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VISUAL FATIGUE AND THE DRIVER

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16. Abstract

The last fifty years of research on visual fatigue are surveyed, with special emphasis on results that may be important in the context of driving. Over that time, ideas about visual fatigue have varied, ranging from a broad application of the label *eyestrain*, to virtually any visual complaint (including poor acuity), to more specific applications of the term to mean visual discomfort associated with lengthy near-vision tasks. Much of the research reviewed concerns visual fatigue in the workplace, and places particular emphasis on extended use of video displays. One consequence of this emphasis on specific workplace circumstances is that substantial portions of the work on visual fatigue may not be fully applicable to driving. The mechanisms developed to explain workplace visual fatigue may not be strongly engaged in driving. This is especially likely for research that links visual fatigue to oculomotor changes in vergence and accommodation after near work. Visual fatigue in driving is likely to be more strongly related to mechanisms such as ocular surface irritation that may occur as a consequence of eyeblink suppression, or to declines in arousal level that may occur over the course of a lengthy drive. Research directions on possible links between visual fatigue and vehicle lighting are discussed, along with options for measurement.

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Introduction

There has been a long history of investigation concerned with the issue of general fatigue and how it affects a person's ability to perform a task. Because performance of many tasks involves heavy reliance on visual input, special attention has been given to the more specific problem of visual fatigue. And, because of its potential effect on worker productivity, visual fatigue has most often been examined in the context of specific work-related tasks. In the past, such tasks involved reading (Griffing & Franz, 1896); and so-called "close" work such as sewing, typewriting, proofreading, and visual inspection tasks in manufacturing settings. In the 1980s through the 1990s, concern focused on office work—particularly work involving computers and the use of video display terminals (e.g., Dainoff, Happ, & Crane, 1981; Murata, Araki, Kawakami, Saito, & Hino, 1991; Murata et al., 1996; Saito, Sotoyama, Saito, & Taptagaporn, 1994; Watten & Lie, 1992). More recently, visual fatigue has also surfaced as a problem with 3D, stereoscopic displays (e.g., Emoto, Nojiri, & Okano, 2004; Hoffman, Girshick, Akeley, & Banks, 2008; Yano, Ide, Mitsuhashi, & Thwaites, 2002).

The term visual fatigue is imprecise. It implies some form of discomfort or complaint associated with the eyes and has often been referred to as "eyestrain" in the popular press, where it has been given some fairly unscientific treatment. At the turn of the 20th century, newspapers frequently carried reports associating eyestrain with alcoholism, crime, and melancholia (e.g., Anon., 1907, April 7). At the time, however, eyestrain may have been most widely associated with nearsightedness. Indeed, some of the more extraordinary effects that were claimed to result from eyestrain (e.g., poor academic performance, social isolation, headaches, and general psychological malaise) were probably indirect consequences of uncorrected nearsightedness. The treatment for eyestrain was typically corrective lenses, and members of the growing profession of oculists (including both ophthalmologists and optometrists) were happy to promote remedies for as many of society's ills as the profession believed it could address. Some oculists would make exaggerated claims in the popular press about possible visual dangers associated with many activities, such as bicycling (e.g., bicycle eye in Anon., 1897, November 28), typing (Anon., 1899, December 10), movie-going, and driving too fast (Anon., 1908, December 6). In one case, an oculist even claimed that excessive drinking observed during theater intermissions was related to eyestrain suffered by the young male patrons who "…have been straining their eyes in the blinding glare of light to distinguish the natural charms which are obscured if not concealed by grease paint and cosmetics." (Anon., 1904, November 26)

Although the term eyestrain is commonly found in the popular press, visual fatigue is also closely associated with the formal medical term asthenopia, as well as with more direct symptom-based or cause-based labels such as tired eyes, red eyes, scratchy eyes, dry eyes, and computer vision syndrome (CVS). Asthenopia includes many nonspecific complaints about the eyes. The International Classification of Diseases (ICD), published by the World Health Organization (WHO), classifies asthenopia (i.e., visual fatigue; ICD-10, H53.1) under the general heading of *subjective* visual disturbances manifest by a degree of visual discomfort typically occurring after some kind of prolonged visual activity. Thus, even the WHO definition of visual fatigue is limited in its precision. Earnest attempts to refine and clarify the concept (e.g., Bartley & Chute, 1945) were later judged as too confining to be of any practical use (e.g., Brozek, 1948). Megaw (1995) offered the following points about visual fatigue:

- *Visual fatigue is not instantaneous; rather it builds over time.* To this, it might be added that visual fatigue is manifest by a decline in visual performance or increase in visual discomfort (or both).

