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16. Abstract
A laboratory study investigated the effects on night vision of windshield transmittance and light-scattering properties in relation to the effects of reduced contrast, glare, night myopia, and age. Three groups of subjects included: (1) ten elder drivers, (2) ten younger drivers who were susceptible to low levels of night myopia, and (3) ten younger drivers who were not susceptible to night myopia. Visual acuity of all subjects was measured for high- and low-contrast targets viewed through five windshields with and without glare that simulated opposing low-beam headlights at 50 m distance. To assess night myopia, visual accommodation of younger subjects was measured objectively under each of the ten windshield-by-glare conditions while they viewed four realistic low-luminance targets. The transmittance of three clean windshields, with different tints and rake angles (ranging from 45° to 75° from the vertical) varied from 0.86 to 0.43. Two additional conditions were created by mounting a dirty windshield at rake angles of 45° and 75,° which produced light transmittances similar to two of the clean windshields but now with a higher degree of light scatter.

The main results are as follows: (1) Reduced transmittance of clean glass elevated low-contrast resolution thresholds by 0.09 log units, but had no effect on high-contrast thresholds. (2) Light-scatter of dirty windshields elevated low-contrast thresholds to unmeasurable levels. (3) Glare elevated low-contrast thresholds by 0.18 log units. (4) Resolution thresholds were 0.28 log units higher for low-contrast than for high-contrast targets. (5) Thresholds for low-contrast targets were 0.31 log units higher for elder than for younger subjects. (6) Tests of accommodation showed significant increases of night myopia with glare and reduced target luminance, as well as a tendency toward greater night myopia for higher luminance targets with the dirty windshields as compared with the clean windshields. (The accommodation data were inconclusive, however, because few subjects had substantial levels of night myopia.) It was concluded that low windshield transmittance due to rake angle and tint has a significant detrimental effects on the visibility in nighttime driving, but these effects are small relative to those of light-scatter from high levels of dirt and wear.

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CONTENTS

INTRODUCTION

Recent design trends include changes in vehicular windshields that could have adverse consequences for nighttime visibility. Partly in response to considerations of aerodynamics, the windshields of many automobiles and light trucks are now installed at increasing rake angles. Many 1992 models on the U.S. market have windshield rake angles that deviate from vertical by angles of 60° to 66°, as compared with 45° to 50° in earlier models. While increased rake angle can reduce the frontal area and aerodynamic resistance of the vehicle, it also reduces light transmittance because of increased reflectance at the external surface of the glass. As illustrated in Appendix I, these losses are relatively small until the rake angle exceeds 60°, where about 9% of incident light is lost through reflectance. At rake angles of 65° and 75°, light losses increase to approximately 12% and 34%, respectively. (These losses are for a clean clear windshield, and they are in relation to the rake angle of 0°.) Reduction of light transmittance results in a corresponding reduction in the luminance of everything viewed through the glass.

Greater rake angles have an additional side effect, which can have still more serious implications for nighttime visibility. Windshields with greater rake angles tend to be larger in area, and their greater area results in increased cabin temperatures through passive solar heating. Tinted glass offers an economical strategy to control interior temperatures. But solar tints also reduce light transmittance and therefore may impede nighttime vision. Similar concerns apply to windshield coatings that are used for electronic deicing. Any tinting or coating, whether for temperature control or deicing, will reduce the optical transmittance of the glass, and the consequent loss of light transmittance is apt to degrade night vision.

The advent of design trends that include reduced transmittance of vehicular glass, and particularly the issues of tinting and installation angle, has attracted renewed attention from regulatory agencies. Among current rulemaking efforts are proposals to change the procedure for measuring transmittance, substituting tests at the angle of installation for the current practice that uses the angle normal to the glass surface (i.e., at a rake angle of 0°). Other proposals call for revised limits of acceptable transmittance (NHTSA, 1991). Action on these proposals, as well as more general questions of safety and design, would benefit from fuller information regarding the effects of windshield transmittance on night vision. It would be particularly useful to have a comparative analysis of the impact of this variable relative to the magnitude of effects due to normal dirt and wear, glare, and human factors such as age.

From the standpoint of visibility, the primary cost of tinting and increased rake angle is reduced luminance. Reduced luminance has little or no effect on vision in daylight, but, as illustrated in Figure 1, visual degradation is likely at luminance levels encountered in night driving. Visual recognition functions are heavily dependant on luminance as levels fall below natural daylight. Acuity, peak contrast sensitivity, and ocular accommodation (the eyes' focusing response) all deteriorate rapidly as luminance falls through the range found in civil twilight (when the sun is less than 6° below the horizon) from about 100 to 0.1 cd/m^2 (Leibowitz & Owens, 1991; Owens, 1991). Contrast sensitivity, the most critical determinant of object recognition, falls to one third of normal photopic (daytime) levels when luminance falls to ~1 cd/m^2, which is typical of objects viewed in mid-twilight, in headlights, or in fixed roadway illumination (Owens, Francis, & Leibowitz, 1989).

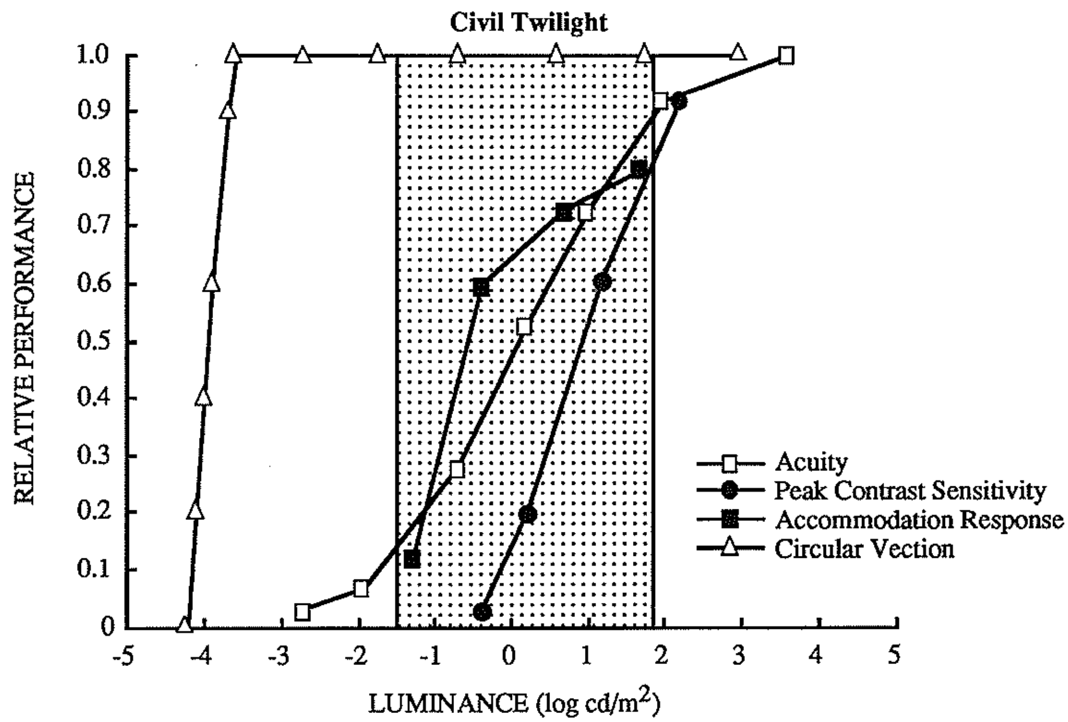

Figure 1. Visual performance as a function of luminance level. Levels encountered in civil twilight, which are indicated in the central shaded region, are characteristic of night driving environment. (Adapted from Owens, 1991.)

Though not generally appreciated by the driving public, significant losses of visibility are inevitable facts of night driving (Leibowitz, Owens, & Post, 1982; Olson, 1987). To a large extent these losses are unavoidable, and they exhibit substantial individual differences, depending on the driver's age and optometric characteristics. Older drivers have special problems related in large part to normal age-related changes in the optical transmission of the pupil, lens, and ocular media, which greatly reduce the amount of light reaching the retina (Olson, 1992; Owsley, 1987; Owsley & Sloane, 1989; Schieber, 1991; Shinar & Schieber, 1991). Young drivers can experience a different problem called "night myopia," which is not suffered by older individuals. In low illumination, younger persons' focusing ability, called accommodation, diminishes as their eyes passively return to their intermediate resting posture or *dark focus* (Leibowitz & Owens, 1975a; Leibowitz & Owens, 1978). Individuals with a near dark focus are most susceptible to night myopia and to consequent losses of acuity and contrast sensitivity for distant objects (Owens, Amazeen, & Engstrom, 1992; Owens & Leibowitz, 1976). A recent survey found that 38% of persons between the ages of 16 and 25 had night myopia of 0.75 D or more, 23% had 1.0 D or more, and 4% had at least 2.5 D (Fejer & Girgis, 1992). Although night myopia is easily corrected, it is not detected by a conventional vision exam, and it is rarely treated.

