleepiness, people have more difficulty maintaining control of their vehicle in terms of both speed and lane keeping.

The simulated driving task used by Ting et al. (2008) also involved a measure of reaction time. Images appeared at random intervals on the screen in which the participant was required to respond with their indicator. Ting et al. found reaction times to images displayed on the screen were significantly longer during the last ten minutes of simulated driving compared to the first ten minutes.

Micro-sleeps occur when people move from wakefulness to sleep and can be used as a measure of sleep onset (Boyle, Tippin, Paul & Rizzo, 2008). Studies investigating the relationship between micro-sleeps and driving performance on a simulator have found micro-sleep episodes are strongly related to an increase in crashes, increased difficulty in maintaining the vehicle's position within the lane and less control over the vehicle's pedals, which may influence the safe travel of other vehicles on the road (Boyle et al., 2008; Moller, Kayumov, Bulmash, Nhan & Shapiro, 2006).

Vehicle control has also been found to deteriorate with sleepiness in a number of other studies. Vehicle control variables have been found to be influenced by increased sleepiness in the form of longer reaction times, increased numbers of crashes, increased exceeding of the speed limit, lane position variability and speed variability (Akerstedt et al., 2010; Akerstedt, Peters, Anund & Kecklund, 2005; Contardi, Pizza, Sancisi, Mondini & Cirignotta, 2004; Ingre, Akerstedt, Peters, Anund & Kecklund, 2006; Pizza, Contardi, Mondini, Trenten & Cirignotta, 2009).

Studies that have investigated the effects of sleep-related factors on driving performance on a simulator in professional drivers and patients with sleep apnoea have provided further support for the detrimental effect of increased sleepiness on driving performance. Truck drivers tested on both standard driving simulators and truck driving simulators were found to have reduced driving performance in the form of reduced control over steering, and the accelerator and brake pedals, with increased sleepiness (Charlton & Baas, 2001; Mortazavi, Eskandarian & Sayed, 2009). Furthermore, an increase in sleepiness has been found to reduce driving performance in the form of increased crashes and lane position variability in patients with sleep apnoea (Pizza, Condardi, Ferlisi, Mondini & Cirignotta, 2008).

The findings above suggest that the effects of sleepiness on driving performance may be similar in various population groups but, as with the findings from the cognitive and psychomotor studies, there is little agreement in the literature as to potential age differences in these effects.

For example, from the findings of a study using a driving simulator at truck stops, depots, and terminals, Charlton and Baas (2001) suggested that older drivers are more susceptible to fatigue. In this study the researchers used an algorithm to calculate performance, which was based on variability in response to divided attention tasks, accelerator use, steering and speed. In addition to finding that greater time spent sleeping or resting during their previous break was associated with fewer driving simulator test failures, they also found older drivers were more likely to fail this test compared to younger drivers (Charlton & Bass, 2001). The researchers suggested this may be due to age differences in fatigue susceptibility but they did not account for potential confounding factors between the groups such as differences in sleep histories or shift-related factors (Charlton & Bass, 2001).

Lowden, Anund, Kecklund, Peters and Akerstedt (2009) compared the driving simulator performance of young drivers (18-24 years) and older drivers (55-64 years) and found that the younger group was more sleepy during night driving compared to the older group. The researchers suggested that this may be because younger drivers are more susceptible to sleepiness but their study did not take into account previous sleep wake histories of the participants, and the younger group also reported more boredom during the task (Lowden et al.). Interestingly, the researchers did not find an age difference in driving performance despite the differing levels of sleepiness (Lowden et al.).

Another group of researchers have also suggested younger drivers may be more susceptible to sleepiness. Campagne, Pebayle and Muzet (2004) compared groups of participants aged 20 to 30, 40 to 50, and 60 to 70 years old. The researchers found, in the older drivers, that the relationship between sleepiness and driving performance was limited to those times when sleepiness was at its highest levels, whereas in the younger and middle aged drivers this relationship existed even with slight changes in sleepiness (Campagne et al.). These results, however, are inconclusive because of measurement-related issues. In this study, Campagne et al. determined levels of sleepiness by measuring alpha signals with an electroencephalogram (EEG). There is a potential confound in comparing alpha waveforms for different age groups as a measure of sleepiness because alpha production also naturally changes with age (Campagne et al.). Therefore, the evidence is inconclusive as to the relationship between sleepiness, age, and driving simulator performance and requires further research.

Overall, the research utilising driving simulators to investigate the effects of sleepiness and driving performance suggests driving performance is detrimentally affected by increased sleepiness. Specifically, simulator studies have found sleepiness to lead to longer reaction times, increased crashes and near-crashes, and greater difficulty in speed maintenance and lane keeping. Age-related factors may have some influence on how affected a driver is by sleepiness and how much impact this will have on performance but determining the effect of age will require further replication and research using stricter methods.

