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Light isn't just for vision anymore: implications for transportation safety

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16. Abstract

In 1998, nearly 30% of all fatal accidents involving large trucks occurred during hours of darkness, according to the Federal Motor Carrier Safety Administration's *Large Truck Crash Profile: The 1998 National Picture*). In about 1.5% of crashes involving large trucks, police reported that drivers visibly appeared to be fatigued or very tired. More than 7% of single-vehicle fatal truck accidents were reported as having driver drowsiness or sleeping as a related factor. The National Highway Safety Administration (NHSTA) reports that 56,000 automobile accidents per year are caused by drivers falling asleep at the wheel. According to the 1990 *World Almanac*, each accident involving a fatality or very serious injury results in a cost of nearly $1.5 million, simply accounting for wage losses, medical expenses and insurance administration.

Humans are diurnal species, programmed to be awake during the day and asleep at night. Therefore, it is not surprising that sleepiness plays an important role in vehicles accidents. The most common preventive action taken by sleepy drivers is to stop driving, change the environment in the vehicle by opening the windows or turning on a loud radio, or consume caffeinated products. Although the preferred preventive action is to stop driving, it is known that this course of action does not always happen due to work demand. Light can, conversely, be used as a non-pharmacological treatment for increasing alertness at night and thereby possibly reducing sleep-related traffic accidents.

Recent research has begun to illustrate the many ways that light and lighting systems affect humans in terms of circadian photobiology, including the characteristics of light necessary to regulate the circadian system. It is well established that light can increase alertness at night or shift the timing of one's sleep to daytime hours instead of nighttime hours. The present report summarizes this research with the objective of providing a framework for integrating circadian photobiology into transportation lighting practice. As will be discussed here, the application of light for impacting the circadian system can be a non-pharmacological tool to increase alertness and possibly reduce sleep-related accidents at night. A framework for future research needed to integrate knowledge of light's impact on nighttime alertness is also discussed.

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LIGHT ISN'T JUST FOR VISION ANYMORE: IMPLICATIONS FOR TRANSPORTATION SAFETY

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INTRODUCTION

In 1998, nearly 30% of all fatal accidents involving large trucks occurred during hours of darkness, according to the Federal Motor Carrier Safety Administration's *Large Truck Crash Profile: The 1998 National Picture* (*42*). In about 1.5% of crashes involving large trucks, police reported that drivers visibly appeared to be fatigued or very tired (*42*). More than 7% of single-vehicle fatal truck accidents were reported as having driver drowsiness or sleeping as a related factor (*42*). The National Highway Safety Administration (NHSTA) reports that 56,000 automobile accidents per year are caused by drivers falling asleep at the wheel. According to the 1990 *World Almanac* (*36*), each accident involving a fatality or very serious injury results in a cost of nearly $1.5 million, simply accounting for wage losses, medical expenses and insurance administration.

Humans are diurnal species, programmed to be awake during the day and asleep at night. Therefore, it is not surprising that sleepiness plays an important role in vehicles accidents. The most common preventive action taken by sleepy drivers is to stop driving, change the environment in the vehicle by opening the windows or turning on a loud radio, or consume caffeinated products. Although the preferred preventive action is to stop driving, it is known that this course of action does not always happen due to work demand. Light can, conversely, be used as a non-pharmacological treatment for increasing alertness at night and thereby possibly reducing sleep-related traffic accidents.

Recent research has begun to illustrate the many ways that light and lighting systems affect humans in terms of circadian photobiology, including the characteristics of light necessary to regulate the circadian system. It is well established that light can increase alertness at night or shift the timing of one's sleep to daytime hours instead of nighttime hours. The present report summarizes this research with the objective of providing a framework for integrating circadian photobiology into transportation lighting practice. As will be discussed here, the application of light for impacting the circadian system can be a non-pharmacological tool to increase alertness and possibly reduce sleep-related accidents at night. A framework for future research needed to integrate knowledge of light's impact on nighttime alertness is also discussed.

BACKGROUND

Circadian Rhythms

All organisms, including humans, exhibit continuous rhythms of neuroendocrine, cellular, and behavioral functions having a period close to 24 h. These rhythms were discovered in the 1700s (22) in plants and have been known to exist in humans since at least the 1950s (*5*). They are called circadian rhythms (*circa* = about, *die* = day) (*68*). Circadian rhythms include the sleep-wake cycle, the core body temperature rhythm, the melatonin production rhythm, alertness and performance among many other rhythms (48). Melatonin is a hormone produced at night and under conditions of darkness. Melatonin is a time messenger, providing the body with daytime and nighttime information. In diurnal species (such as humans), melatonin is associated with sleepiness because it "tells" the body it is nighttime and therefore it is time to sleep.

Regulation of these rhythms appears to be largely under the control of the suprachiasmatic nuclei (SCN) in the hypothalamus of the brain, which receive input about environmental conditions and transmit information to the rest of the body about time of day. Endogenous circadian rhythms free run in the absence of time cues, that is, in humans, they will run with a period slightly greater than 24 hrs (on average, the free running period of the circadian rhythms in humans is 24.2 hrs) and light/dark patterns synchronize these rhythms to exactly 24 hrs (*48*).