In the night driving environment, any reduction of target luminance is likely to degrade or delay visual recognition. It follows that losses of luminance through reduced transmittance of windshield glass may have negative consequences for safety in nighttime driving, and such problems may be especially serious for those drivers who already have visual difficulties at night. Thus, a key consideration for design, as well as promulgation of appropriate regulatory standards, concerns the extent to which increased rake angle and tinting will actually affect performance. These two design features can be treated in combination as a single variable of *transmittance*.

It is important to recognize, however, that transmittance is not the only optical characteristic of windshield glass that affects night vision. Optical degradation created by dirt and normal wear is also a wide-spread problem (Helmers & Lundkvist, 1988; Merritt, Newton, Sanderson, & Seltzer, 1978; Timmerman & Gehring, 1986). In this case, *light scatter* created by refraction of micro-texture on the glass surface, which may have little effect on overall light transmittance, becomes the critical variable. Light scattered by dirt and wear introduces veiling glare from external light sources. This reduces the luminance contrast of all objects in the central field of view. Reduced contrast can seriously debilitate performance in the night road environment, where important stimuli such as pedestrians, animals, or potholes are often near or below the threshold for seeing.

The present report summarizes a laboratory study of the effects of the light transmittance and scattering properties of windshields on night vision. Three windshields were in new condition, having a range of tints currently available and mounted at rake angles exceeding the range of current designs (up to 75°), so that effective transmittance ranged from 0.86 to 0.43. Two additional conditions, in which a dirty and worn windshield was mounted at rake angles of 45° and 75° (transmittance of 0.64 and 0.37, respectively), were used to evaluate the effects of scatter. Three groups of subjects, including elderly drivers and two groups of young drivers with differing levels of night myopia, were tested for visual acuity for targets of high and low contrast. Also tested was the ability of the young drivers to accommodate through the windshields for pedestrian and road sign targets. All tests were conducted with and without a glare source that simulated opposing low-beam headlights at a distance of approximately 50 m. Our goal was to determine the effect of windshield transmittance and light-scattering properties in relation to visual deficits related to age, night myopia, reduced stimulus contrast, and glare.

METHOD

Subjects

Thirty volunteers were paid to participate as subjects. All were licensed drivers with distance acuity of at least 20/20. The sample was divided into three groups according to age and susceptibility to night myopia. The *Elder Group* included 10 persons (5 females and 5 males), ranging in age from 62 to 78 years (mean age = 69.9). Two groups of younger subjects were formed from a sample of 20 volunteers (10 females and 10 males) whose ages ranged from 20 to 34 years (mean age = 25.5). Based on measures of their dark focus, they were divided by a median split into groups that would be more or less susceptible to night myopia. The *NearYoung Group* included the 10 individuals (3 females and 7 males) who were most susceptible to night myopia; their dark focus values ranged from 0.49 D to 1.64 D (mean = 0.86 D)[1], a range associated with low levels of night myopia. The *FarYoung Group* included the 10 subjects (7 females and 3 males) who were least susceptible to night myopia; their dark focus values ranged from -0.80 D to 0.40 D (mean = 0.05 D). All subjects wore their normal refractive correction for distance throughout the experiment.

Apparatus

Windshields. Four windshields were used to create the following five viewing conditions, which were selected to cover a range from best- to worst-case glass surfaces: (1) *Clear*: a brand new untinted windshield mounted at a rake angle of 45°, with a transmittance of 0.86; (2) *Blue*: a brand new tinted windshield mounted at a rake angle of 65°, with transmittance of 0.65; (3) *Gold*: a relatively new windshield (used for one year) coated with conductive film for electronic deicing and mounted at a rake angle of 75°, with a transmittance of 0.43; (4) *Dirty45 (D45)*: a worn and dirty windshield mounted at 45°, with a transmittance of 0.64; and (5) *Dirty75 (D75)*: the same worn and dirty windshield mounted at a rake angle of 75°, with a transmittance of 0.37. An adjustable platform, which permitted rapid changes of windshield glass and accurate adjustment of rake angle, was used to position the windshields at a distance of 91 cm from the subjects' eyes. All transmittance values were measured with a Pritchard photometer along the line of sight at the experimental installation angle. The transmittance values were obtained using a tungsten/halogen light source–the same type of light source that was used for presentation of stimuli in the actual study.

The *Dirty* windshield was selected to create a poor, yet realistic visibility condition. Its surface was covered with a fairly uniform layer of dirt that was accumulated while lying uncovered in an automotive workshop. This film appeared to have light-scattering properties

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[1] Measures of accommodation and *dark focus* are given as the refractive power of the eye relative to infinity. Note that this notation uses the opposite sign of that found in clinical prescriptions, which refer to the power of the spectacle or contact lens required to equate the eye's refractive power to optical infinity. This is simply a sign convention: Here myopic measures appear as positive and hyperopic as negative dioptric values; in clinical prescriptions, equivalent myopic prescriptions would appear as negative and hyperopic as positive values.

similar to those produced by road dirt or smeared insects, except there were no notable streaks or texture as commonly produced by wipers. In addition to the film, insect remains were simulated by applying an irregular pattern of mustard splotches (1 to 2.5 cm in diameter) on the exterior surface of the windshield. No mustard splotches were located near the line of sight, as a central region of 18 cm vertically by 28 cm horizontally remained unsplotched. Additional information regarding the light scattering characteristics of the experimental windshields can be found in Appendix II.

Test Stimuli. Two sets of photographic transparencies were projected onto a large screen located 7.9 m from the subject. The first set, which was used to test the acuity of all three groups, was produced by photographing the central column of letters of the Bailey-Lovie acuity charts (University of California, 1988) at several levels of magnification. The Bailey-Lovie charts provide letters at two levels of contrast with sizes increasing in steps of 0.1 log MAR (minimum angle of resolution). As projected, the high-contrast letters had luminance contrast of 0.90, and the low-contrast letters 0.10 (defined as Lmax - Lmin/Lmax + Lmin). Projected sizes of the letters covered a range of acuity levels from -0.5 to 1.3 log MAR (20/6 to 20/400) in 0.1 log MAR steps. Projected letters appeared on a brighter background field of size that varied in proportion to letter size, with boundary dimensions approximately 1.5 letter-widths. Mean luminance of the background was 1.06 cd/m^2 and ranged from 0.87 cd/m^2 for the largest targets to 1.26 cd/m^2 for the smallest targets. These luminances correspond to a surface with reflectance of 8% to 12% under illumination equivalent to the middle of civil twilight (33 lux).

The second set of transparencies, consisting of four photographs of realistic objects from the night road environment, was used to test accommodation of the younger subjects. The four targets were a speed-limit sign and a single pedestrian projected at three levels of contrast. The projected images appeared in a dark surround at luminances closely matched to actual conditions. The pedestrian wore white clothing, and neutral density filters were used to yield projected luminances of 11 cd/m^2, 0.9 cd/m^2, and 0.09 cd/m^2, which simulated clothing reflectances of approximately 100%, 10%, and 1% when illuminated at 35 lux.

Oncoming glare was created during tests of both acuity and accommodation by a slide projector, which projected a beam toward the subject through an aperture that was located 2° left of the projected targets. Neutral filters were used to adjust the intensity of the glare at the eye to 0.7 lux, a level comparable to that obtained from U.S low-beam headlights viewed from an adjacent lane at a distance of 50 m (Sivak, Helmers, Owens, & Flannagan, 1992).

Accommodation and pupillary dilation were measured with a Canon R-1 autorefractor. The cylindrical (astigmatic) component of all measures was used to compute the equivalent spherical refraction.[2] Accommodation was not tested in the Elder Group because (1) measures are imprecise for eyes with small pupils, which are characteristic of older subjects, and (2) all of the older subjects had advanced beyond the age of presbyopia when accommodation ceases to function.

A stable head position was assured for all subjects through use of the chin and forehead supports of the autorefractor. In order to simulate the near field of headlight illumination, an electroluminescent panel was mounted on the top surface of the autorefractor console. Luminance of the foreground panel was 1.0 cd/m^2; its location in the visual field covered the area from approximately 25° left to 25° right, and from approximately 2° down to 9° down. A schematic diagram of the experimental setup is shown in Figure 2.