- *It is not to be confused with mental workload.* In the context of driving, it may not be easy to distinguish between general fatigue and visual fatigue. Indeed, when a driver becomes sleepy, it becomes difficult to focus the eyes or even keep them open. This kind of general fatigue or decline in arousal level might easily be reported as tired eyes, even if no actual visual discomfort (asthenopia) is experienced.

- *It is possible to recover from visual fatigue by rest or a change in task; there are no long-term harmful effects.* The length of this recovery period may vary significantly, depending on the nature of the fatigue. There are no established bounds on recovery time. In some cases, recovery could occur within minutes.

- *It is not an adaptive response of the visual system.* At face value, this statement seems relatively clear; however, there may be indirect visual fatigue effects that arise as a consequence of a visual adaptation. For example, adaptation to light could reduce contrast sensitivity, reducing the accuracy of vergence and accommodation. This, in turn, could result in visual fatigue. There is also some evidence that spatial frequency adaptation, especially after reading lines of text (Watten, Lie, & Magnussen, 1992), may be associated with visual fatigue.
- *Symptoms of asthenopia are the primary evidence for visual fatigue.* This is not the same as saying that asthenopia is a necessary condition for visual fatigue—a decline in visual performance might occur without reported discomfort. It seems reasonable to expect that both reported visual discomfort (asthenopia) *and* a decline in visual performance should result from visual fatigue. However, some studies have reported objective evidence of fatigue without specific reports of visual discomfort. For example, Wolska and Switula (1999) report a reduction in accommodation amplitude without subjective fatigue. More frequently, reports of discomfort occur with little objective evidence of fatigue (e.g., Mocci, Serra, & Corrias, 2001).
- *Visual fatigue may be influenced by both environmental factors and individual factors*. That is to say, visual fatigue is influenced by more than visual activity alone. Environmental factors (e.g., dust, pollen, dry air) as well as an individual person's refractive error or medication use may also influence susceptibility to visual fatigue.

This review is intended to emphasize causes of visual fatigue that may plausibly occur as consequences of driving. Thus, although factors such as screen refresh rates and radiation emissions have been related to visual fatigue in the context of computer vision syndrome (Blehm, Vishnu, Khattak, Mitra, & Yee, 2005; Jainta, Jaschinski, & Baccino, 2004; Jaschinski, Bonacker, & Alshuth, 1996; Kennedy, Brysbaert, & Murray, 1998), they have limited relevance for driving and are not discussed in this review. Also excluded are environmental factors (e.g., airborne irritants) that lead to visual discomfort but are unrelated to driving. In this review, visual fatigue is considered a consequence of prolonged visual activity that leads to a deterioration of visual performance or a report of visual discomfort.

Symptoms of Visual Fatigue

The symptoms of visual fatigue can be categorized into three kinds of discomfort: ocular-surface related, oculomotor related, and nonocular. Ocular-surface related symptoms include complaints about dry, burning, or scratchy eyes and are associated with both environmental irritants and insufficient lubrication of the eye. Oculomotor related symptoms are associated with changes in the accommodation, vergence, or version response of the eye; they may also involve changes in the pupillary response, or changes in eyeblink response. Prolonged demand on these oculomotor functions is thought to diminish their responsiveness, and result in blurred or double vision, glare, or delays in visually acquiring targets. Unlike ocular-surface related symptoms, this form of visual fatigue is amenable to objective measurement. Nonocular symptoms of visual fatigue include reports of headache, neck pain, back pain, drowsiness, or diminished levels of arousal or engagement in a task. These factors are most often identified in subjective reports from the individuals involved, and may not be reliably associated with particular visual activities. For example, although neck pain may be reported as a symptom of visual fatigue, it may be more closely related to characteristics of an individual's seating posture during performance of a visual task. Similarly, reports of diminished arousal levels may be more a consequence of an individual's general fatigue level or boredom in performing a monotonous task than of a specifically visual condition. It is also likely that general fatigue is often reported as visual fatigue when observers have difficulty keeping their eyes open.