Light

Light is the main synchronizer of the circadian rhythms to the 24-hr solar day. Depending on when light is applied, it can have longer-term effects on the master clock by phase shifting the timing of the master clock. As discussed below, light can also have acute effects on humans, such as cessation of nocturnal melatonin production or enhancement of brain activities as measured by electroencephalogram (EEG).

Longer-Term Effects of Light

As mentioned above, the free running period of circadian rhythms in humans appears to be slightly longer than 24 h (*48*). It is thought that the 24-h cycle of the solar day acts not only in a short-term manner to affect circadian-related functions, but that it also entrains these functions to a 24 h day. In fact, depending upon the precise time that bright light exposure is given to an individual, that exposure could result in advancing the cycle of circadian functions such as the melatonin production or body temperature cycles (e.g., peak melatonin levels will occur at an earlier time), or delaying these cycles (e.g., peak of melatonin levels will occur at later times), taking several days to stabilize. During transmeridian (cross-time zone) travel, for example, the shift in clock time caused by the solar day at another location will eventually be realized through shifted rhythms of body temperature, melatonin, sleep/wake cycle and other functions, largely caused by the shifted light-dark cycle and secondarily through other environmental cues (e.g., meals or social interaction).

Acute Effects of Light

Lewy et al. (*44*) demonstrated that high levels of white light (2500 lux [lx] at the eye; lx is a measure of illuminance [lumens per square meter], which is also sometimes characterized in terms of footcandles [fc, lumens per square foot] - 1 fc = 10.76 lx) was needed to reliably suppress nocturnal melatonin production in humans [in comparison, typical light levels in building interiors are 300-500 lx; this corresponds to about 60-100 lx at the eyes of occupants (*54*)]. Subsequent studies have shown that with careful control of lighting, illuminances of several hundred lx of white light (still a relatively bright exposure) at subjects' eyes could reliably suppress melatonin (*46, 47, 55, 56, 71*). Following sustained exposure to enough light, melatonin levels will decrease to near-daytime levels (*55, 71*). Similarly, bright light has been shown to elicit increases in body temperature and even to impact, temporarily, feelings of wakefulness and alertness (*11, 16, 25*). Outdoor nighttime lighting rarely exceeds 10 lux at the cornea and is not a strong enough stimulus to activate the circadian system (*52*).

Characteristics of Light as it Impacts Circadian Functioning

The characteristics of light to support vision are quite different than those to impact the human circadian system (*57*). In order to use light as a non-pharmacological means of enhancing nighttime alertness to reduce sleep-related traffic accidents, it is important to understand the lighting characteristics impacting the visual and circadian system and how they might be integrated to work together to improve both visibility and wakefulness at night.

Quantity

Most visual processing is adequately supported by quite low light levels (*53*), as evidenced by the lighting recommendations for exterior locations published by the Illuminating Engineering Society of North America (*54*). Considering that the illuminances from the sun and sky found outdoors during the solar day regularly exceed 10,000 lx, and that this cycle has been largely responsible for maintaining circadian entrainment, it is perhaps not surprising that the human circadian system requires much higher quantities of light than the visual system for maintaining entrainment or shifting circadian rhythms (*44, 46, 47, 55, 56, 71*). In comparison, most light levels experienced indoors away from windows are relatively low (*57*), adequate for visual function but near threshold levels for activating the human circadian system (see Figure 1) (*52, 71*).

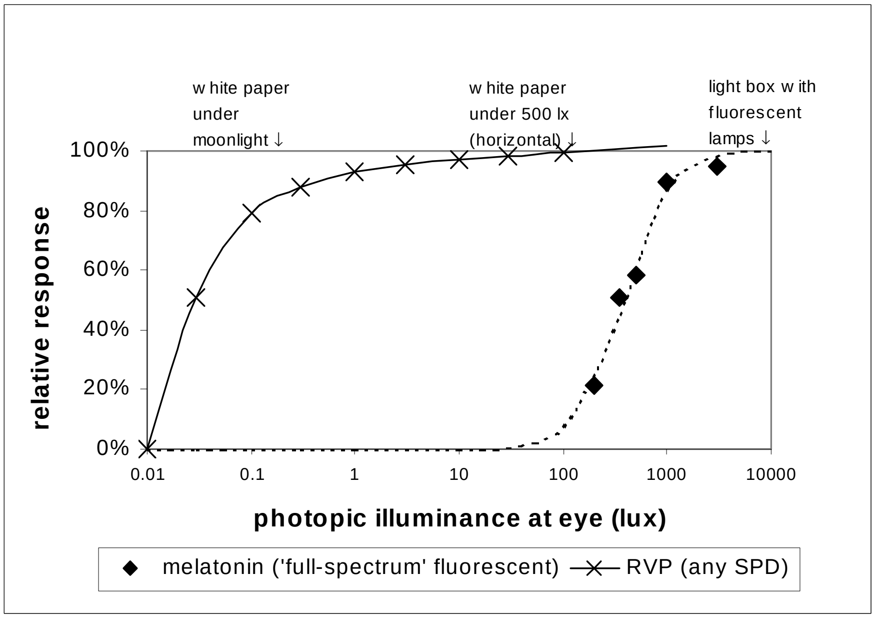

Figure 1: Relative visual performance for high contrast reading material, and relative melatonin suppression by light as a function of illuminance at the eye. This image was developed by (*57*), based on studies from (*53*) and (*46-47*).