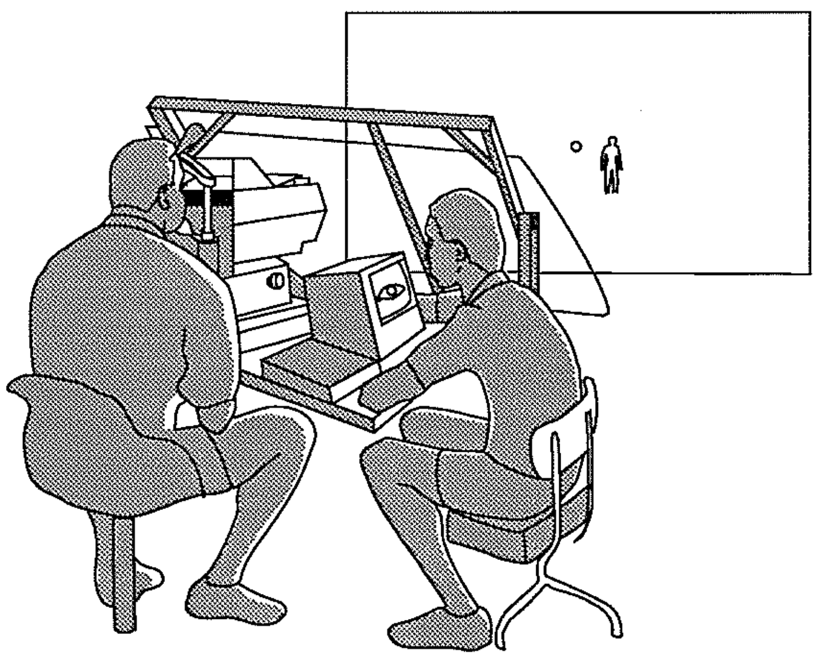


Figure 2. A schematic of the experimental setup.

[2] Measurements of the Canon R-1 autorefractor include separate components for spherical and cylindrical (astigmatic) refraction as is necessary for prescription of corrective lenses. For the present purposes, all measures of accommodation and *dark focus* were converted to the corresponding average refractive power. This is called the *equivalent spherical power* and is defined as the sum of the spherical component plus one-half the power of the cylindrical component (Michaels, 1985; Ogle, 1971).

Procedure

Subjects were tested individually. After briefing each subject about the general objectives of the study and obtaining informed consent for participation, she/he was escorted into the laboratory and seated at the autorefractor. The seat and chin-rest were adjusted to position the eyes at a height of 122 cm (48 in), and initial screening measures of visual acuity and refractive error were taken while the subject viewed a projected high-contrast acuity chart. Younger subjects then served in tests of accommodation, interleaved with tests of acuity, which in combination required approximately one hour to complete. Older subjects served in only the tests of visual acuity, which involved a test session of approximately 40 minutes.

Tests of accommodation began and ended with measures of the dark focus. For these measures, subjects were instructed to relax and gaze straight ahead into the darkness, holding fixation between two dim red areas that could be seen in near peripheral vision and were produced by the infrared illuminators of the autorefractor. The refractive power of the dominant eye was measured, while the nondominant eye was occluded by a panel that was attached to the headrest of the autorefractor and did not contact the subject's face. Five to six measures were taken over a period of approximately 1.5 minutes, and the mean spherical equivalent refractive power was taken as the subject's dark focus. Each measurement took about 200 milliseconds. Following the initial dark-focus measure, the subject viewed binocularly each of the four targets (the speed-limit sign and a pedestrian at three luminances) successively through each of the five windshield conditions. All targets were seen through a given windshield before changing viewing conditions. Six measures of accommodation were taken over a period of about 30 seconds as the subject fixated the target carefully, and the mean spherical equivalent refractive power was taken as an estimate of the subject's steady-state accommodation. Presentation orders for the targets and windshield conditions were counterbalanced among subjects. Following the last windshield condition, the subject's dark focus was measured again as at the outset of the accommodation measures; the mean of the pre- and post-test dark-focus measures was used to classify subjects according to their susceptibility to night myopia.

Acuity tests followed an ascending method-of-limits procedure. Each test series began by projecting a subthreshold array of letters, and the subject was asked to report any letters that could be seen. They were encouraged to guess. Progressively larger arrays of letters were projected until the subject correctly identified two successive letters. The threshold MAR (minimum angle of resolution) for each trial was defined as the visual angle of the critical detail of the smaller of the two correctly identified letters. Two series of trials, which used alternating sets of target slides, were conducted for each viewing condition and contrast level. For the younger subjects, the acuity measures were interleaved with tests of accommodation, each following immediately after the last measurement with the Canon for a pedestrian or speed-limit-sign focusing target. For all subjects, the order of acuity tests was (1) high contrast/ no glare, (2) high contrast/ glare, (3) low contrast/ no glare, and (4) low contrast/ glare. The order of windshield conditions was random.

RESULTS

The mean acuity (i.e., log MAR) and accommodation measures under each of the viewing conditions were calculated for each subject. Analyses of variance (mixed design) were then used to analyze the effects of windshield characteristics, glare, and subject classification on acuity. Separate analyses were done for high- and low-contrast acuity because low-contrast acuity was degraded beyond our range of measurement in the most difficult viewing conditions. For the young subjects, similar analyses of variance were used to analyze the effects of windshield condition, glare, target type, and subjects' dark focus level on accommodation (night myopia) for the distant stimuli.

Acuity

The **effects of subject characteristics and contrast** on acuity are illustrated in Figure 3. One should keep in mind that the primary dependent variable is log MAR, so the familiar acuity standard of 1.0 arcmin (Snellen ratio of 20/20 or 6/6) corresponds to a value of zero; lower values indicate better acuity, and higher values indicate poorer acuity. A log MAR of 1.0 designates a resolution threshold of 10 arcmin (Snellen ratio of 20/200 or 6/60).

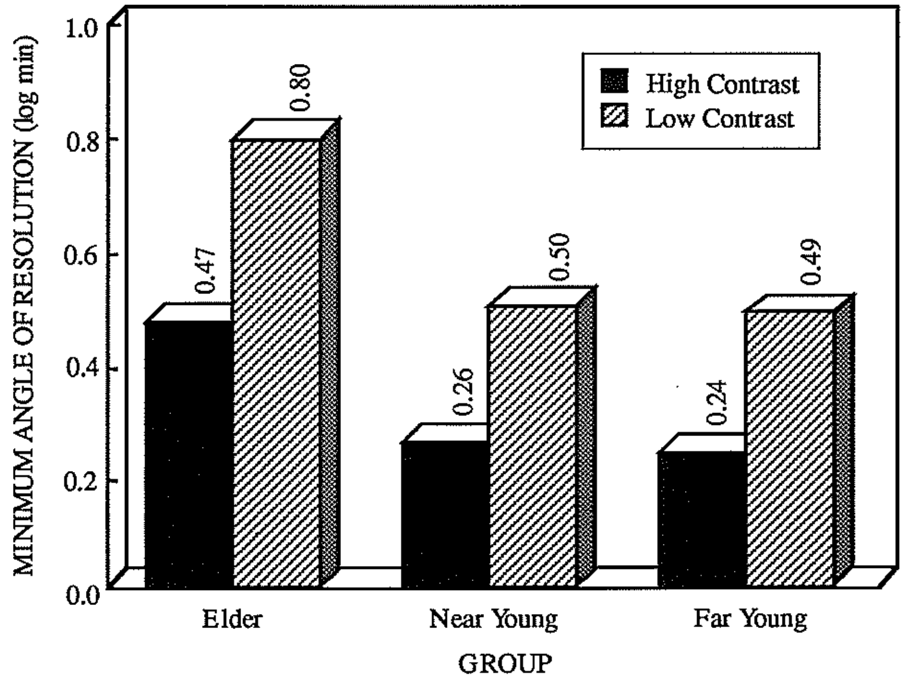


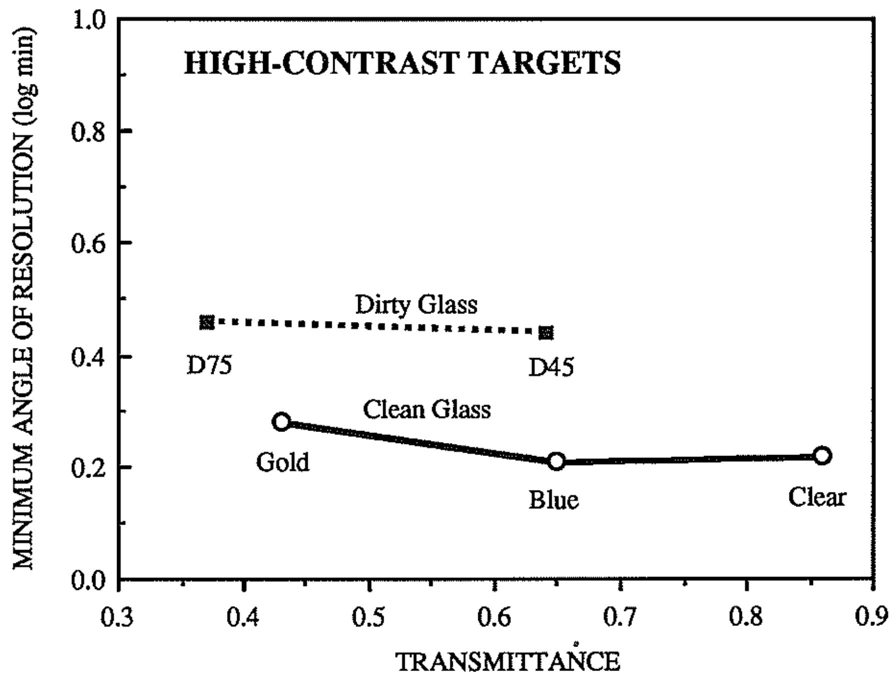
Figure 3. Mean resolution thresholds of each group for high- and low-contrast targets.