4.3 Sleepiness and on-road driving performance

Driving simulators provide a great insight into the potential difficulties drivers may experience while sleepy but there are questions over the external validity of these studies. For example, participants will be aware that falling asleep during a simulated driving task will not have the same consequences as when on-road (Papadelis et al., 2007; Philip et al., 2005). Also, the simulated environment may differ in stimulation to on-road driving, with some researchers speculating that simulators may provide a lower level of stimulation and therefore have stronger soporific effects than on-road driving (Akerstedt et al., 2010; Akerstedt, Peters, Anund & Kecklund, 2005; Philip et al., 2005). Additionally, the difficulty in operationalising a crash outcome could prove problematic for generalising simulator findings (i.e., a crash may be described as four wheels exiting the lane on a simulator, but on-road this may be a near-miss).

Despite many researchers emphasising the importance of on road-studies (e.g., Akerstedt et al., 2010; Akerstedt, Peters, Anund & Kecklund, 2005; Pizza, Contardi, Ferlisi, Mondini & Cirignotta, 2008; Vakulin et al., 2007), there is relatively little research that has used on-road methods due to the difficulties in designing and conducting these studies, both ethically and practically.

In an early study of the on-road effects of sleepiness, participants were asked to drive around a 5km track until they fell asleep while an experimenter recorded details of their behaviour (Lisper, Laureall, & Loon, 1986). After the driving task had concluded the participants were asked to report on their level of sleepiness. All participants who fell asleep while driving stated they were fighting sleep prior to this event (Lisper et al.). In addition to these findings, during the driving task an audio stimulus was presented quasi-randomly to the participants. The participants were required to respond to this stimulus by pressing a button with their foot. Reaction times were found to increase with increasing sleepiness (Lisper et al.).

Another study involving on-road driving and sleepiness featured both a simulated driving task and a real driving task. The latter task involved participants driving back and forth down identical segments of road (Philip et al., 2005). Video was recorded of the road and then analysed to determine inappropriate lane crossings. Sleepiness was rated in the middle of each driving segment by participants giving a verbal response to a well-validated measure of point of time sleepiness (the Karolinska Sleepiness Scale). Philip et al. found sleepiness did not increase over time during the study but those participants who were fully sleep deprived before the task, compared to those who were partially sleep deprived, reported higher levels of sleepiness and also produced a greater number of lane crossings. These findings were replicated by Philip et al. (2006) who found both sleepiness and video recorded lane crossings significantly increased from daytime to night-time highway driving sessions.

In a study of truck drivers, Hanowski et al. (2003) monitored driving performance using on-board camera systems for approximately two weeks of driving. Hanowski et al. found drowsy drivers were highly over-represented in the driving incidents (near-crashes) that occurred during the testing period and suggested that poor quality and quantity of prior sleep was a strong risk factor, over and above that of monotonous driving.

Finally, Schmidt et al. (2009) conducted an on-road study in which the participants were required to drive on a low traffic highway in Germany for approximately four hours. The participants responded to an auditory tone presented in 20 minute intervals while driving with a subjective rating of sleepiness using the Karolinska Sleepiness Scale. Objective sleepiness was also measured using an EEG. An auditory oddball task was also used to measure reaction time during the driving task. As would be expected, the researchers found an increase in reaction time to the auditory stimulus with increasing sleepiness (Schmidt et al., 2009).

Although the above on-road studies have consistently reported performance decrements associated with sleepiness, a study looking at patients with Parkinson's Disease contradicted these findings (Amick, D'Abreu, Moro-de-Casillas, Chou, & Ott, 2007). Patients suffering from Parkinson's disease often suffer from excessive daytime sleepiness but this study found no relationship between sleepiness and driving performance. This may have been due to the study's methodology, however. Unlike the other sleepiness field studies, Amick et al. tested impairment by measuring performance on a formal driving test. These are relatively short tests and, as suggested by Amick et al., the nature of the examining environment, may have lead the patients to be more alert and conscious of falling asleep than in normal circumstances.

4.4 Summary

As demonstrated through the preceding review, there is a wealth of evidence to indicate that increased sleepiness leads to deterioration in driving performance. The evidence comes from a variety of sources including studies looking at sleepiness and cognitive and psychomotor performance, studies using driving simulators, and on-road investigations. The extent of driving performance deterioration due to sleepiness has also been compared to alcohol intoxication. Sleepiness seems to affect driving performance through its detrimental effect on various aspects of attention, information processing, and response. Sleepiness is likely to influence the ability of drivers to exert adequate control over the vehicle, which is evident in increased difficulty in speed and lane keeping, and can lead to increased near-misses and crashes.

5 The measurement of sleepiness

Studies investigating sleepiness often involve the use of self-report sleepiness questionnaires. These questionnaires are designed to either measure sleepiness at a point in time or act as a trait-like measurement of sleepiness. Some studies also use objective measures of sleepiness such as physiological recordings, video analyses, or circadian rhythm estimates.

The objective measures are useful in that they are often used as a virtually continuous measure, and are not influenced by possible self-reporting biases. However, they also have their disadvantages, as they may not necessarily be a direct and specific measure of sleepiness, and can be much more costly and difficult to administer.

5.1 Objective measures of sleepiness

Objective measures of sleepiness often include physiological recordings from an electroencephalograph (EEG) measuring brain activity, or measurements of eye movements and eye closure via an electrooculogram (EOG). Eye blinks have also been measured using analysis of video recordings.