Spectrum

At light levels typical of building interiors, the visual system is driven by cone photoreceptors. The photopic luminous efficiency function (V_λ) that emulates our daytime vision has a peak spectral sensitivity at the middle wavelengths (green-yellow) portion of the visible spectrum (*54*). At lower light levels typical of many exterior lighting applications (e.g., roadways and parking lots, [*7*]), the spectral sensitivity of the peripheral visual system is shifted somewhat toward shorter wavelengths (blue-green light) (*14, 35, 58*) representing a mix of cone and rod photoreceptors at these levels. (At very low light levels, lower than any where electric lighting is used, pure rod vision occurs.)

The circadian system, on the other hand, is maximally sensitive to the short-wavelength (blue) portion of the visible spectrum (*12, 45, 55, 56, 64, 66, 69, 70*); in simple words, it can be said that the circadian system is a "blue sky detector." A combination of classical photoreceptors (rods and cones) and a recently discovered novel photoreceptor in the retina (*9, 20, 34*), intrinsically-photosensitive retinal ganglion cells (maximally sensitive to blue light near 480 nm), participate in circadian phototransduction, the process whereby retinal photopigments absorb light signals and convert them into neural signals. Moreover, it has been shown that the human circadian system seems to respond to light in such a way that, in some instances, adding long-wavelength (yellow) light to short-wavelength (blue) light actually reduces the effectiveness compared to the original short-wavelength light (*26, 27*).

A mathematical model for human circadian phototransduction has been developed and was used to calculate the circadian effectiveness of various light sources (*59*). This model has been validated using broadband spectra from fluorescent lamps with differing color appearance (*28*). As shown in Table 1, monochromatic blue light (peak at 470 nm) is almost 30 times more effective in activating the circadian system than an incandescent lamp, for the same photopic light level at the cornea.

Table 1: Calculation results for relative (to incandescent) effectiveness of various light sources for circadian responses. The relative ratio was normalized to incandescent lamp.

Light source	Illuminance at eye (lx)	Circadian Stimulus (CS)	Relative CS Ratio for Equal Illuminance
2856K Inc.	1000	0.172	1
blue LED 470nm	1000	4.829	28.2
white LED	1000	0.371	2.17
MH	1000	0.224	1.31
HPS	1000	0.059	0.34
D65	1000	0.344	2.0
7500K	1000	0.285	1.66

Spatial Distribution

Patterns of light and dark in the field of view are important for the visual system and can affect visual performance (*53*). Indeed, without luminance contrast, much of what we see, including the letters on this page, would be invisible. The circadian system, on the other hand, appears to be simply concerned with total amount of light reaching the retina, without regard to the location of origin (*2, 65*) although it does appear that the circadian system is more sensitive to light coming from the sides rather than straight on (*65*).

Timing

The visual system responds to a light stimulus at any time of the day or night. Depending on the timing of exposure, however, light can either phase advance or phase delay the master clock (*39*). As discussed above, phase advances shift the master clock to an earlier time and phase delay shifts the master clock to a later time (Figure 2) (*48*). When light is applied during the morning hours, a phase advance will occur, while light applied in the evening or late night hours will result in a phase delay of the master clock. As it will be discussed later, light can have an acute alerting effect on humans, but it cannot by itself overcome factors such as accumulated sleep deficits in individuals. Over sufficient time, light can assist in shifting circadian rhythms in an individual who is unable to wake at an appropriate time (e.g., teenagers), but light will not allow an individual to overcome lack of sleep. Rather, light is presumed to have a role whereby proper alignment between circadian rhythms (of body temperature or hormone production) and the timing of required tasks (e.g., night shift driver alertness at night) is expected to influence alertness and performance in a positive way.

Conversely, light can have unwanted consequences when it is presented at a time that is conducive to a phase shift that is not desirable, possibly resulting in a phase shift that negatively impacts performance at the time it is required, or contributing to difficulties sleeping at an appropriate time. Control of darkness as well as light is probably therefore an important consideration in the management of circadian rhythms.

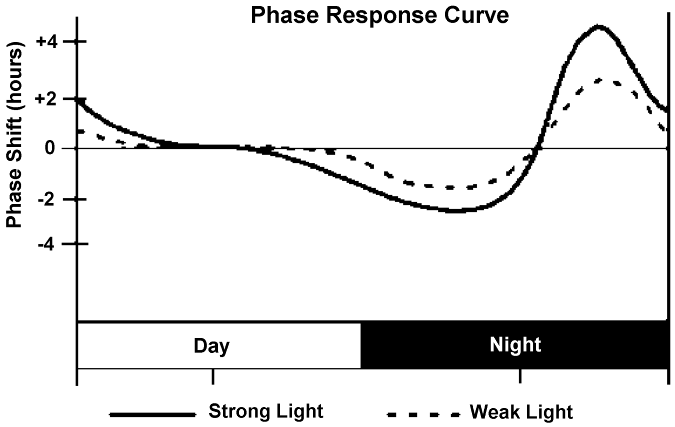

Figure 2: The effect of the time of light application on phase shifting of the core body temperature rhythm in nocturnal animals for two different light levels *(Adapted from 48).*

Duration

The visual system responds to a light stimulus relatively rapidly (in less than 1 s) (*38*). The duration of light exposure needed to suppress melatonin is much longer than the duration of light exposure needed to activate the visual system. It is shown in the literature (*44, 46, 47*) that suppression of melatonin content in the bloodstream starts approximately 10 min. after the initiation of bright light exposure. In general, exposure to a higher light level will require a shorter duration of exposure to achieve a similar effect on the circadian system. For example, based on studies conducted by McIntyre and colleagues (*46, 47*), the amount of time required to measure 50% human melatonin suppression by light at night is about 28 minutes if one is exposed to 3000 lux at the eye (equivalent to outdoor morning light), 33 minutes if one is exposed to 1000 lux at the eye (equivalent to looking out a clear window), and it seems that, one will never achieve 50% melatonin suppression if exposed to 100 lux of white light at the eye, no matter how long the exposure.