As expected, thresholds for all groups were higher for low- than for high-contrast targets (means of 0.61 and 0.32, respectively). For both contrasts, there were significant differences in mean threshold among the three groups ($F[2,27] = 12.46$ for low contrast and $F[2,27] = 9.10$ for high contrast, in both cases $p < 0.001$). Post-hoc tests indicated that, for both contrast levels, thresholds of the Elder group were significantly higher than those for the younger groups (in both cases $p < 0.01$). There were no significant differences between the two groups of younger subjects.

The **effects of windshield variables** for both contrast levels are illustrated in Figure 4. Here the mean thresholds for the combined groups are plotted as a function of windshield transmittance, with separate functions for the clean and dirty windshields. Data for the dirty windshields are not illustrated for the low-contrast condition because the thresholds of all subjects exceeded the largest target in at least one condition (i.e., the threshold was greater than 1.3 log MAR or 20 arcmin). This problem also occurred in a few cases under the other conditions. For high-contrast tests, six of 300 thresholds were greater than 1.3 log MAR. Five of these (including 4 elder and 1 younger subject) were with the dirty or gold windshield plus glare; the sixth (an elder subject) was with the gold windshield without glare. For the low-contrast tests, 10 of 180 thresholds, all for elder subjects, exceeded the limit of measurement. Nine of these occurred under conditions of glare (2 with the Clear, 3 with the Blue, and 4 with the Gold windshield); the tenth occurred for the Gold windshield without glare. In each of these instances, a value of 1.5 log MAR (32 arcmin) was substituted for the missing measurement before conducting statistical analyses.[3]

Analyses of variance showed significant differences in performance among the various windshields for both high- and low-contrast targets ($F[4,108] = 22.78$, $p < 0.0001$ for high contrast, and $F[2,54] = 7.63$; $p = 0.001$ for low contrast). High-contrast thresholds for the clean windshields ranged from 0.21 for the Blue windshield to 0.28 for the Gold windshield; those for the Dirty windshield were 0.44 at the 45° angle and 0.46 at the 75° angle. Post-hoc tests of the high-contrast data showed that there were no significant differences among the three clear windshields, nor between the two dirty windshields, but thresholds for both dirty windshields were significantly worse ($p < 0.01$) than those for all clean windshields. This indicates that the thresholds for high-contrast targets were affected by light-scatter but not by transmittance over the range of 0.86 to 0.43. Low-contrast thresholds follow a different pattern. Here the transmittance of clean windshields had a significant effect, with thresholds increasing from 0.56 to 0.65 as transmittance decreased from 0.86 (Clear) to 0.43 (Gold). There was no significant difference, however, between the 0.86 and 0.65 transmittance levels. Although quantitative comparisons are not possible, one can infer that the effects of light-scatter were also substantial for low-contrast targets, given that the thresholds with dirty windshield were all higher than the 1.3 limit of measurement.

[3] The 1.5 value was selected in an effort not to exaggerate nor to underestimate visual performance when subjects were unable to recognize any of the targets. Separate analyses of variance on data in which missing values were replaced with 1.3 rather than 1.5 yielded essentially identical inferential statistical outcomes (i.e., similar significant main effects and interactions). In our judgement, however, use of the 1.3 value would serve to underestimate the actual differences among conditions in the descriptive statistics because, in many cases, the subjects' behavior indicated that the largest target (1.3 log MAR) was still well below threshold. While it is not possible to specify the actual value of unmeasurable acuities, the 1.5 value is considered to be more accurate than 1.3 log MAR.



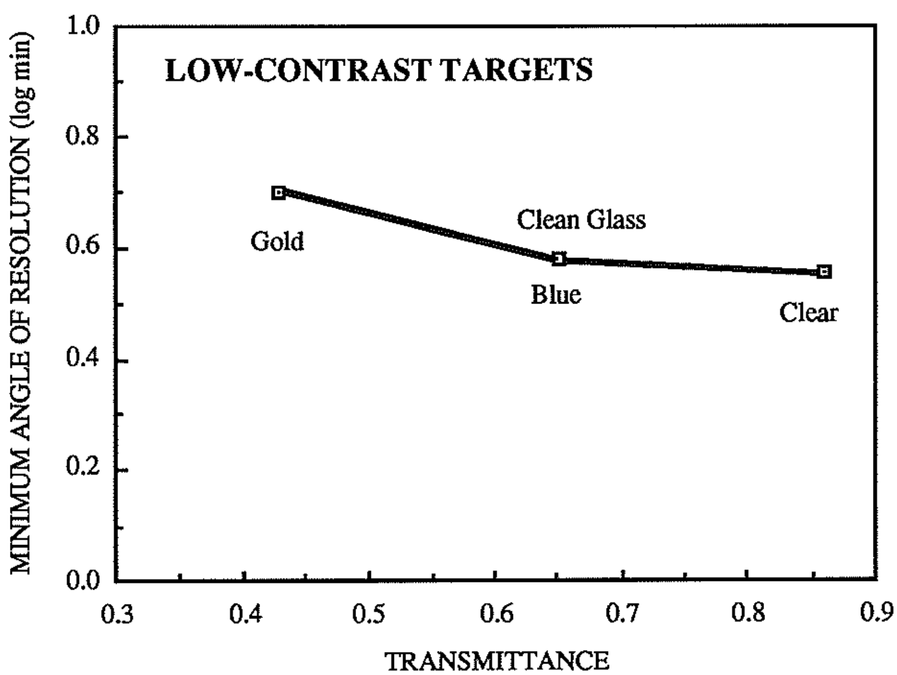


Figure 4. Mean resolution thresholds for high- and low-contrast targets as a function of windshield transmittance and clarity.

Glare also had a significant effect on resolution thresholds for both high- and low-contrast targets ($F[1,27] = 57.51$ for low- and $F[1,27] = 66.86$ for high-contrast, in both cases $p < 0.0001$). As illustrated in Figure 5, mean high-contrast thresholds increased from 0.24 to 0.41, and those for low-contrast increased from 0.53 to 0.69 when glare was introduced.

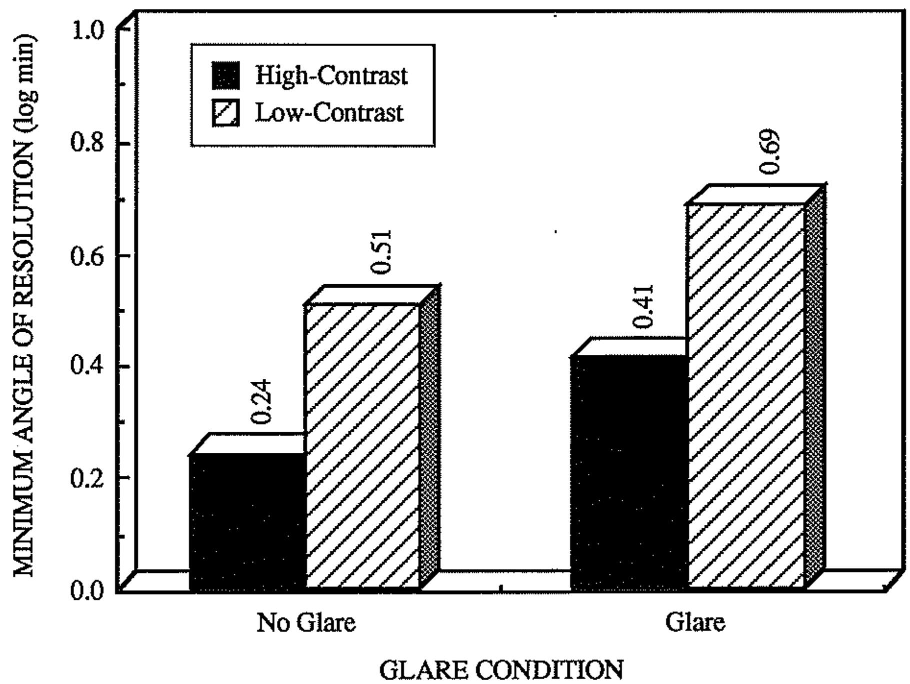


Figure 5. Effect of glare on the resolution thresholds for high- and low-contrast targets.