Ocular surface complaints

Reports of asthenopia fall into two symptom constellations: external symptoms and internal symptoms (Sheedy, Hayes, & Engle, 2003). External symptoms include complaints of sore, dry, or scratchy eyes and appear to be related to holding the eyelid open, glare, upward gaze, reading a small font, and flickering displays. Internal symptoms include ache, strain, or headaches and appear to be related to close viewing distances and other accommodative and vergence stress.

While ocular surface complaints may occasionally be related to the air quality of a vehicle's passenger compartment, they may also have some relationship to a driver's visual behavior. That is, some visual behaviors may promote more fluid evaporation from the surface of the eye than others, leading to complaints of dry or irritated eyes. When the eyes are elevated, the raised eyelids expose more surface area of the eyes, resulting in greater fluid evaporation than when the eyes are directed downward (Blehm et al., 2005). If an instrument display is placed in the upper visual field (e.g., near the rearview mirror) and requires frequent viewing, it is likely to result in more reports of visual fatigue than a similar display located in the lower visual field.

Likewise, a reduction in eyeblink rate might also increase ocular surface evaporation. Increased visual workload has been associated with reduction in eyeblink rate (Hancock, Meshkati, & Robertson, 1985; Hancock, Wulf, Thom, & Fassnacht, 1990; Veltman & Gaillard, 1998). Perhaps reduction in eyeblink rate also leads to increased drying of the eyes, which in turn might later lead to an increased blink rate. Increased eyeblink rate has long been reported as evidence of visual fatigue (e.g., Luckiesh, 1947; Mourant, Lakshmanan, & Chantadisai, 1981). Moreover, some have also noted that eyeblink suppression is often followed by a period of "catch-up" eyeblinks that occur at a higher than usual rate (Stern, Boyer, & Schroeder, 1994). While this pattern appears to fit an explanation that suggests eyeblink suppression might lead to a drying of the eyes that is followed by a higher eyeblink rate to recover from this drying, some have posited that a more central source of fatigue is at work. Stern, Boyer, and Schroeder (1994) suggest that inhibitory control of eyeblinks (i.e., suppression) declines after periods of high inhibitory demand (i.e., visual workload). That is, the explanation of the eventual increase in eyeblink rate does not specifically involve insufficient eye lubrication. (Perhaps because eyeblink rate remains high even after the lubrication problem has been resolved.)

In terms of the roadway and driver, visually challenging roadway conditions (for example, a poorly-marked roadway) might produce episodes of eyeblink suppression that could eventually lead to increased visual fatigue. Any measure that improves roadway visibility—improved roadway marking, forward vehicle lighting, fixed roadway lighting, or perhaps vision enhancement systems—could potentially reduce the amount of eyeblink suppression and reduce fatigue as a consequence.

Oculomotor related symptoms

Accommodation and vergence. Visual fatigue has most frequently been investigated by examining objective changes in oculomotor function in relation to specific characteristics of a visual task. The primary focus of this work has been directed to mechanisms of visual accommodation and vergence. Accommodation refers to the action of the ciliary muscles within the eye to change the curvature of the eye's flexible lens to focus the image on the retina. A near object is focused by contracting the ciliary muscles, which releases tension on the zonular fibers (that normally flatten the lens), allowing the curvature of the lens to increase; a far object is focused by relaxing the muscles, which decreases lens curvature (see Figure 1). Accommodation usually works in conjunction with vergence eye movements. Vergence is the coordinated control of the rotation of each eye to converge on a target and maintain single binocular vision. As an observer watches an approaching object, the observer's eyes normally rotate inward toward each other; as an object recedes from the observer, the eyes turn outward, away from each other (see Figure 2).