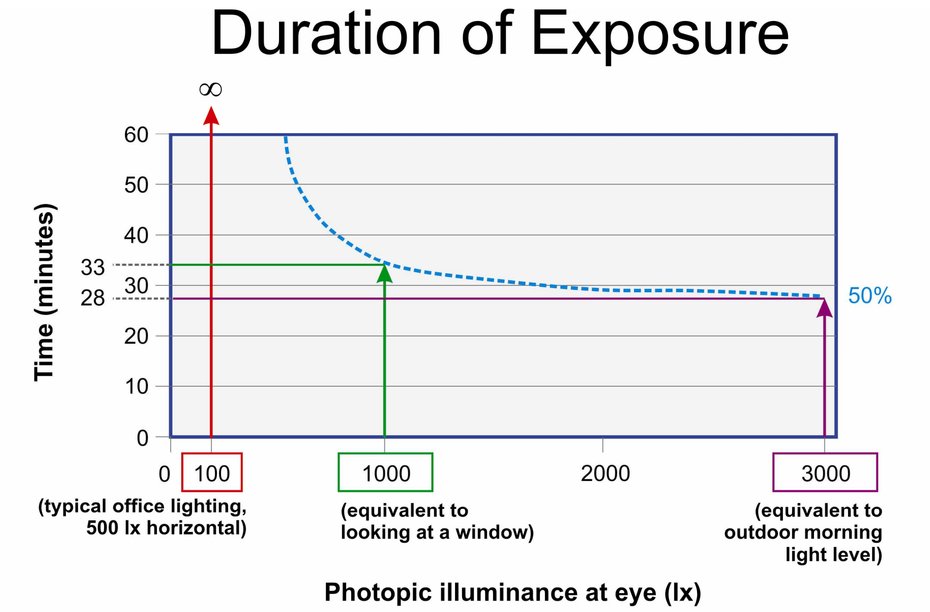

Figure 3: This graph shows the amount of time required to measure nocturnal melatonin suppression by light in humans, as a function of the illuminance provided at the eye (*Based on 46 and 47*).

In sum, light can have an acute or a phase shifting impact on the circadian system. A recent report from the Transportation Research Board (*19*) indicates that disruption of circadian rhythms associated with nighttime driving shifts may have negative impacts on the general health of workers. In addition to the short-term alerting effects of light, lighting could perhaps also be used as a non-pharmacological tool to help mitigate the negative impact of shift work on worker health. Light can be applied and removed at specific times throughout the 24-hr day to shift the master clock so that the worker is programmed to sleep during the day and be awake at night. Although it can be argued that phase shifting the master clock is the ideal solution to overcome sleepiness associated with nighttime driving, it may not be the most practical solution. In general, shift workers want to continue to be “daytime people working at night” because they have a social and a family life outside work. Moreover, maintaining the clock shift for many consecutive days is not possible without a complete control of the 24-hr light exposure, including daylight exposures. Therefore, although ideal, promoting phase shifting of the master clock to improve safety in our highways and minimize the health impact of shift work may not yet be a viable solution. Ultimately, society will have to decide how much longer it is willing to accept the risks and onuses associated with nightshift work. Until then, temporary solutions to alleviate these problems should be implemented. In this report, the acute effects of light on the circadian system will be emphasized. More specifically, this report is concerned with the acute effects of light on nighttime alertness and how light can be used as a non-pharmacological tool to increase alertness and reduce sleepiness at night, and therefore, possibly reduce sleep-related vehicle accidents (SRVA).

Light and Alertness

Especially with regard to some of the acute (short-term) effects of light, it is increasingly clear that relatively brief exposure to light (15 to 30 minutes) can have a positive impact on alertness, wakefulness and even performance of certain tasks, even if for only a temporary amount of time, in individuals who are not sleep deprived (in such people, light cannot overcome the need to sleep). Badia and colleagues (*8*) conducted a study to test the effects of bright white light on body temperature, alertness, and performance. In their study, subjects (who normally would be diurnal, that is, awake during the day and asleep at night) were exposed to 90-min. blocks of alternating bright (5000 to 10,000 lx) and dim (50 lx) light during daytime and nighttime hours. Body temperature, alertness (measured using electrophysiological brain activity measure by EEG) and performance were higher after exposure to bright light than after exposure to dim light during the nighttime hours, but not during daytime hours. Campbell and colleagues (*18*) exposed subjects (again, on a diurnal schedule) to bright (1000 lx) and dim (10 and 100 lx) ambient light for 8 h at night. Subjective and objective measures of alertness showed that subjects were more alert after exposure to bright light than after exposure to dim light, especially at the latter part of the night.