With low-contrast targets, glare was more debilitating for older than for younger subjects. Figure 6 presents the effects of glare for each of the groups separately for high- and low-contrast stimuli. With the high-contrast targets, glare produced an increase of roughly 0.2 log units in the resolution thresholds of all groups; there was no significant interaction between Groups and Glare here ($F[2,27] = 1.53$, $p = 0.23$). With low-contrast targets, however, there was a significant interaction between Groups and Glare ($F[2,27] = 17.13$, $p < 0.0001$); glare was more debilitating for the elder group, producing an increase in mean resolution threshold of 0.37 as compared with increases of 0.10 and 0.06 for the younger groups.

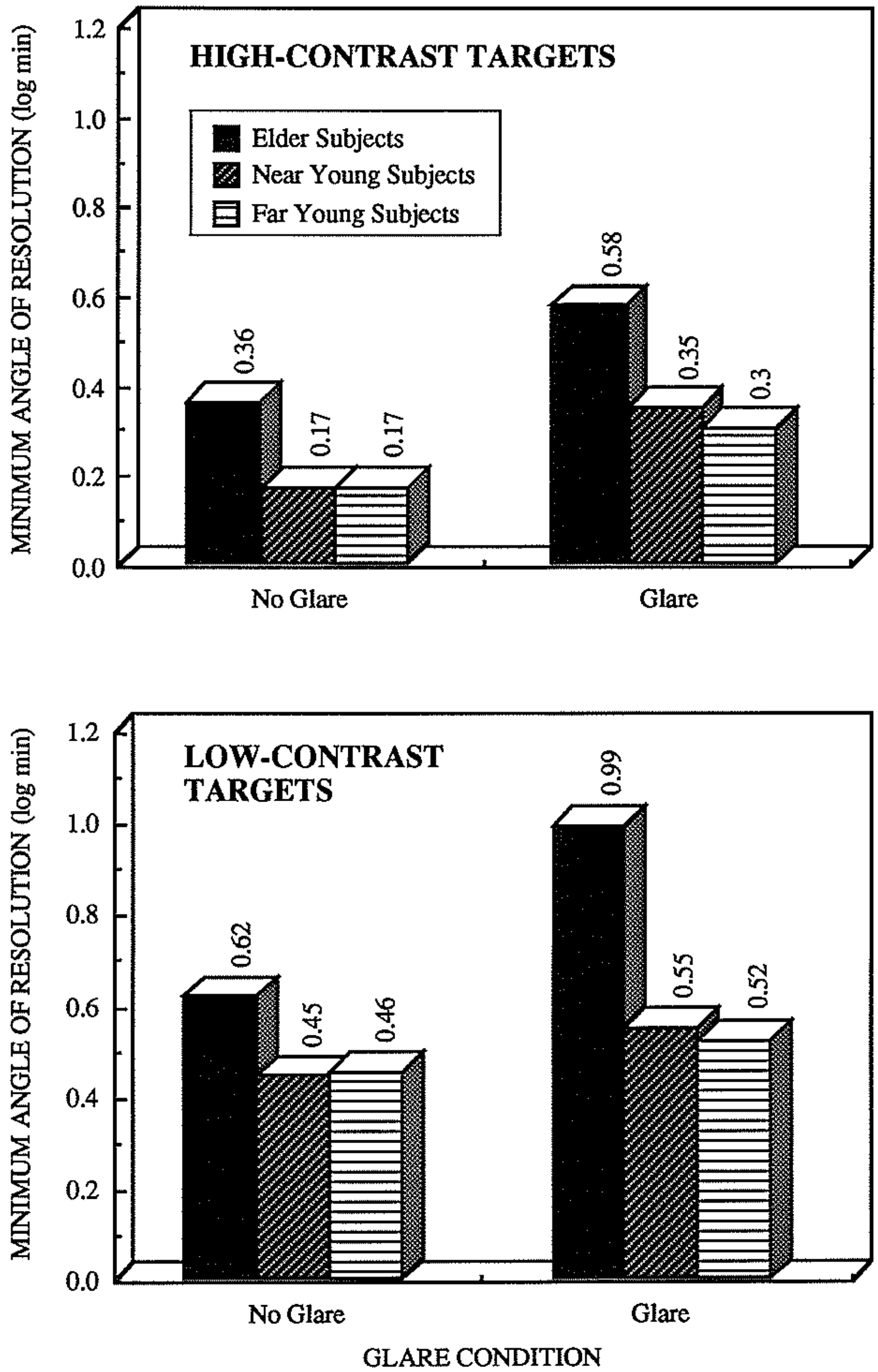


Figure 6. Effects of glare on mean resolution thresholds for three subject groups with high- and low-contrast targets.

The effects of **Glare interacted with Windshield** characteristics for the high-contrast targets ($F[4,108] = 22.91$, $p < 0.0001$), but not for the low-contrast targets ($F[2,54] = 0.29$, $p > 0.05$). These results are illustrated in Figure 7. For the high-contrast targets, post-hoc tests showed that thresholds for the Gold Glass/ Plus Glare (0.30) and for the Dirty75° Glass/ No Glare (0.31) were significantly higher ($p < 0.01$) than those for the Clear and Blue Glass/ No Glare (both 0.18). The highest resolution thresholds at 0.62 were obtained for Dirty Windshields with Glare; these were significantly higher than thresholds for all other viewing conditions, including Clean Windshields with Glare, which averaged 0.27. For the low-contrast data, the main effects of glare and transmittance are evident, while there is clearly no interaction between these variables.

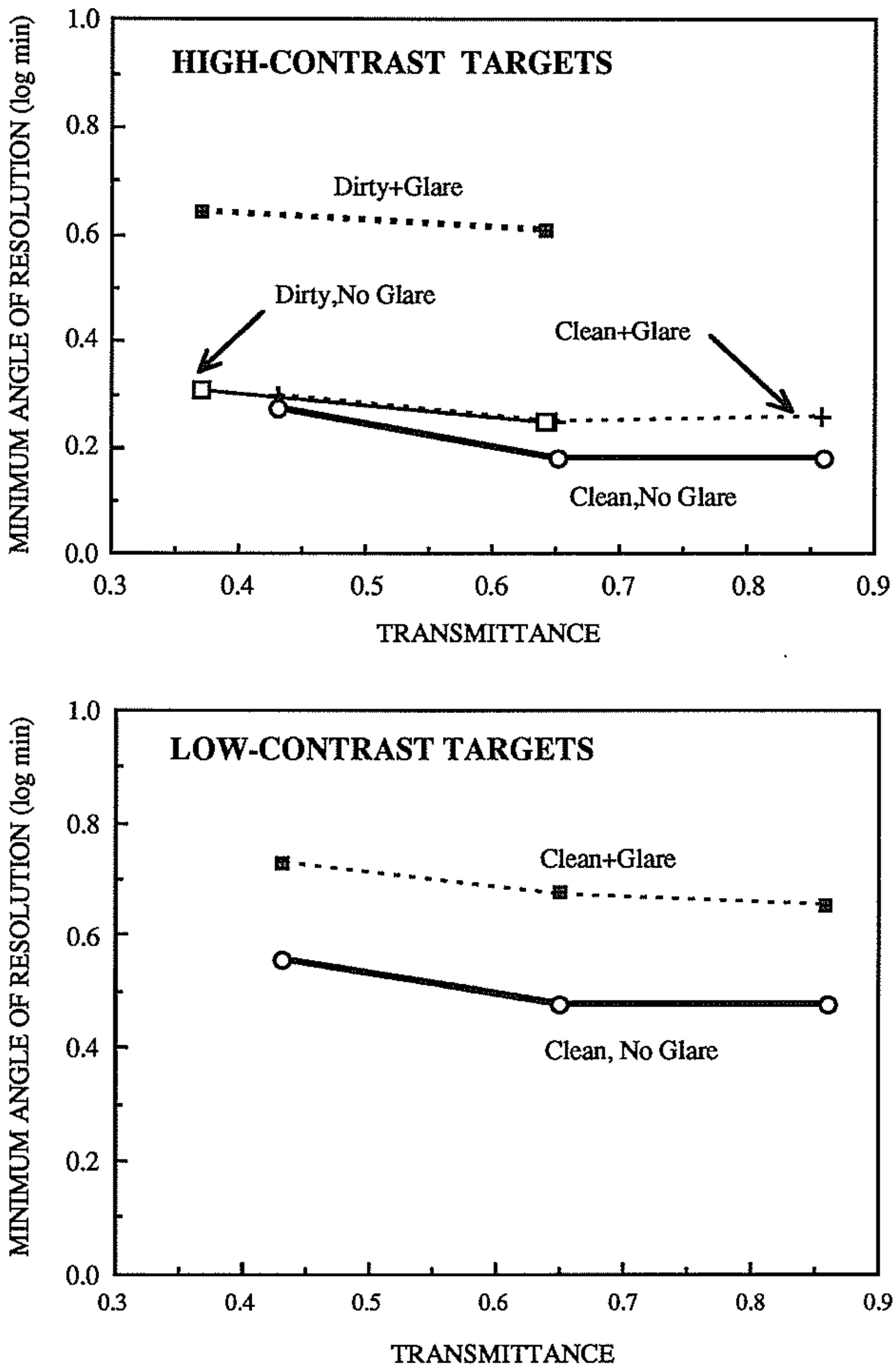


Figure 7. Effects of glare on resolution thresholds for various windshields with high- and low-contrast targets.