The Multiple Sleep Latency Test (MSLT) and the Maintenance of Wakefulness Test (MWT) have been used in various studies of sleepiness and driving (e.g., Franzen, Siegle & Buysse, 2008; Moller, Kayumov, Bulmash, Nhan & Shapiro, 2006; Pizza, Contardi, Ferlisi, Mondini & Cirignotta, 2008; Pizza, Contardi, Mondini, Trentin & Cirignotta, 2009; Santos et al., 2004). Both tests utilize an EEG to determine when a participant is entering sleep. The main difference between the two tests is that the MSLT involves lying in a dark room where the participant is instructed to initiate sleep, whereas the MWT involves sitting on a comfortable chair in a semi-dark room where the participant is instructed to try to avoid falling asleep (Moller et al., 2006; Pizza et al., 2009). The sooner the participant enters sleep the higher their objective sleepiness rating. The validity of using these tests in sleepiness and driving studies is questionable, particularly for the MSLT. This is because both tests provide an environment which is very different to the driving environment, both environments are conductive to sleep and do not require the participant to conduct tasks similar to driving. In addition, the MSLT actually instructs the participant to try to sleep; it is unlikely a driver would be intentionally trying to fall asleep at the wheel, suggesting this test may be less valid compared to the MWT (Moller et al., 2006). Nonetheless, the MSLT and MWT have been found to correlate with subjective sleepiness measures, driving performance indicators, and have shown sensitivity to sleep deprivation (Franzen, Siegle & Buysse, 2008; Moller et al., 2006; Pizza et al., 2008; Pizza et al., 2009).

Researchers have also utilised EEG recordings to detect sleepiness without the need for the participant to fall asleep in order to achieve a sleepiness rating. This type of objective sleepiness measure may be more indicative of a participant's current state of sleepiness rather than sleep propensity as measured prior to a driving task (such as during the MSLT and MWT). Researchers in this area often report a relationship between EEG recordings and sleepiness. Changes in alpha and theta activity have been found to relate to changes in subjective sleepiness (Akerstedt & Gillberg, 1990; Horne & Baulk, 2004). Although EEG activity has been found to relate to subjective sleepiness, the EEG recordings have been criticised for their difficulty in differentiating changes in levels of sleepiness before sleepiness has already reached an extreme (Akerstedt & Gillberg, 1990; Kaida et al., 2006). Papadelis et al. (2007) found the relative band ratio of alpha and delta waves significantly increased with time on a real driving task, while the relative ratio of beta and gamma waves decreased. The researchers suggested that this was because sleepiness increased over time. Furthermore, there have been mixed findings as to which frequency bands relate to changes in sleepiness. As shown above, some studies suggest alpha and theta while others have found no relationship between theta and sleepiness but have reported related changes in alpha, beta, delta, and gamma waves (Papadelis et al., 2007). Perhaps utilising and building upon a theoretical framework to explain the relevance of changes in these waveforms may provide better insight into their relationship with sleepiness. These theories exist within many fields of sleep research but are often not referred to within the domain of driver sleepiness.

Researchers have reported large individual differences in the relationship between measures of subjective sleepiness and EEG recordings (Akerstedt & Gillberg, 1990, Horne & Baulk, 2004; Ingre et al., 2006), suggesting a possible lack of specificity of the EEG. In support of this contention, although an increase in alpha bursts were noted by the researchers as occurring prior to driving errors in Papadelis et al.'s (2007) study, these alpha bursts did not occur exclusively prior to the driving errors. Nonetheless, EEG recordings have been utilised in a number of sleep-related on-road and simulated driving studies appearing within this review (e.g., Akerstedt et al., 2010; Boyle, Tippin, Paul & Rizzo. 2008; Campagne, Pebayle & Muzet, 2004; Horne & Baulk, 2004; Lowden, Anund, Kecklund, Peters & Akerstedt; Moller, Kayumov, Bulmash, Nhan & Shapiro, 2006; Schmidt et al., 2009; Vakulin et al., 2007).

Objective measures of sleepiness utilising EOG and eye blink recordings have provided only a similar level of success to the EEG. EOG and eye blink recordings have often been reported as changing with levels of sleepiness. Papadelis et al. (2007) found an increase in eye blink duration with an increase in assumed sleepiness. Increases in slow eye movements and eye blink duration have also been reported in conjunction with increasing subjective sleepiness by other researchers (Akerstedt & Gillberg, 1990; Akerstedt, Peters, Anund & Kecklund, 2005).

Although the above results seem promising, large individual differences have also been found in the relationship between eye movements and sleepiness (Ingre et al., 2006), suggesting a lack of specificity of eye movement measures similar to the EEG. Specific levels of sleepiness have also proved difficult to differentiate with eye movement recordings. Ingre et al. reported that changes in eye movements are obvious only once sleepiness has reached an extreme. Furthermore, in a literature review, Horne and Reyner (1999) suggested that eye movement recordings can be influenced by many factors in the driving environment such as lights, ventilation systems, and temperature.