Boyce and colleagues (*11*) submitted subjects undergoing a night shift routine over three successive nights to four different lighting conditions (using white light): low (250 lx), high (2800 lx), increasing (from 200 to 2800 lux over an 8-h shift), and decreasing (from 2800 to 200 lx over an 8-h shift). They found that the two "early bright light" conditions (high and decreasing) improved performance of certain types of tasks, increased level of arousal, improved quality of sleep as the number of nights on shift work increased, and delayed the time the subjects went to bed after the night shift. Figueiro and colleagues (*25*) exposed night-shift nurses working in a newborn intensive care unit to 15 min of bright white light (at least 500 lx at the eye) or dim light (less than 100 lx at the eye). They showed that subjective feelings of wakefulness, alertness, and overall well-being were improved after brief periodic exposures to bright white light than exposure to dim light.

Cajochen and colleagues (*16*) exposed subjects to illuminances ranging from 3 to 9100 lx for 6.5 h during the early night. They found an acute alerting response to light as assessed by a recorded electrophysiological brain activity, as well as a reduction in self-reported sleepiness. More recently, Cajochen and colleagues (*17*), building on knowledge that light has an alerting effect at night and on the knowledge that the circadian system is maximally sensitive to short-wavelength radiation (blue light), were able to show results similar to Badia and colleagues (*8*), but with much lower intensities of monochromatic short-wavelength (blue) light: 5 lx of blue light at a wavelength of 460 nm for a duration of about 40 min., in comparison with the much higher light levels used by Badia and colleagues (*8*): 5000 to 10,000 lx of white light for 90 min.

More recently, Figueiro and colleagues (*29*) demonstrated that subjective (Norris Scale) and objective (EEG) measures of alertness are highly correlated and increase monotonically with four blue (peak at 470 nm) light levels (5, 10, 20 and 40 lx at the cornea). Moreover, they demonstrated that objective measures of alertness were highly correlated with predictions of melatonin suppression for the same circadian stimulus (CS) calculated using a mathematical model of human circadian phototransduction (*59*), suggesting that the SCN play a role in light's alerting effects in humans. These results are consistent with the work done by Saper and colleagues (*61-63*), who have recently elucidated the neural pathways important to sleep and alertness. More specifically, they have identified various independent pathways emanating from the SCN that differentially affect alertness, sleep, core body temperature, and melatonin synthesis (*61-63*).

Sleep and Alertness Drive in Humans

Sleep is largely influenced by the homeostatic drive, that is, the time since last asleep, but it is also affected by the circadian system. Borbely (*10*) was the first to propose a two-process model for sleep regulation in which a homeostatic process (sleep drive) interacts with the circadian process, which was thought to be independent of the sleep/wake cycle. In 1993, Edgar and colleagues (*24*) posed an opponent process model, where the circadian clock acted as an opposing force to the sleep drive, actively facilitating the initiation and maintenance of wakefulness during the circadian day. Sleep consolidation, on the other hand, is believed to occur as a result of increased circadian drive for sleep during nighttime hours, opposing the reduction of the homeostatic sleep drive during sleep (*1*). In sum, nighttime sleep is a result of homeostatic drive (sleep debt) and circadian drive, which sends us alerting signals during the day and sleeping signals at night.

Performance and Circadian Rhythms in Humans

As with sleep, alertness and performance are also strongly influenced by the timing of the master clock. Although performance measures have shown diurnal patterns, different diurnal patterns are associated with different levels of mental load (*3, 30, 31*). For example, repetitive tasks had higher performance during the day, but with lower levels in the morning and evening, while short-term memory tasks decline throughout the day (*31*). In general, however, performance is lowest when minimum core body temperature occurs, about 1.5h prior to normal waking (*40*). Minimum core body temperature is used as a marker of the master clock. Core body temperature follows a circadian pattern, with peak occurring late afternoon/early evening and trough occurring in the second half of the night (*40*).

It has also been shown that performance is affected by the duration of the time awake (*3, 31*). In sleep deprivation studies, performance rapidly decreases during the hours immediately following awakening followed by a gradual leveling out at low levels after 40 to 72 hours of being awake (*3*). Other studies indicate that when sleep duration is less than 7 hours night after night, a steadily growing impairment in performance is observed day after day (*3, 31*).

Shift Work and Performance

Shift work has been associated with a variety of health problems, including cardiovascular disease, impaired glucose metabolism, weakened immune system, gastrointestinal discomfort, reproductive difficulty, and cancer. In fact, recently the World Health Organization classified shift work as probable carcinogenic. A variety of studies have investigated the fatigue-related accidents during the nightshift mainly because alertness and performance are known to be worse towards the latter part of the night, when the circadian nadir of alertness interacts with the increased sleep debt. In fact, some of the worse accidents, such as Three Mile Island and Chernobyl, occurred during nighttime hours and have been linked to shiftworker fatigue. Folkard (*32*) and Akerstedt (*5*) reviewed the literature on shiftwork safety and showed that the risk was significantly higher on the afternoon shift than on the morning shift. They also showed that nightshift had still a higher risk.