Accommodation

Recall that the young subjects were divided into two groups on the basis of their dark-focus values because those with higher dark-focus values are generally more susceptible to night myopia. A four-factor analysis of variance (Groups X Windshields X Targets X Glare) on their accommodation for distant targets viewed through the windshields confirmed this expectation showing that the overall mean accommodation measures for the Near Dark-Focus Group (0.45 D) were significantly greater than for the Far Dark-Focus Group (0.03 D; $F[1,18] = 30.60$, $p < 0.0001$).

There was no main effect of **Windshield** condition on accommodation ($F[4,72] = 0.87$). Nor were the interactions between Windshield and Groups ($F[4,72] = 1.06$; $p = 0.38$), or between Windshield and Glare ($F[4,72] = 0.83$; $p = 0.51$) significant, although the **interaction between Windshields and Targets** approached the conventional criterion of statistical significance ($F[12,216] = 1.65$; $p < 0.08$). A simple main effects analysis showed that this interaction depended largely on measures with the clean windshield, where increased night myopia was evident for the Dim and Dark Pedestrian targets as compared with the Sign and Bright Pedestrian targets. This effect was significant for the Clean windshield ($F[3,54] = 5.44$; $p = 0.002$); marginally significant for the Blue ($F[3,54] = 2.54$; $p = 0.07$) and the Gold windshields ($F[3,54] = 2.53$; $p = 0.07$); and it was not evident for either of the dirty windshields (for D45, $F[3,54] = 1.89$, $p = 0.14$; for D75, $F[3,54] = 0.52$, $p = 0.67$). The differential effect of target quality for the various windshields is summarized in Figure 8, which presents separate curves for the average data of the three clean and the two dirty windshields. Although the differences are small (because few if any of the subjects exhibited substantial levels of night myopia), with clean glass night myopia tends to increase with reduced target quality, while with dirty glass night myopia maintains a fairly stable level, which is somewhat higher for the speed-limit sign and bright pedestrian targets.

Combining the data across Groups and Windshields, the main effect of **Targets** on accommodation is significant ($F[3,54] = 7.39$; $p = 0.0003$). As shown in Figure 9, this effect is due largely to the results from the Near Dark-Focus Group. The **interaction between Targets and Groups** is significant ($F[3,54] = 6.19$; $p = .001$). A simple main effects analysis confirmed that accommodation for the various targets differed significantly for the Near Dark-Focus Group ($F[3,54] = 12.84$; $p < 0.001$), but not for the Far Dark-Focus Group ($F[3,54] = 0.74$).

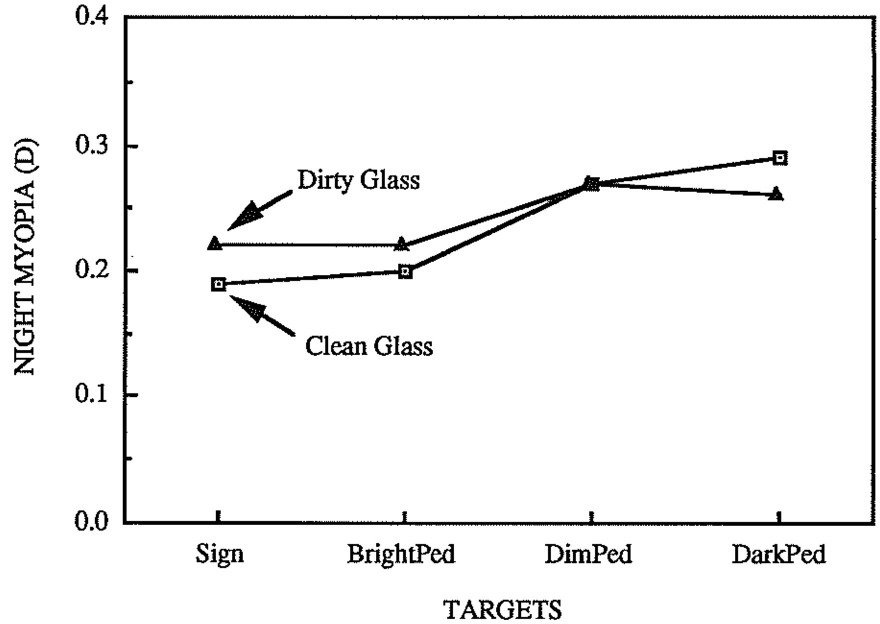


Figure 8. Mean levels of night myopia for four realistic targets viewed through clean and dirty windshields.

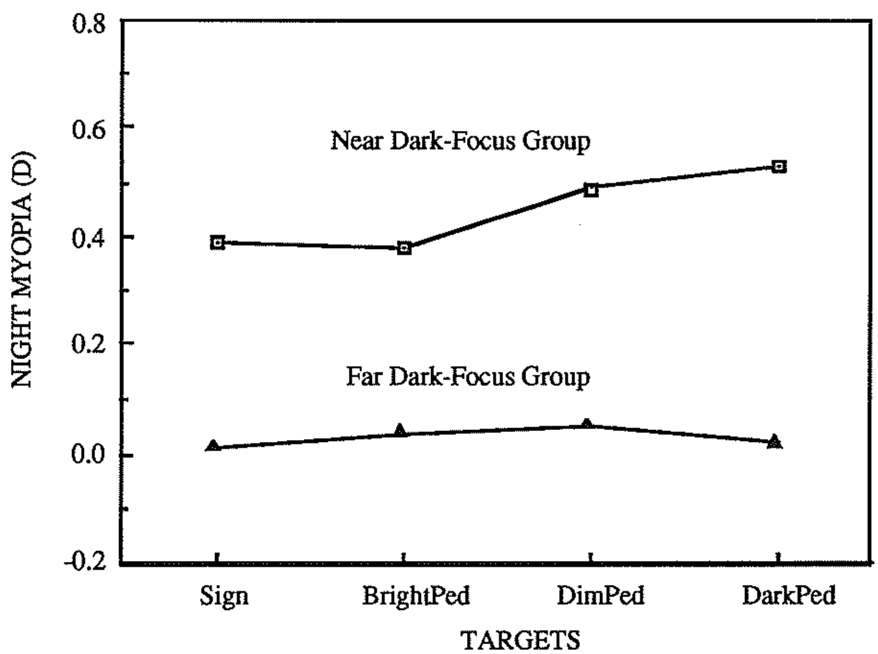


Figure 9. Mean level of night myopia of near and far dark-focus groups for speed-limit sign and pedestrian targets.

Glare also produced a small but significant main effect, increasing the overall level of night myopia from 0.21 D to 0.27 D ($F[1,18] = 15.52$; $p = 0.001$). Figure 10 shows that this main effect is also due largely to the results of the Near Dark-Focus Group. The **interaction between Groups and Glare** approached the conventional level of statistical significance ($F[1,18] = 3.25$; $p = 0.088$). A simple main effects analysis revealed that Glare had a significant effect on accommodation of the Near Dark-Focus Group ($F[1,18] = 16.49$; $p = 0.001$), but had no significant effect on accommodation for the Far Dark-Focus Group ($F[1,18] = 2.28$; $p = 0.15$).