Visual tasks which make repeated use of these muscles are believed to contribute to visual fatigue. Increased use might occur for a variety of reasons, including conditions of reduced contrast, extended periods of work at close viewing distances, repeated shifts in gaze between near and far distances, or vergence and accommodation conflicts associated with stereoscopic displays (Emoto et al., 2004; Hoffman et al., 2008; Okada et al., 2006). Reduced contrast may make it difficult to accurately bring an object into focus, perhaps resulting in some degree of accommodative fluctuation which, in turn, might result in accommodative fatigue. Close viewing requires active and sustained convergence and accommodation, which is likely to tire the eye muscles involved, especially if the stimulus position differs markedly from the normal resting position of accommodation and vergence. The resting position of the accommodative system, called dark focus, is determined by measuring the resting focus of the lens when no visual stimulus is present; it is usually measured in darkness. Similarly, the resting position of the vergence system, called dark vergence, is determined by measuring the vergence distance of the eyes in darkness. Jaschinski-Kruza (1988) reported that subjects with far dark focus locations are more likely to report higher levels of fatigue and perform the visual task more slowly than subjects with near dark focus locations. Tyrrell and Leibowitz (1990) and Jaschinski-Kruza (1991) observed that subjects are more likely to report eyestrain when viewing objects at short distance when that distance greatly deviates from the subject's dark vergence. If a subject's dark vergence is far, reports of eyestrain after near work are more likely than if that subject's dark vergence is relatively near.

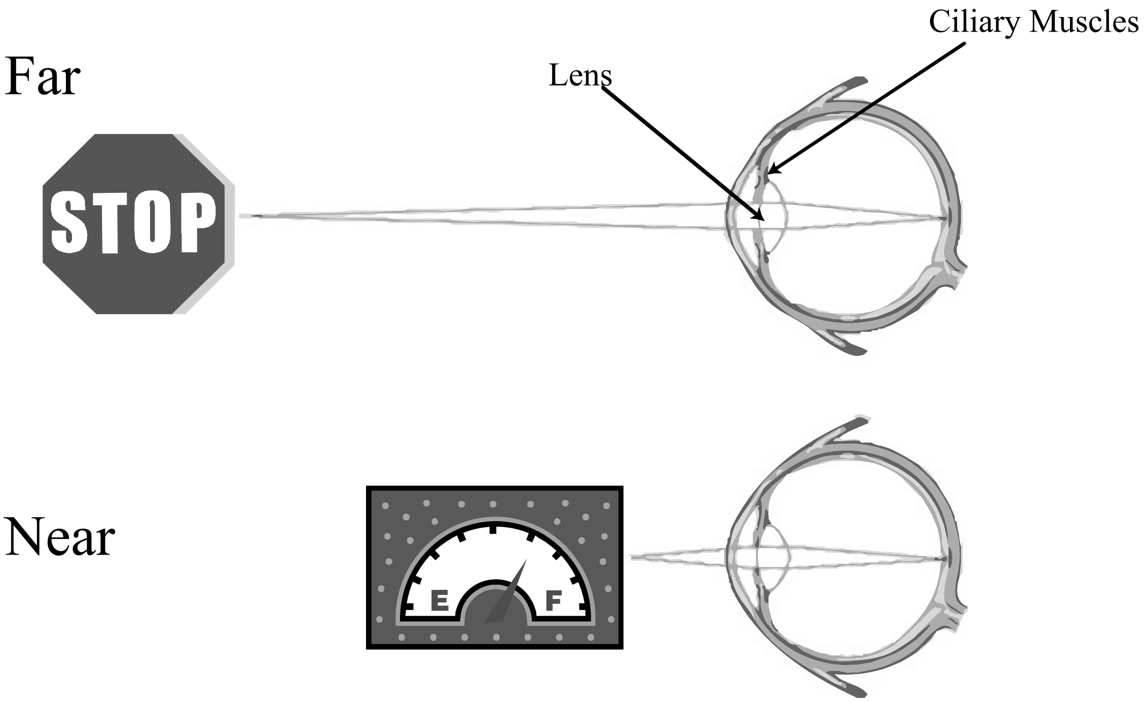

Figure 1. When the eye accommodates to an object at a near distance, the ciliary muscles in the eye contract and increase the curvature of the lens.