Several researchers have developed mathematical models to predict work-related fatigue associated with shift workers schedules. In brief, these models take into account the length and the circadian timing of work and non-work periods. As an example, Moore-Ede and colleagues (*49*) proposed a model (Circadian Alertness Simulator [CAS]) for assessing the risk of diminished alertness at work. The model is based on the two-process model of sleep regulation, where sleep timing and duration is determined by the circadian (phase, period, amplitude) and homeostatic (sleep and wake duration) factors. They tested the validity of the CAS to predict truck driver fatigue risk and correlated predictions with actual accident rates and costs of the trucking operation. More specifically, they calculated cumulative fatigue score for various duty/rest schedules using the CAS and used these predictions to plan driving and working hours of truck drivers. Their studies showed that a reduction in CAS fatigue score was associated with a reduction in the number and severity of accidents (*49*).

Folkard (*32*) reviewed and analyzed a series of published studies to determine whether accident risks in transport operation changes over time. His analyses showed that there is a time of day effect in road accident, with “black times” being associated with time of day and time on task. A peak in traffic accidents occur at 03:00 and a secondary peak occur at 15:00. In a review paper, Horne and Reyner (*37*) discuss SRVA. They also found that there is a clear time of day effect for SRVAs, with peak around 02:00-06:00 and 14:00-16:00. They argue that at 06:00, drivers are more than 20 times more likely to fall asleep at the wheel than at around 10:00. At 16:00, they are about three times more likely to fall asleep at wheel than at 10:00 or 19:00. The circadian system will also impact sleepiness produced by prescribed drugs, alcohol, and other substances. For example, alcohol consumed early in the afternoon results in twice the sleepiness and driving impairment than when consumed in the early evening. Drivers’ age can also impact sleepiness. Horne and Reyner (*37*) found that drivers under the age of 30 years old are more likely to be involved accidents in early morning hours, while the peak sleep-related accidents in the age group of 50-69 years of age occur in the early afternoon.

Practical Countermeasures

A great deal of research effort in the area of transportation has gone into optimizing lighting systems for visibility. The results of this research have been translated into standards and recommended practices for such applications as driving under fixed lighting systems (*7*) and with vehicle headlamps (*60*), and rail, air and sea operation (*54*). Clearly, however, SRVAs are associated with the circadian system and new guidelines could be developed to add light as a non-pharmacological tool to help increase alertness and well-being of nighttime drivers. Transportation operators on the road, on the rails, in the air and on the sea must make increasingly complex decisions throughout a 24-h day. Even a reduction of a single accident could result in a significant return on an investment in understanding how light could impact performance in transportation applications. Most of the field research on the acute alerting effects of light has not been performed using transportation operators as the subject cohort, but the impacts on this population would not be expected to differ greatly.

The evidence presented here suggests that the application of light to influence circadian rhythms could play a role in increasing safety and efficiency of our nation's transportation systems. Indeed, a few studies looking into the effects of light on alertness and sleepiness while driving at night have been conducted. Landstrom and colleagues (*41*) investigated the effects of a 30-minute exposure to bright light during a 9-hour nighttime drive. They did not find an effect of bright white light on subjective alertness. Akerstedt and colleagues (*4*) exposed subjects to 30 minutes of bright light at night. Their results indicate that bright light exposure significantly reduced subjective sleepiness in the subjects but did not have significant effects on brain activity. No published studies to date, however, have investigated the potential effects of blue light on alertness while driving at night although Figueiro and colleagues showed that nocturnal exposure to very low levels of blue light had an alerting effect in humans (*29*).

In order to investigate the most efficacious light source for the circadian system that could be applied to truck drivers to help maintain alertness, a CS calculator was developed based on the mathematical model of human circadian phototransduction developed by Rea and colleagues (*59*). The calculator determines CS based on the spectral power distribution (SPD) of the light source and the light level at the cornea.

One major concern associated with the use of light as an alerting stimulus at night is loss of visibility. Any light that is added to the driver’s eyes can result in discomfort or disability glare. Discomfort glare is a sensation of annoyance or distraction by luminance in the field of view that does not necessarily impact visual performance (*13*). Disability glare occurs when the light from a glare source gets scattered in the eye and is perceived as a luminous veil over the scene (*13*). This luminous veil reduces the contrast of objects and their visibility. At night, any light that is introduced in the field of view of the driver is a potential source of disability glare. In general, glare increases when the glare source’s luminance increases, the background luminance decreases, and the angle between the line of sight and the direction of the light source decreases.

The circadian system spectral sensitivity peaks at shorter wavelengths than the photopic luminous efficiency function used to calculate glare. Calculations were made to determine whether photopic illuminance levels could be minimal if a light source peaking at 450 nm was used to stimulate the circadian system. The calculations of CS were based on a study conducted by Figueiro and colleagues (26), who showed that one hour exposure to 18 lx at the cornea of a light emitting diode (LED) peaking at 470 nm resulted in 35% melatonin suppression. As shown in Table 2, the shorter the peak wavelength, the lower the photopic light levels needed to achieve the same criterion response (i.e., 35% melatonin suppression) for the circadian system.