Recording of eye movements via video rather than EOG has also lead to difficulties. Researchers attempting to analyse and quantify this data subjectively should be blinded to any experimental conditions or expectations in order to reduce possible biases. They also have the time consuming and potentially difficult task of determining what is considered an eye blink or movement. Some eye movements may be difficult to categorise leading to problems with consistency. Particular issues may include subjectively determining how closed the participant's eye must be (e.g., 30% closure, 70% closure) and how long the eye can be closed before it is no longer defined as a blink. Some researchers have avoided this issue as they have recorded eye movements and utilised computer software to detect the eye movements and blinks (e.g., Kircher et al. (2009)). However, accuracy of recordings for both video and computer software can be influenced by many factors including facial attributes (e.g., beards and mascara), clothing (e.g., headbands and glasses), hand movements (e.g., face touching) and other factors (e.g., extra tall or short drivers, or driver changes) (Kircher et al; Mortazavi, Eskandarian & Sayed, 2009). Eye closure measures such as 'PERCLOS', which utilises video recordings to determine the percentage of time an eye-lid closed to at least 80%, may not pick up on drowsiness involving eye open blank stares such as during microsleeps (Boyle et al., 2008; Johns, 2003; Mortazavi, Eskandarian & Sayed, 2009).

Recent technological advances in measures of eye movements show promise for this area of research but there are still issues to overcome. For example, the 'Seeing Machine DSS' is a commercially available drowsiness detector (Seeing Machines, 2010). A sensor is placed on the dashboard and measures eyelid closure. The Seeing Machine DSS has been designed to cope with driver changes so that it does not require any changes to set up for a new driver, nor does the driver need any technical knowledge about the device to use it. In the commercial trucking industry, drivers will not only receive a warning that they are becoming sleepy, but this information can be instantly relayed to fleet managers. The Seeing Machine DSS utilises 'PERCLOS' to collect driver information (Seeing Machines, 2010), but as mentioned previously the sensitivity of this measure is questionable (Boyle et al., 2008; Johns, 2003; Mortazavi, Eskandarian & Sayed, 2009).

The Optalert Driver Safety System is also a relatively new and commercially available drowsiness monitor (Optalert, 2010). The Optalert system requires the driver to wear a special set of lightweight adjustable glasses that send and receive infrared light pulses to measure the velocity of the driver's eyelid. A computer system is installed to process this information and provide feedback on drowsiness in the form of a score displayed on the dashboard (Optalert, 2010). The velocity of eyelid closure has been found to be slower in participants after sleep deprivation compared to when alert (Johns & Tucker, 2005; Johns, Tucker, Chapman, Michael & Beale, 2006; Tucker & Johns, 2005) but changes in velocity were seen only after approximately 19 hours of wakefulness in John's (2003) study. The sensitivity of the Optalert system to all levels of sleepiness (minor through to extreme) and sleepiness over time needs to be established.

An evaluation of objective fatigue detection technologies was conducted by Caterpillar (2008). This review focused on the application of fatigue detection technologies in the mining industry and Optalert was recommended. The authors also noted that the Optalert glasses require professional fitting and any slipping or misalignment of the glasses can lead to poor performance of the system. Additionally, at the time of evaluation the cost of the Optalert system was priced at $16,000 (including one pair of glasses) (Caterpillar, 2008). This price may be reasonable in the commercial trucking industry but is unlikely to be acceptable for public use.

From the above discussion it is apparent there are some important technical issues associated with objective measures of sleepiness. Of major importance is the difficulty in differentiating levels of sleepiness and the specificity of recordings, i.e., whether sleepiness, rather than a related concept, is actually being measured. In addition to these issues, physiological measures can be more time consuming, can be difficult to set up, and can be highly costly and relatively easily damaged (Kircher et al., 2009; Wierwille & Ellisworth, 1994).

As noted earlier, objective measures are useful as they often produce continuous data, with the exception of the MSLT and MWT, and are not influenced by self-report biases. However, in light of the issues associated with objective measures, the advantages do not seem to outweigh the disadvantages. In a review, Horne and Reyner (1999) also suggested subjective sleepiness measures are more accurate compared to objective measures. Furthermore, researchers suggest it is not until sleepiness has already reached an extreme that physiological changes are likely to occur (Akerstedt & Gillberg, 1990; Ingre et al., 2006; Kaida et al., 2006).

5.2 Subjective measures of sleepiness

Subjective measures of sleepiness include single item self report measures such as the questions, "how sleepy do you feel now?" or "do you feel sleepy?". These questions are often designed specifically for the research project, appear on their own, and have not previously been used or tested to determine their psychometric properties. Therefore, these measures may not provide accurate results and there is a strong argument for the use of more advanced subjective measures of sleepiness. Such measures include the commonly utilised Epworth Sleepiness Scale (Johns, 1991), Stanford Sleepiness Scale (Hoddes, Dement & Zarcone, 1972), and the Karolinska Sleepiness Scale (Akerstedt & Gillberg, 1990). The potential of these subjective measures of sleepiness is discussed in the following.

The Karolinska Sleepiness Scale (KSS) is a single item scale that assesses point of time subjective sleepiness where the participant is required to rate (often verbally) their sleepiness on a scale of 1 ‘extremely alert’ to 9 ‘extremely sleepy – fighting sleep’ (Akerstedt & Gillberg, 1990). Strong evidence of this scale’s validity has been demonstrated through its relationship with other subjective measures of sleepiness and electrophysiological data (Akerstedt & Gillberg; Horne & Baulk, 2004; Kaida et al., 2006). Kaida et al. have also noted that the scale has adequate reliability.