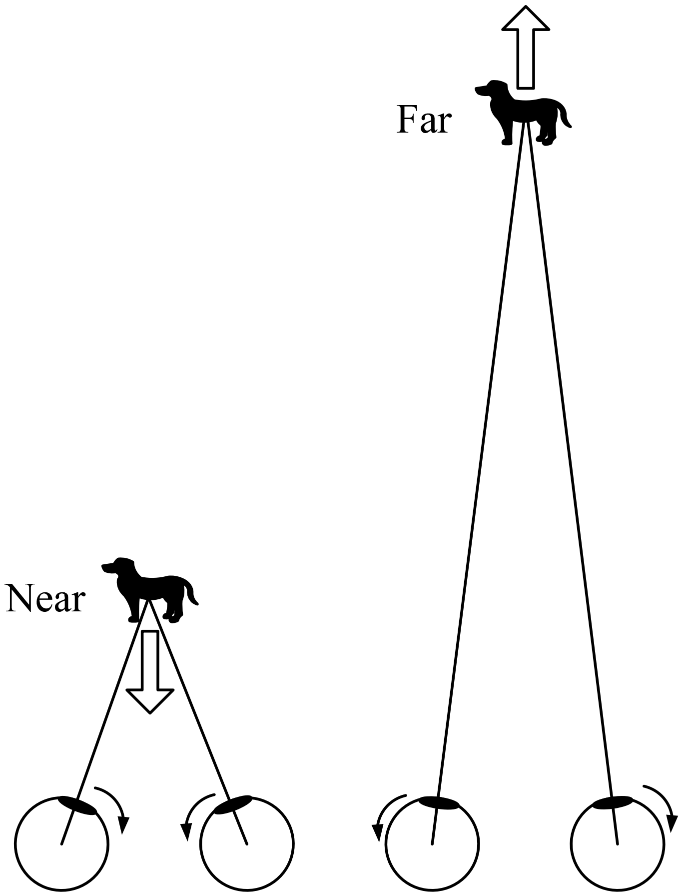

Figure 2. In binocular vision, vergence eye movements move inward as an object draws nearer, and outward as an object moves away.

Repeated shifts in depth of gaze could also fatigue eye muscles involved in vergence and accommodation. Relevant to this issue, Yuan and Semmlow (2000) found that after 100 responses to step changes in vergence, peak velocity of vergence saccades declined by 20%; however Vilupuru, Kasthurirangan, and Glasser (2005) found no evidence of fatigue after up to 450 repeated accommodative responses to six-diopter changes in stimulus depth. Other reports of changes in accommodation have been associated with subjective reports of visual fatigue after sustained near fixations (e.g., Jaschinski-Kruza, 1988; Mourant et al., 1981; Ostberg, 1980; Owens & Wolf-Kelly, 1987). Reported effects have included reduction in accommodative power (Gur & Ron, 1992; Gur, Ron, & Heicklen-Klein, 1994), increase in the near point of accommodation (Gur et al., 1994), delay in accommodative response speed and latency (Iwasaki & Kurimoto, 1988; Iwasaki, Kurimoto, & Noro, 1989), and inward shift of dark focus

(Jaschinski-Kruza, 1988). Changes in the operating characteristics of the vergence system have also been reported as consequences of visual fatigue. For example, reductions have been reported in near-point convergence (e.g., Murata et al., 1996) as well as in vergence range (Gur et al., 1994), and in near point and dark vergence (Jaschinski-Kruza, 1991).

In addition to visual discomfort, observers experiencing visual fatigue may also report blurred vision, double vision, transient myopia (Ong & Ciuffreda, 1995), or other visual difficulties associated with declines in the responsiveness of accommodation and vergence control systems.