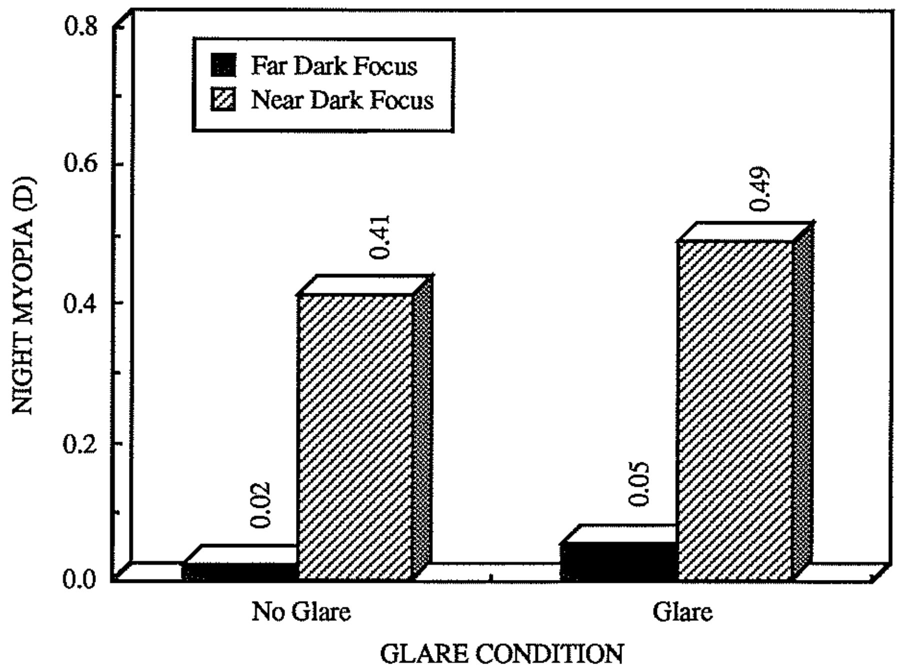


Figure 10. Effect of glare on the mean level of night myopia of near and far dark-focus groups.

As illustrated in Figure 11, the effect of **Glare also interacted with** the effect of **Targets** (F[3,54] = 6.50; p = 0.0008). A simple main effects analysis confirmed the apparent trend toward greater effects of glare with the lower visibility targets. The effect of Glare was greatest for the Dark Pedestrian (F[1,18] = 16.98; p = 0.001), and it was also significant for the Dim Pedestrian (F[1,18] = 6.07; p = 0.02), but it had no significant effect on accommodation for the Bright Pedestrian or Speed Limit Sign targets (F[1,18] = 0.23 and F[1,18] = 1.82, respectively).

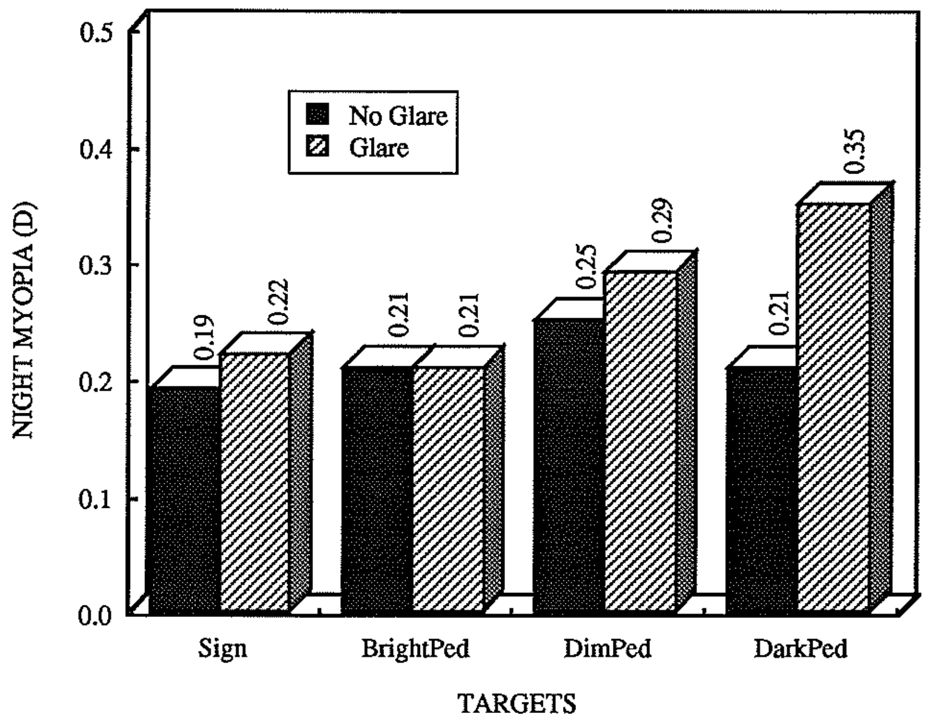


Figure 11. The effect of glare on night myopia for speed-limit sign and pedestrian targets.

DISCUSSION

The primary impetus for this study was to assess the consequences of changes in the light transmittance of windshields that arise through variations in rake angle and tinting. In order to provide a fuller context for evaluating the effects of transmittance, we also assessed the effects of five additional variables – light scatter, target contrast, glare, age, and night myopia, all of which were expected to influence nighttime visual performance and potentially to interact with the effects of transmittance. The results show that reduction of transmittance of clean glass from 0.85 to 0.43 significantly degraded visibility, but this occurred only for low-contrast targets where the log MAR increased from 0.56 to 0.65 (Figure 4; i.e., 20/73 to 20/89). These low-contrast data are of practical importance, however, because low contrast is characteristic of many of the hazardous obstacles encountered on the road at night (e.g., dark-clad pedestrians).

In addition to the effects of transmittance, the results clearly demonstrate that light scatter due to dirt and wear can dramatically impair nighttime visibility. Not surprisingly, these effects are most troublesome in the presence of glare, which greatly increases the veiling glare from light scattered by the diffusing surface. Comparing the overall results for clean and dirty windshields with similar transmittance values (collapsed across glare and no-glare conditions, Figure 4), one finds that the mean log MAR for high-contrast targets with the clean glass was 0.24 (20/35) and with the dirty windshield was 0.45 (20/56). Acuity for the low-contrast targets was too poor to measure with the dirty windshield. As shown in Figure 7, without glare, high-contrast thresholds for dirty windshields, which averaged 0.28 (20/38), were only slightly higher than those for the clean windshields of similar transmittance (0.22). In the presence of glare, however, a wider difference was obtained, with the mean threshold for the dirty windshields reaching 0.62 (20/83), while that for the clean windshields of similar transmittance increasing only to 0.28 (20/38).

Different optical factors are responsible for the effects of transmittance and light-scattering properties of windshields on night vision. Reduced transmittance degrades visibility because it reduces the luminance of all objects and surfaces in the road environment. When the targets are already dim, small additional losses of luminance result in degraded acuity, contrast sensitivity, and object recognition (Figure 1). Dirt and wear introduce an additional effect. Besides reducing luminance, the dirty or worn glass also reduces the effective contrast of the scene ahead as microtexture on the glass surface scatters incoming light, creating a veiling luminance. This veiling glare will mask low-contrast objects. In the present study, light-scattering properties of the dirty windshields had little effect on the visibility of high-contrast targets in the absence of glare, but they strongly degraded visibility of high-contrast targets in the presence of glare, and they resulted in unmeasurably poor visibility for low-contrast targets in all conditions (Figure 7). In addition to reduction of the targets' effective contrast (i.e., at the eye), veiling glare created by dirty windshield might also unnecessarily elevate the driver's level of light adaptation.

It is not possible from the present findings to infer the relative importance of light scatter for traffic safety at large. Little is known regarding the condition of windshields on the road today, or about frequency of routine cleaning. Casual observations and preliminary field tests (Timmerman & Gehring, 1986) suggest that many vehicles often have dirty windshields. In addition to small scratches due to abrasion from road dirt and cleaning, diffusing films readily accumulate on both the inside and outside surfaces of the glass. There may be strong seasonal variations in these problems. Our results indicate that in the presence of oncoming glare, losses of visibility resulting from dirt and wear can be much greater than those due to low transmittance of clean glass. Our dirty windshield was selected because it appeared to be worse than average, yet within the range of normal experience. It is important to note, however, that we cannot specify whether the condition of this glass would fall at the 10th, 5th, or even lower percentile of the vehicle fleet. Further research on the quality of roadworn windshields is sorely needed. It would be most useful to determine the optical modulation transfer functions of a representative sample of windshields in active service. The effects of light transmittance, which seem to be the focus of current interest, would clearly add to any negative effects of dirt and wear. However, it appears likely that variations of light-scattering properties are greater than those of light transmittance, and at least when facing on-coming traffic, the light-scattering properties are probably more important for nighttime visibility.