The KSS has been used during both simulated and real driving tasks, and has shown sensitivity to sleep-related factors such as the circadian rhythm (Akerstedt & Gillberg, 1990; Akerstedt, Peters, Anund & Kecklund, 2005; Ingre, Akerstedt, Peters, Anund & Kecklund, 2006). Horne and Baulk (2004) have suggested caution in interpretation of scores obtained on the KSS during driving tasks because asking a driver about their sleepiness may make them more aware of their sleepiness than they would be otherwise. It may also make them more alert because it provides a potential form of stimulation, particularly if the participants’ eyes are mostly closed or are experiencing a micro-sleep and the reminder to provide a sleepiness rating is presented in auditory form. It seems the ability for the KSS to be used retrospectively has not previously been investigated, if it were able to be used in this manner the issues of the KSS potentially interfering with sleepiness and the driving task could be overcome.

The Stanford Sleepiness Scale (SSS) was designed as a measure of subjective sleepiness for any specified time interval. This means it can be used as a point of time measurement or a more general measurement (Hoddes, Dement, & Zarcone, 1972). The SSS asks the participants to rate their sleepiness on a scale of 1 ‘Feeling active and vital; alert; wide awake’ to 7 ‘almost in reverie; sleep onset soon; lost struggle to remain awake’ (Hoddes et al.). Evidence for the validity of the SSS has been demonstrated because the SSS has shown sensitivity to sleep deprivation, performance measures often influenced by sleep loss, and changes with clinical states (Hoddes et al., 1972; Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973). Hoddes et al. (1972) also provided evidence for the strong reliability of the SSS (r=.88). Despite these positive findings, the SSS has been criticised for measuring different dimensions of sleepiness such as the likelihood of falling asleep and the subjective internal state (MacLean, Fekken, Saskin, & Knowles, 1992; Pilcher, Pury, & Muth, 2003). MacLean et al. also suggested the various terms on each level of the scale are not equivalent to each other, for example, at level 6 of the scale ‘I would prefer to be lying down’ is quite different to ‘I am fighting sleep’. In support of this, MacLean et al. found when participants rated the items of the SSS separately as ‘true’ or ‘false’, and also rated their sleepiness on the SSS, the majority of participants who agreed that they would prefer to be lying down only rated their sleepiness at level 3 on the SSS.

The SSS has been used as a measure of sleepiness in automotive research utilising driving simulators and hazard perception tests. Despite criticisms of the scale, this research has shown the SSS to be sensitive to expected time of day changes in sleepiness and relates as expected to outcome measures of driving performance (Contardi, Pizza, Sancisi, Mondini, & Cirignotta, 2004) and hazard perception (Smith, Horsiwell, Chambers, & Welton, 2009). In most cases the SSS was used as a point of time measurement.

The Epworth Sleepiness Scale (ESS) was originally developed as a measure of excessive daytime sleepiness to aid in the assessment of sleep disorders. The ESS is a general, trait-like measure of sleepiness that provides the participant with eight brief scenarios of differing levels of sleep-inducing tendency such as ‘sitting and reading’ or ‘sitting and talking to someone’ (Johns, 1991). The participant then rates their likelihood of falling asleep in that situation on a scale of 0 'would never doze' to 3 'high chance of dozing'. This measure has been reported as assessing a slightly different type of sleepiness compared to other subjective measures. That is, it measures sleep propensity rather than the subjective state or feeling of sleepiness, although these concepts are likely to be somewhat related (Johns, 1991; Johns, 1992). The ESS has demonstrated strong test-retest reliability over a five-month period in both healthy students and patients with sleep apnoea, as well as solid internal consistency with a Cronbach's α of .73 to .88 (Johns, 1992). The validity of the measure has also been demonstrated through factor analysis, showing the measure loads on a single factor (Johns, 1992; Pilcher, Pury, & Muth, 2003), and the scores for different patient groups differ as expected based on knowledge of the various sleep disorders and treatment changes (Johns, 1992).

The ESS has been extensively used as a research tool in studies of road crashes and driver impairment. The ESS is often used as a screening tool in studies to exclude participants who are considered to be likely to be suffering from a sleep disorder. However, the ESS has also been used in these studies as a primary measure of sleepiness. Used in the latter form, the ESS has provided mixed results. Some studies have found positive relationships between the ESS and crashes (Maycock, 1996), while others have found no such relationship (Gander, Marshall, Harris, & Reid, 2005). Both of these studies have utilised the number of retrospective self-reported crashes as the outcome measure. It is possible that this relatively unreliable outcome measure (retrospective self-reported crashes) produced the differing results. Due to the ESS being a trait-like measure it may also underestimate the relationship between sleepiness and crashes or driving performance decrements because it is not sensitive to daily fluctuations in sleepiness. This idea is in accordance with Phillip et al. (2005)'s suggestion that driving performance decrements are only related to sleepiness at the moment in time.