The visual fatigue research that examines oculomotor factors is primarily applicable to tasks involving near-vision work over sustained periods of time—such as office work in which an observer reads text presented on a visual display terminal (VDT) positioned about 50 centimeters away from the observer's eyes. While some in-vehicle instrumentation may be positioned at a comparable distance to a driver's eyes, the visual demands on drivers generally require an assortment of looking behaviors over a wide range of distances, both inside and outside the vehicle. Much of this involves looking down the roadway at distances significantly farther than those involved in VDT viewing. In some cases, such variation in visual activity may, in fact, contribute to a *reduction* in visual fatigue. Indeed, one prescription for the relief of VDT-based eyestrain is to look at a distant object every half hour (Cheu, 1998). The fatigue research related to oculomotor factors seems directly relevant to lengthy work sessions at a computer screen, but it is unclear how much of this work is directly relevant to driving.

Near/far shifts in gaze. A potential cause of visual fatigue that may be important in driving is repeated changes between near and far viewing. Perhaps frequent changes between viewing the instrument panel and the external visual scene contribute to visual fatigue in a vehicle. There is, in fact, little direct research that examines visual fatigue after repeated near/far shifts in accommodation and vergence, although characteristics of the dynamics of such shifts have been used in measuring the oculomotor effects of sustained near fixation (e.g., Richter, Crenshaw, & Lyskov, 2007). Indeed, in the dominant model of oculomotor fatigue, sustained near vergence and accommodation are considered the principal sources of fatigue.

In any case, shifts between near and far locations may not contribute to visual fatigue in driving because, for most drivers, there are actually few such shifts. In terms of vehicle geometry, this shift in vergence and accommodation ranges between a near point of about 80-90 cm (the instrument panel) and a far point of 50 to 100 m (the roadway). This represents a relatively small accommodation/vergence range of about 1 diopter. Normative data describing the characteristics of eye movements during driving (Mourant & Rockwell, 1970; Shinar, 2008) suggest that modal areas of fixation are up and to the right (near the location of roadway signs), in the forward direction down the roadway, or fixed on the rear of a followed car. In one study by Recarte and Nunes (2000) less than 5% of eye fixations were made to the speedometer and less than 3% were made to mirrors. It thus seems unlikely that significant visual fatigue would develop as a consequence of normal eye movements during driving.

Foreground and background luminance levels. When the eye shifts between a brightly lit area and a darkened area, a reflexive pupillary response occurs such that the iris dilates to admit more light into the eye. When the eye shifts from a dark area of the visual field to a brightly lit area, the iris contracts, reducing the amount of light admitted. It has been suggested that inhomogeneous distribution of light about the visual field could result in the fatigue of the pupillary reflex (e.g., Pollard, Chawla, Delong, Hashimoto, & Samei, 2008), although there is some doubt that the sphincter muscle of the iris can actually be fatigued (Campbell & Whiteside, 1950). This raises the question whether, at night, the difference between high illumination produced by headlamps on the roadway and the low illumination of the passenger compartment leads to increased visual fatigue.

While it may be true that the sphincter muscle cannot be fatigued, there may be other less direct consequences of pupillary function. For example, pupil contraction also results in an increase in depth of field, which might lighten the accommodative demand on the eye. One investigation of foreground and background luminance disparity (Wolska & Switula, 1999) reported that, while there seemed to be no effect of the surrounding luminance level on reported visual discomfort (asthenopia), a large luminance ratio between the foreground and background (1:170) seemed to result in reduced accommodative response over time. It is clear that very bright ambient light should generally be avoided with VDT displays because ambient light reflected from the display screen can reduce visual contrast (by adding veiling luminance), thus reducing display legibility. To eliminate such veiling luminance, the common approach is to reduce background luminance levels to a minimum. However some recent work suggests that minimizing background luminance may not always be optimal. Pollard et al. (2008) report that detection of low contrast objects in radiological displays may be improved if background light levels are raised to match the foreground luminance level of the display. This result has interesting implications for night driving. Perhaps visual performance during night driving would be enhanced if the light level of the passenger compartment were raised to match the foreground level of the roadway.