Table 2: Required illuminance at eye for different peak wavelength blue LEDs referred to circadian stimulus by 470nm LED delivering 18 lx at the cornea

LED at different peak wavelength (nm)	Illuminance at eyes (lx)	CS	Irradiance (W/m^2)
470	18	0.053	0.22
438	5	0.053	0.199
450	8	0.053	0.199
460	12.5	0.053	0.2
490	78	0.053	0.36

Another important factor to be addressed if light is to be used as an alerting stimulus for truck drivers at night is to determine the appropriate light spatial distribution. Light has to reach the retina of the users with minimal annoyance and minimal interference with nighttime driving visibility. It was hypothesized that a diffuse rectangular luminous panel placed directly above the windshield or placed on the both sides of the driver's eyes could be used for this purpose. Initially, it was assumed that a blue LED peaking at 450 nm would be used. A 450 nm light source was selected because currently it is a more common light source than one peaking at 438 nm. Calculations were conducted and results showed that a panel measuring 42 cm in length and 17.5 cm in width with a luminance value of 25 cd/m^2 would deliver 8 lx at driver's eyes when placed at horizontal and vertical distances of 10 cm.

Glare calculations (discomfort and disability) were performed to investigate whether the proposed lighting solution was viable (*6*). A discomfort glare (DG) sensitivity function has been developed by Dee (*23*) and validated by Watkinson (*67*). This discomfort glare sensitivity function was applied to the various LEDs in Table 2 to calculate a DG illuminance. A DG spectral factor was obtained by dividing the DG illuminance by the illuminance at the eye for each peak wavelength. Because the proposed lighting distribution will be an area source, rather than a point source, such as the one used by Dee (*23*), it was necessary to calculate DG luminance. Once DG luminance was calculated, the relationship between DG luminance and the De Boer Scale (*21*) used in Dee's study was established. The purpose was to determine whether the DG luminance for each light source in Table 2 was going to be perceived as uncomfortable. Figure 4 shows that the DG luminance for all light sources correspond to a discomfort glare rating of 7 or above, which is rated as satisfactory (note that in the De Boer Scale, the higher the number, the more comfortable the light source is perceived; maximum number in the scale is 9).

De Boer Scale (*21*):

1 unbearable
2
3 disturbing
4
5 just permissible
6
7 satisfactory
8
9 just noticeable glare

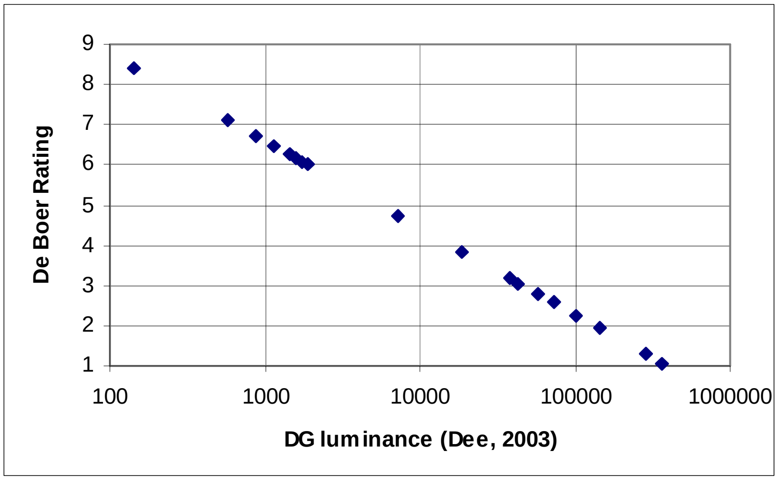

Figure 4: Plot of De Boer rating as a function of DG luminance. DG luminance was scaled from the DG illuminance from Dee's study (*23*).

Disability glare was calculated using the following veiling luminance equation (*33*):

$$L_v = 9.2 \times \sum_{i=1}^{n} \frac{E_i}{\theta_i \times (\theta_i + 1.5)} \qquad \text{(Equation 1)}$$

Where L_v is the veiling photopic luminance (in cd/m²),
E_i is the photopic illuminance at the eye from the i^{th} light source (in lx),
θ_i is the visual angle for the i^{th} light source (in degrees).

For the purpose of this calculation, E_i was considered a constant value for a stimulus specification. Therefore, the disability glare was only determined by the visual angle: the larger the visual angle, the lower the veiling luminance will be. The visual angle is proportional to the ratio of vertical and horizontal distances; therefore, a larger visual field is achieved when the vertical distance above the eye is large and the horizontal distance is small. Different veiling luminance from the same light panel can be achieved by moving the light panel away or close to the driver.

Based on calculations detailed above, minimum veiling luminance for a 450 nm LED producing 8 lx at the eye from a visual angle of 45 degrees is 0.03 cd/m^2. This is achieved when a maximum vertical distance is 0.1 m and the minimum horizontal distance is 0.1 m.

A reasonable background luminance for nighttime driving in rural locations is 0.1 cd/m^2 (*23*). Calculations to determine the veiling luminance produced by the proposed lighting system showed that the visual task contrast will be reduced by 26%, based on Equation 2 below.

$$\text{Visual task contrast} = \frac{L_t - L_b}{L_b + L_v} \qquad \text{(Equation 2)}$$

Where L_t is target luminance,

L_b is background luminance

L_v is veiling luminance

It is not known, however, how a 26% reduction in visual task contrast will affect driving safety. A comparison with two common forms of automotive interior lighting, a dashboard illumination system and a map light, was considered as a reference threshold value of veiling luminance that would not adversely affect visual task for nighttime driving.