Overall, in most situations it is likely the KSS would be the most appropriate measure to use in research, as the SSS may not be structurally sound in terms of underlying factors, and the ESS, being a trait measure, is not sensitive to fluctuations of sleepiness during small time periods, meaning that the temporal relationship between sleepiness and driving errors or crashes is difficult to determine and use of the ESS may underestimate this relationship. On the other hand, trait measures such as the ESS have the advantage of not influencing the behaviour of the driver or outcomes of the driving task by constantly drawing attention to their sleepiness.

5.3 Summary

From the above review it would seem the most useful measure of sleepiness is largely dependent on the expertise and resources available to the researchers as well as study design. Objective measures can be costly, time consuming, and more difficult to administer than subjective measures but they are useful in that they provide continuous data, unaffected by self-report biases, and also provide less avenues for deception. For this reason an area of research where objective measures are likely to be particularly useful would be in the development of in-car sleepiness countermeasures.

It is also important to note that measures of eye blinks may miss important evidence of drowsiness, such as when someone enters a micro-sleep with their eyes open, and may also be influenced by the driver's environment (e.g., temperature and airflow). It is suggested that EEG studies should be regarded with caution until a more solid theoretical framework is determined and agreed upon regarding the meaning and sensitivity of the different waveforms in relation to sleepiness.

Subjective measures have some advantages as they can be quick and easy to administer, are less costly than the objective measures, and can provide both point of time and trait sleepiness values. However selecting which subjective measure to use requires consideration. Researchers should aim to use well-validated, reliable measures of sleepiness such as the KSS, SSS, or ESS. The potential for such subjective scales to be used as a retrospective measure are currently unclear. The ESS is a trait-like measure so there is likely to be some correlation between this measure of sleepiness and that during a driving task but, because it is not sensitive to daily fluctuations in sleepiness, the relationship is likely to be weak. Retrospective self-reports of point of time sleepiness using the SSS or KSS may be more effective but their potential to be used in this manner would need to be validated with further research.

6 Summary and conclusions

The preceding review demonstrates the need for further efforts to be made to research the issue of sleepiness and driving. Firstly, there is a high prevalence of sleepy driving, particularly in fatal crashes, and although people seem to be aware that driving while sleepy is dangerous, and of countermeasures which may be useful to prevent this, they continue to drive while sleepy. Secondly, retrospectively determining the involvement of sleepiness in a given crash can be problematic due to difficulties in differentiating the effects of sleepiness from those of other factors such as alcohol intoxication, and so the involvement of sleepiness in crashes is likely to be underreported. Finally, the measurement of sleepiness in research studies requires further attention. Currently there are issues of validity, sensitivity, and specificity in objective measures, while subjective measures are at risk of biases, may be distracting, and may influence driver behaviour and awareness of sleepiness throughout a driving task. Subjective measures of the trait of sleepiness may also lack the sensitivity to provide an accurate measure of the strength of the relationship between sleepiness and crashes or driving performance.

In addition, this review postulates that sleepiness affects a range of factors in human performance from perception to information processing and response. These human performance decrements are likely to influence driving performance and may explain how sleepiness leads to poorer performance on simulated and on-road studies. These findings may also explain, for example, how someone experiencing sleepiness has an increased risk of crashing despite not falling asleep at the wheel and being on the road for only a few minutes. This is likely to occur regardless of crash type because sleepiness-related performance decrements not only include an increase in reaction time but also increased lapses and errors or commission, a slowing of cognitive processing, and difficulties with attention, change detection and awareness of the body's position and movements.

With all of these issues, there is scope for further research and/or the development of countermeasures. The first issue of high prevalence of sleepy driving seems to suggest that drivers' understanding that sleepiness while driving is dangerous, and their knowledge of effective countermeasures, is adequate. There may be an effect of age or driving experience on levels of understanding or knowledge but this requires further research. Nordbakke and Sagberg (2007) suggested younger drivers are more vulnerable to sleep-related accidents as they have not had time to gain knowledge from experience and therefore should learn about effective countermeasures without having to first experience sleep at the wheel. Philip et al. (1996) also found that pre-trip countermeasures, such as ensuring minimal sleep debt, were less common among young drivers. These findings are inconclusive because age comparisons were not made on the participants' knowledge of effective countermeasures. These findings could be due to age differences in attitudes, risk taking, and lifestyle, rather than knowledge of effective countermeasures or the dangerousness of sleepiness while driving.

In addition to determining potential age differences in drivers' knowledge of sleepiness and countermeasures, drivers' abilities to assess their own deteriorating performance, the attitudes of drivers, and their risk-taking behaviour despite their knowledge, needs to be addressed. It may be useful to have media campaigns demonstrating that falling asleep at the wheel is not the only danger of sleepy driving, by focusing on the relationship between sleepiness and driving performance decrements. Drivers may then begin to understand that they are at constant risk while driving in a sleepy state, whether or not they are aware of it at the time, or on a short trip and feel they are unlikely to fall asleep during that period. Also, making a connection between driving while sleepy and culpability may be useful. It seems that, although drivers are aware that driving while sleepy is dangerous, if they perceive someone as knowingly driving while sleepy and in turn causing a crash, they will not necessarily believe that person is culpable. Therefore, there may be issues associated with drivers taking responsibility for the consequences of sleepy driving. If people do not believe they are responsible for an event they may be less likely to act in a way to avoid that event. Charges for sleepiness-related crashes and enforcement could also improve this issue, but a valid and reliable way of assessing the involvement of sleepiness in a crash would be needed for this to be an appropriate avenue of addressing the problem.