Nonocular visual fatigue

Nonocular symptoms of visual fatigue cannot be directly associated with either oculomotor or ocular surface causes. Many of the symptoms that appear in subjective reports of visual fatigue are not easily associated with visual measures (Dainoff et al., 1981). Some symptoms, for example, may be associated with workplace ergonomics rather than visual difficulty (e.g., neck or back pain). Other symptoms may be related to systemic states of the central nervous system (e.g., headaches) that may be secondarily aggravated by visual stimuli (e.g., a bright light). Evaluation of nonocular fatigue is usually accomplished using some kind of self-reporting method (see Dillon & Emurian, 1995 for a review of these methods). The direct association of these self-reports to objectively measured visual fatigue is occasionally questioned. For example, Mocci, Serra, and Corrias (2001) remark that "psychological factors" (e.g., work satisfaction, self esteem, interpersonal conflict, and mental workload) seem to play some role in subjective reports of visual fatigue.

Another common measure of nonocular effects of visual fatigue is called the critical flicker fusion frequency threshold (CFF). This is the frequency at which a pulsing light becomes indistinguishable from a steadily illuminated light. It has been used as a measure of fatigue since the 1940s (Simonson & Brozek, 1948; Simonson & Enzer, 1941) and continues to be popular today (e.g., Luczak & Sobolewski, 2005). In broad theoretical terms, it is thought that as the central nervous system becomes fatigued, a person's ability to distinguish separate pulses of light declines. Thus, fatigue is measured as the amount of decline in an individual's CFF threshold. While quite popular, perhaps because of the ease with which the measure can be taken, the CFF frequently produces inconsistent results. In a comprehensive review, Simonson and Brozek (1952) concluded that the measure was not altogether reliable. They suggested that it may not be related directly to subjective fatigue, but instead to 'some state of the central nervous system.' In particular, they abandoned the fatigue hypothesis when no correlation was found between the subjective effects of alcohol ingestion and measured CFF.

Despite this early disclaimer by key proponents of the measure, the use of CFF continues in research on fatigue, especially in architectural lighting and office ergonomics. For example, Maas, Jayson, and Kleiber (1974) reported less visual fatigue under the influence of "full spectrum fluorescent lighting" using CFF. In a more recent review, Veitch and McColl (2001) note that other researchers observed *increased* visual fatigue with similar lighting using CFF. In general, it appears that one should use caution when employing CFF as a measure of visual fatigue. A recent study has also suggested that changes in CFF are subject to strong individual differences and significant longitudinal fluctuation (Luczak & Sobolewski, 2005).

Another measure of central fatigue that has been used is the visual evoked potential (VEP), or more generally, event related potential (ERP). The VEP is a pattern of surface electrical activity near the visual cortex that is time-locked to the presentation of a visual stimulus (the event). Measures of VEP include the amplitude and latency of this activity. Changes in these measures are taken to be associated with changes in fatigue level. For example, Iwasaki and Kurimoto (1988) report that the latency of the initial positive peak in electrical activity of a VEP increases with visual fatigue. Like CFF, measures of ERP are thought to reflect changes in the responsiveness of the nervous system.

Short wavelength lighting and general fatigue. Yet other symptoms of visual fatigue may be indirectly associated with a driver's general arousal level. This is especially likely for repetitive visual tasks in which mental fatigue may play a significant role. In some of these cases, subjective reports of visual fatigue might result from an individual erroneously associating "heavy" eyelids with a specifically visual problem.

While associations between the spectral characteristics of light and its role in visual fatigue have been reported since the turn of the past century, clear scientific evidence has been difficult to find (Eperjesi, Fowler, & Evans, 2002; McColl & Veitch, 2001; Veitch & McColl, 2001). In many cases, claims are based on largely anecdotal evidence. In an interesting new development in this area, an association has been found between exposure to certain spectral ranges of light and the suppression of the melatonin hormone (Brainard et al., 2001), known to increase during the normal sleep cycle and thought to be related to declines in arousal level. It is suspected that a specialized photoreceptor in the eye plays a role in the regulation of circadian cycles and melatonin secretion. The most potent wavelength range found to regulate melatonin is 446-477 nm. In a follow-up study, Lockley et al. (2006) directly compared the effects of light of different spectral ranges (around 460 nm and 555 nm) on arousal using subjective measures of arousal level and auditory reaction time. They concluded that the short-wavelength light was more effective in suppression of the circadian drive for sleep. In an investigation of the dose-response relationship between illuminance level for white light and subjective alertness (Cajochen, Zeitzer, Czeisler, & Dijk, 2000), the dose-response curve suggests that a maximum alerting response may be achieved with approximately 500 lux of white light, while little effect is evident below 50 lux.