According to Perry (*50*), industry practice on dashboard luminance value is 5.14 cd/m^2, which is about 0.1 lx at the eye[1]. The calculated veiling luminance for this condition was 0.001 cd/m^2 and the visual task contrast was reduced by 1%. Map light illuminance measurements were made in a car (Toyota Camry) and were approximately 0.3 lx at eye. The calculated veiling luminance from map reading lights was 0.003 cd/m^2 and the visual task contrast was reduced by approximately 3%. Although discomfort glare would not seem to be an issue with the proposed lighting solution for nighttime alertness, disability glare could be a potential issue affecting the night time driving safety. Therefore, before the proposed lighting solution is adopted, more research is needed to investigate how it would impact driver's visibility at night.

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[1] Such a value is based on scaling the measured of illuminance (0.02 lux) regarding visual angle of 29 degree at eye's position by a factor of industry practice luminance to measured luminance (1cd/m2) from a 1999 Toyota Camry dashboard lighting.

Finally, the circadian system trades off intensity and duration of exposure, so an extended light exposure to a lower light level may result in similar impact on the circadian system, as long as the light level is above threshold for impacting the circadian system. This intensity-duration relationship has not been established yet and further studies are needed before a recommendation of reduced light levels can be made.

SUMMARY

While further research is no doubt necessary before lighting criteria for the circadian system will have equal weight as visual criteria in the design of transportation lighting systems, it is becoming increasingly evident that lighting practice will eventually have to consider circadian photobiology. Presented here was a summary of the impact of light on the circadian systems and nighttime alertness in humans. Also discussed here was the development of a lighting system that could potentially be used by drivers to increase their nighttime alertness. The author is currently working on a grant from the Office of Naval Research to investigate the impact of blue light on daytime alertness of sleep deprived and non-sleep deprived subjects. These findings will also be applicable to transportation applications, since the accident rates during the afternoon hours are still higher than in the morning hours (*5, 32*).

Based on the investigations presented here, a lighting system with a light source peaking at 450 nm producing 8 lx at the eye level for a 1-hour exposure duration would be an efficacious lighting system for the circadian system, and therefore, for increasing nighttime alertness. The only issue that still remains to be investigated is the possibility of disability glare caused by this lighting system and how it would impact driver's safety. A further study is imperative to investigate the veiling luminance effect on the visual task. A laboratory human factor experiment on a prototype will also help to evaluate the validation of the calculation on glare.

In addition to implementing a new lighting system for drivers while on duty, incorporating lighting systems for circadian activation in break rooms, highway rest stops, airports and other facilities might also be a viable solution. Such "light showers" could perhaps become standard features of such facilities in the future, if research evidence continues to mount.

As a next step of this work, it is proposed that a research program be established to investigate the potential use of light as an alerting stimulus at night. The following research projects should be conducted to validate some of the concepts discussed here:

1. Laboratory Human Factors Study

The purpose of the proposed follow-up research project is to investigate the impact of a lighting system that is designed to be used by drivers to increase nighttime alertness. The work performed under the UTRC Mini-Grant for Junior Faculty laid the foundation for the development of such lighting system that has potential to reduce

SRVAs. It is still unknown, however, how the use of this lighting system would impact nighttime driving performance. It is proposed that, as a next step, a laboratory human factors study to test the effectiveness of 3 light levels (2.5, 5 and 7.5 lux at the cornea) and 2 spectra (438 and 450 nm) on objective and subjective alertness (as measured by EEG and subjective sleepiness scale) following the protocol used by Figueiro et al. (2007) be conducted as a follow up of this research paper. The P300 response will also be measured. Electrophysiological measurements of event related potential (ERP) latency and amplitude will also be performed. More specifically, an ERP response parameter called P300, which appears about 300 milliseconds after the onset of a stimulus, will be measured. P300 reduction in amplitude and increase in latency has been linked to fatigue and sleepiness (*15, 43, 51*). A prototype of the lighting system discussed here will be built for the experiment. Calculation of discomfort glare, veiling luminance and disability glare for each of the lighting conditions will be performed. The impact of light levels on driving performance in a simulated environment will be tested using a driving simulator. Driving performance will be measured by speed change, lane shift, and number of crashes. At the end of the laboratory study, the specifications of the lighting system proposed here will be revised to reflect the new findings of the laboratory study.

2. Investigate the temporal characteristics of the lighting system

Another viable option is to use light in rest stops or similar applications, where drivers stop to get a “light shower” when feeling sleepy. Before this can be applied in real life, two questions remain unanswered: 1) what is the intensity-duration relationship so that drivers do not need to stop for too long and 2) how long the alerting effects of light remain after the removal of the stimulus. The first question is also relevant to the application of light inside the vehicle because light levels may be reduced if duration of exposure is increased inside the vehicle. The opposite would be true for rest stops applications. This task would be a follow up of the laboratory study detailed above.

3. Investigate the effectiveness of light in increasing alertness and reducing sleepiness in real-life applications.

Once the lighting system specification is fully developed and its effectiveness on increasing nocturnal alertness while driving is tested in laboratory conditions, it will be necessary to test the effectiveness of such a lighting system in real-life applications.

CONCLUSIONS

Light isn’t just for vision anymore! Lighting for transportation applications should be designed so that it meets the needs of the visual and circadian systems. Although lighting recommendations in the area of transportation have been limited to the visual needs (*54*), it is clear that light can impact more than just the visual system. Light can be used as a tool to increase alertness at night, and possibly reduce SRVA. It is hoped that this short paper will stimulate discussion among researchers and decision-makers alike in deliberating if, how and when lighting practice will consider circadian photobiology.

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