This leads to the second issue: the ability to detect sleepiness post-crash. If measures to detect sleepiness post-crash could be improved, not only would crash statistics be improved, leading to a better understanding of the extent to which sleepiness is involved in crashes, but the potential for enforcement would also be increased. At the moment, the use of crash investigators trained in the identification of sleepiness seems to be the best avenue for identifying sleepiness post-crash. Further developing the criteria for sleepiness-related accidents and possible use of the additional variables as suggested by Anund and Patten (2010) could improve the accuracy of sleepiness identification. However, there is still the difficulty of ruling out other factors such as alcohol use, so in order to make progress in this area, a measurement needs to be developed that is specific to sleepiness. This is unlikely to be possible post-crash as the psychological and physiological state of the driver will be changed by the crash. Retrospective self-reporting of sleepiness post-crash may also be problematic for fear of prosecution or memory difficulties due to trauma. In addition, the validation of self-report measures to be used in a retrospective manner would be required.

Here the need for sleepiness measures that are prospective can be seen. This may include subjective and/or objective measures of sleepiness. Currently, subjective measures of sleepiness seem to be more psychometrically advanced compared to the objective measures, as well as more cost effective and easily administered. Due to this reason, at present they are likely to be of more use in research projects compared to objective measures, especially the more sensitive point of time subjective measures that can be administered during the driving task. However, although subjective measures can be useful in furthering knowledge, they are unlikely to lead to detection of sleepiness in real life crash situations due to fear of prosecution. Furthermore, they may be dangerous to use on-road in everyday life because they are a potential source of driver distraction.

Therefore, in order for continued advancement in the detection and reduction of sleepiness-related crashes, objective measures which are valid, reliable, specific, sensitive, easy to administer and cost-effective need to be developed. There is no such measure. A solid objective measure will not be influenced by people trying to avoid prosecution, by the effects of severe injuries, or by memory difficulties due to trauma. Objective measures can provide a continuous measure of sleepiness that does not require driver input, therefore avoiding issues of distraction. This would also improve the ecological validity of research studies by preventing a possible influence to sleepiness awareness by constantly reminding the driver to assess their sleepiness. Furthermore, such a measure may be tailored to produce driver sleepiness warnings, may be used as a form of black-box so police and researchers can detect sleepiness post-crash, and may help with enforcement and work as a deterrent by providing evidence for possible prosecution. All of these aspects are unlikely to be achieved with a subjective measure.

Unfortunately, most of the objective measures available today fall short in some way from reaching these goals. This may be in part due to much research previously focusing on the relationship between subjective and objective measures. This research has been useful but it now seems more useful to understand the various strengths, weaknesses, and potential uses of both types of measures rather than continuing to debate which is better overall. The most useful measure depends on what the research is aiming to achieve. Therefore, resources should be directed toward finding ways of improving some of the shortcomings of these measures. For example, eye movement measures such as an EOG are easier to set up compared to an EEG, but the eye movements of a driver are likely to be influenced by many factors including lighting, temperature, and airflow. On the other hand, video analysis of eye movements can be time consuming and expensive, and if analysed by computer software, often cannot cope with changes of driver or glasses. If the computer software is designed to detect driver changes, or eye movement measures could incorporate measurements of lighting, temperature, and airflow, there may still be increased potential for these measures. Recent technological advances in measures of eye movements, such as those in Optalert (2010) and Seeing Machines (2010) show promise for this area of research but, as suggested previously in this review, there are still issues that need to be resolved in relation to these technologies.

Currently an EEG seems to be the most promising for detecting sleepiness but an EEG is not easily set up, is time consuming to analyse, and may be difficult to use in the field due to signal interference. Although large individual differences have been found in brain wave patterns of sleepy drivers, this may not be an issue for driver sleepiness countermeasures, as within the same individual brain wave patterns are relatively consistent (Andreassi, 2000). Therefore, if a type of baseline was determined for drivers, and the equipment could recognise different drivers, these individual differences may not be so troublesome. The specificity of the EEG in recognising sleepiness may also be an issue but studies into sleepiness and EEG topography may lead to advancement in this area. Studies of sleepiness and EEG topography (e.g., Zerouali, Jemel & Godbout, 2010; Papadelis et al., 2007) suggest specific brain regions may be more affected by sleepiness, such as frontal and parietal regions. Focusing on the changes in brain waves of these regions may provide greater information in regards to sleepiness.

As an alternative to these objective measures of sleepiness, performance decrements that are likely to reduce with sleepiness could be measured and used within sleepiness countermeasures. Factors such as lane positioning and speed variability could be measured, or even reaction time tasks could be used if they were implemented in a way that would not distract the driver. This alternative again is unlikely to be specific to sleepiness; other factors such as alcohol intoxication may produce similar results but this type of system may be suitable for use as a warning system or countermeasure for general driver impairment.