While these results suggest the interesting possibility that driver fatigue may be combated by manipulating the amount of in-vehicle lighting or its spectral content, more detail is needed to determine whether this idea can be practically applied to vehicle lighting. For example, the dose-response luminance levels needed to influence subjective alertness are much higher than may be practically used for lighting applications in the passenger compartment of a vehicle at night. In addition, much of the reported effect of short wavelength light is related to a *reduction* in the circadian rise in melatonin, not a complete suppression of melatonin. That is, melatonin levels rise less rapidly in the presence of short wavelength light, but are not altogether suppressed.

Conclusions

Much of the research on visual fatigue has examined the effects of prolonged near-vision tasks, such as reading printed text or computer work in an office environment. In the context of driving, concern about visual fatigue is largely a question of avoiding visual discomfort during prolonged periods of driving. The application areas are quite different, and concerns about the office environment may not mesh well with concerns about the driving environment. For example, fatigue associated with screen flicker, VDT radiation, and prolonged near-point fixations is not likely to be of concern for driving. As a result, some of the research on visual fatigue appears to have little relevance to driving, especially research focusing on near work.

Visual fatigue in driving is primarily a problem at night, although glare from bright sunlight may also produce some visual discomfort. At night, low illumination levels, inhomogeneities in the distribution of light, and reduced features in the visual field may all contribute to visual fatigue. In addition, mental fatigue and decline in arousal level may also occur as a consequence of the monotony of driving or because of normal circadian cycles. Early research on illumination levels has supported the idea that increased illumination improves both subjective and objective measures, indicating decreased fatigue and improved performance (Simonson & Brozek, 1948). Investigation of inhomogeneous background lighting has also suggested that there might be improved discrimination if the background is better balanced (Pollard et al., 2008; Wolska & Switula, 1999). There has been less firm evidence about the effect of reduced features in the visual field on visual fatigue.

It also seems that much of the oculomotor research, which associates changes in vergence and accommodative response to near viewing, may not be directly applicable to driving. This is unfortunate, because the oculomotor research relates visual fatigue to measures that are objective, reliable, and easily understood as direct consequences of prolonged oculomotor strain. Although other objective measures are available, their association with visual fatigue is somewhat less direct. CFF and ERP, while objective, are thought to reflect more central states of the nervous system and may not be as straightforwardly associated with visual performance as oculomotor measures. Task performance measures are also objective, but may be subject to practice effects, changes in arousal level, or mental fatigue. Finally, subjective measures do not appear to always represent actual visual discomfort (Mocci et al., 2001) and are subject to varying interpretations.

The research on visual fatigue seems to suggest that several factors, operating at different levels of the nervous system, can contribute to visual fatigue. Although in some areas the evidence appears to be mixed, it may be reasonable to investigate the relationships between visual fatigue and factors that can be directly influenced by vehicle lighting. For example, it might be useful to examine whether visual fatigue can be reduced by increasing headlamp foreground illumination level in a fashion analogous to the previous reports of reductions under increased illumination (Simonson & Brozek, 1948). Perhaps the level of interior vehicle lighting level could be balanced with exterior foreground light, as was done with diagnostic reading rooms (Pollard et al., 2008). Or perhaps spectral modification of headlamp or cabin light may inhibit fatigue over long trips.

Identification of promising visual factors is only part of constructing an investigation of visual fatigue. Identifying a reliable set of dependent measures is also important. Although subjective reports of visual fatigue may be problematic, they nonetheless may provide valuable initial reference points. Use of performance-based visual tasks may offer more promise, in so far as they can be designed to involve actual driving-related activities. For example, this approach could take the form of an object-detection task in which low contrast targets are identified as they are encountered along a roadway. Of course, as mentioned earlier, care must be taken to ensure that other factors (e.g., practice) do not obscure the influence of fatigue on such measures. Finally, some objective measures may be employed, although it seems that the most reliable ones are associated with oculomotor activity and are unlikely to play a role in driving.

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