Therefore, from the above discussion it is obvious there is great potential and need for future research into the measurement of sleepiness. In addition to the measurement of sleepiness, the preceding review sheds light on other interesting and useful areas for future research. Firstly, there have been a large number of studies undertaken on driving simulators but there are very few on-road studies which investigate sleepiness and driving. This is an issue because the ecological validity of simulators is still questionable, and, although great progress has been made in this area, on-road studies are important to validate the findings of this research.

Simulator studies themselves could also be improved to increase their ecological validity. Many of the simulator studies use auditory cues such as a beep to remind participants to rate their level of sleepiness. This may be more alerting to a participant who is in a micro sleep compared to a visual cue, therefore directly influencing their sleepiness state. Also, reaction time as measured during simulator studies using auditory cues could be underestimating the influence of sleepiness for other modalities which are also important for the driving task. A recent study compared the influence of sleepiness on different sensory modalities and found that sleepiness had an enhanced detrimental impact on visual compared to auditory vigilance (Jung, Ronda, Czeisler & Wright, 2010).

It would also be beneficial to focus on population groups who may be at higher risk of sleepiness-related crashes, such as shift workers, professional drivers, young or inexperienced drivers, carers, parents of young children, and patients with sleep apnoea and Parkinson's disease. The effect of age on susceptibility to sleepiness and performance decrements would also be useful in order to focus campaigns on those most at risk of a crash, especially when prevalence and driving exposure are taken into account. Media campaigns should aim to target people in both metropolitan and rural regions as sleepiness can lead to deterioration in driving performance even on short trips and in environments that would not generally be considered as being monotonous.

The loss of REM sleep, as manifested in early waking, compared to NREM sleep, may have greater influence on aspects vital to safe driving such as the restoration of attentional capacity (Zerouali, Jemel & Godbout, 2010). If this effect is similar for other important driving capacities, there may be a benefit in educating shift workers especially, but also the general public, on not simply managing their hours of sleep loss but also trying to ensure uninterrupted sleep that allows them to gain appropriate amounts of REM sleep.

An area of research that was considered beyond the scope of this review was the effect of substances on sleepiness and related performance decrements. Future research into this area would be beneficial. Various medications are known to cause drowsiness, such as some medications used in the treatment of anxiety and sleep disorders (ADF, 2008; Charlton et al., 2010). Patients who take these medications may be of particular risk when driving and may experience changes in their ability to monitor sleepiness or their likelihood of falling asleep. Also, future research aimed at investigating the performance decrements associated with alcohol use in combination with sleepiness would be beneficial. Finally, research investigating the effects of drowsiness-causing medications combined with alcohol use would be worthwhile. For example, the combination of alcohol and benzodiazepines are likely to have an additive depressant effect leading to greater drowsiness (ADF, 2008; Linnoila, 1990). As therapeutic levels of benzodiazepines have been related to increases in crash risk and reductions in driving performance (Charlton et al., 2010), these studies together suggest that therapeutic levels of some drowsiness-causing medications in combination with relatively low doses of alcohol may produce greater levels of sleepiness than either of these substances alone. This could have implications for the current prescribed level of alcohol considered safe for driving (BAC <0.05g/100ml) when used in combination with these medications.

Driver behaviour change due to sleepiness may also be a useful avenue for further research. Increases in risk taking, for example, have been found in laboratory studies of sleepy participants (Killgore, Kamimori & Balkin, 2010). This study utilised a computer-based risk taking task revolving around monetary gains and losses and so did not involve any form of driving task. Whether similar increases in risk taking occur in driving situations would need to be investigated. This is especially because risk taking in terms of personal safety may be different to that related to monetary loss. If risk taking in relation to driving tasks increases with sleepiness, this is likely to further increase the chances of a crash. Also, drivers may be less likely to use countermeasures when sleepy due to such changes in risk taking behaviour.

Finally, there is evidence in this review that the effects of distractions may be greater for sleepy drivers. This is because, as mentioned previously, research suggests that automatic attention may be more affected by sleepiness than selective attention (Zerouali, Jemel & Godbout, 2010). When functioning optimally, a driver selectively attends to the road ahead and uses their automatic attention to identify hazards in the periphery. When a hazard is identified, the selective attention of the driver is recruited to focus on the hazard. If a driver is sleepy, crash risk is increased because their automatic attention is impaired and hazards in the periphery are less likely to be identified. However, if a driver is distracted by, for example, a mobile phone, their safety is more dependent on automatic attention to identify hazards, as all aspects of the driving environment are now in the periphery. For this reason, it is possible that a sleepy driver may be more at risk when distracted than a non-sleepy driver.

Overall, the preceding review demonstrates the dangers of sleepiness while driving and presents important avenues for future research. The prevalence of sleepiness while driving is of concern, particularly given more recent findings correcting for the underestimates reported in earlier research. There is a strong need for improvement in the accuracy of sleepiness measures in order to better understand the effects of different levels of sleepiness. Effective objective measures would be particularly useful in the development of sleepiness countermeasures. The improvement in the ecological validity of simulators, and conducting carefully designed on-road studies to validate the findings of simulator studies is important as there are relatively few on-road studies to date. Identification of factors that may put individuals at greater risk of a sleepiness-related crash may also help to tailor campaigns to reduce these crashes in the future.

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