Aside from the effects of windshield variables, the present results provide new evidence regarding the role of subject variables in night visual performance. Consistent with previous work, elderly subjects, who were believed to be in good visual health, exhibited significantly poorer low-luminance acuity and greater losses of acuity due to glare than did their younger counterparts. Combining data from all viewing conditions, the mean log MAR of Elder subjects was 0.64 (20/87), while that for younger subjects was 0.37 (20/47). In the absence of glare, mean thresholds of older subjects were 0.36 (20/46) for high-contrast and 0.62 (20/83) for low-contrast targets, values that are comparable to those of younger subjects viewing the same targets in the presence of glare (Figure 6). It is interesting to note the differential effects of glare on older and younger subjects with high- and low-contrast targets. In the high-contrast condition, where both clean and dirty windshields were tested, glare produced a 60% increase in the log resolution thresholds of the older subjects and a 90% increase in the log thresholds of the younger subjects. In the low-contrast condition, however, where only the clean glass could be tested, glare again produced a 60% increase in the log resolution thresholds of the older subjects, but only a 10% increase the log thresholds of the younger subjects. This difference can probably be attributed to the age-related increase in ocular opacities (Kline & Schieber, 1985; Owsley, 1987; Owsley & Sloane, 1989; Schieber, 1991), which results in increased light scattering *within* the eyes of older persons. In effect, because of intraocular light scatter, older drivers already suffer difficulties with clean windshields that are experienced by younger drivers only with dirty windshields.

Night myopia, on the other hand, represents a problem that is experienced only by younger drivers. One should keep in mind that night myopia is an accommodative rather than an anatomical refractive error, and it is not corrected by standard refractive prescriptions. It occurs when the eyes' focusing system shifts toward the resting posture because of inadequate stimulation. As seen in Figure 9, individuals with a distant dark focus have no problem, while those with a nearer dark focus have correspondingly greater night myopia whenever visibility deteriorates. One should also note that subjects in the present study who were nominally susceptible, the Near Dark-Focus group, exhibited only low levels of night myopia. Their mean dark focus and overall mean night myopia were 0.86 D and 0.45 D, respectively. This coincides with previous findings that night myopia on the road is approximately one-half the level predicted by the dark focus (Owens & Leibowitz, 1976), but the dark focus of our sample was relatively low compared with earlier reports, which are typically 1.5 to 1.7 D (e.g., Leibowitz & Owens, 1975b).[4] A recent clinical survey (Fejer & Girgis, 1992) found that 38% of patients between the ages of 16 and 25 had night myopia of 0.75 D or more. In the present study, only 10% (1 of 10) of the "near" subjects exhibited this level of night myopia under the best-case condition (i.e., speed-limit sign target/clear windshield/no glare), and only 30% (3 of 10) did under worst-case conditions (i.e., dark pedestrian target/dirty windshield/with glare). Further study of individuals with higher levels of night myopia will be necessary for full assessment of the potential contribution of windshield variables to night myopia in driving.

Despite the low levels of night myopia, the present findings suggest that windshield variables and glare, as well as target quality, affect the magnitude of night myopia in night driving. As shown in Figure 8, variations in the magnitude of night myopia were greater with clean than with dirty glass. Although of marginal statistical significance, night myopia was minimal through clear glass when viewing a relatively bright target (speed-limit sign or pedestrian), and it tended to increase for the dimmer (pedestrian) targets. This was not evident for the dirty windshields, when night myopia tended to be present also for the brighter targets. This is consistent with earlier research, which showed that night myopia increases progressively with decreased target visibility (e.g., Leibowitz & Owens, 1975a; Owens, 1984). Dirty windshields, especially in the presence of glare, would be expected to result in greater night myopia because they reduce the effective contrast of all targets. The present data also provide new evidence that night myopia is greater in the presence of glare (Figure 10) and when viewing low-luminance targets that are typical of the night road environment (Figure 9). Furthermore, there was a significant interaction of the effects of glare and target luminance resulting in greatest night myopia for low-luminance targets in the presence of glare (Figure 11). These results are also consistent with previous findings that night myopia increases with reduced target visibility. But again, the effects are small (though

[4] Part of this difference in dark focus may be related to the use of an objective autorefractor, which tends to record lower levels of dark focus than subjective instruments like the laser optometer (Post, Johnson, & Owens, 1985).

statistically significant), and therefore in need of confirmation through further research on individuals who exhibit greater night myopia.

While the present results indicate that glare and reduced target luminance contribute to night myopia when driving, they provide no clear evidence that this had an effect on visibility. None of the acuity measures revealed a significant difference between the two groups of young subjects (Figures 3 and 6). This should not be taken as reason to dismiss the potential impact of night myopia on night driving, however. It is possible that tests of individuals who suffer greater levels of night myopia would reveal associated losses of visual acuity. Moreover, the present acuity measures may have been insensitive to the effects of night myopia. Recent studies indicate that night myopia of 0.75 D or more produces substantial losses in contrast sensitivity even at relatively low spatial frequencies (Bedell, 1987; Owens et al., 1992). In general, the contrast sensitivity function is more informative than visual acuity as an index of visual recognition, and further investigations of the potential effects of night myopia, including those related to the effects of windshields, should use this superior test.

In summary, the present study took a rather broad approach to assess the effects of light transmittance and scatter by windshields on nighttime visual performance. The visual problems encountered in night driving are important and complex. They involve individual differences in human factors such as age and night myopia, situational variables such as object contrast and glare, as well as vehicle characteristics such as headlights and windshields. It may be impractical to study all of these variables in one experiment, but it could also be unrealistic, and even misleading, to isolate a single variable without consideration of its relationship to other aspects of night vision and driving. This investigation took a preliminary step toward evaluating the effects of windshield variables in the context of relevant characteristics of the driver and the night driving situation. From these data, one can estimate, for example, the effects of transmittance relative to those of light scatter, or to those of glare or age, but further research will be necessary to refine the precision of these estimates. It would be especially helpful to obtain fuller information regarding the condition of windshields in active service, the prevalence and magnitude of night myopia in the driving public, and the validity of laboratory tests of vision for predicting performance on the road. Meanwhile, the present findings may provide useful information for designing windshields and government regulations, as well as future investigations.

CONCLUSIONS

The present study found that each of the following factors had significant effects on nighttime visual performance: transmittance of the windshield (manipulated by rake angle and tint), age of the observer, presence/absence of glare, contrast of the visual stimulus, and light scatter. Table 1 compares the magnitudes of the main effects of each of these variables under selected conditions. The results are summarized in terms of changes in log threshold (MAR), as well as in the more familiar terms of Snellen ratio.

Table 1. Variables with statistically significant effects on visual resolution performance. The values given represent simple main effects averaged across other variables. Conditions have been selected as indicated to estimate effects that are most pertinent to night driving (e.g., low-contrast objects).

Variable	Range tested	Source	Change in log threshold (MAR)	Change in Snellen ratio
Transmittance*	0.86 - 0.43	Figure 4 (low contrast)	0.09	20/73 -> 20/89
Age of the observer*	26 - 70 years (means)	Figure 6 (low contrast)	0.31	20/62 -> 20/126
Glare*	0 - 0.7 lux	Figure 5 (low contrast)	0.18	20/65 -> 20/98
Target contrast	0.9 - 0.1	Figure 3	0.28	20/42 -> 20/80
Light scatter**	clean & dirty windshields	Figure 7 (high contrast)	0.34	20/38 -> 20/84

*These data are for low-contrast stimuli and clean windshields only.

**These data are for high-contrast thresholds measured with glare through clean windshields with transmittance of 0.65 and 0.43, and dirty windshields with transmittance of 0.64 and 0.37. Low-contrast thresholds for the dirty windshields exceeded the range of measurement.

Over the ranges tested, age, glare, target contrast, and light-scatter had greater effects on resolution performance than transmittance. Light-scatter produced the largest effect, with a threshold elevation of 0.34 log units for high-contrast stimuli viewed in the presence of glare. Age and contrast had slightly smaller effects, with threshold elevations of 0.31 and 0.28 log units, respectively. Glare had an intermediate effect, with a threshold elevation of 0.18 log units. (Note that this refers to the effect of glare on the threshold for low-contrast targets with clean windshields. The overall effect of glare, including both clean and dirty windshields, on the threshold for high-contrast targets was also 0.18 log units.) In this context, the effect of windshield transmittance is relatively small, though statistically significant, resulting in a threshold elevation of 0.09 log units for low-contrast stimuli.

Focusing on the consequences of windshield variables for nighttime visual performance, these results indicate that the effects of light scatter from dirt or wear are more troublesome than those due to reduced windshield transmittance. This comparison should be made with caution, however, because (1) it is uncertain how representative the experimental dirty windshield was relative to the active vehicle fleet, (2) light-scatter had little effect on resolution in the absence of glare (Figure 7), and (3) the effects of light-scatter may have been different, perhaps greater, for low-contrast targets. Although the effects of reduced transmittance are smaller, they represent loss of visibility for stimuli that are particularly relevant to hazards encountered in nighttime driving, and these losses are expected to interact or combine additively with losses due to other variables that degrade nighttime visibility. From the standpoint of safety, windshield transmittance could well be an important variable in events where timely recognition of a low-contrast object, such as a pedestrian, is essential to avoid an accident.

Tests of visual accommodation indicated that, for young susceptible individuals, night myopia is exacerbated by reduced target luminance and glare. There was also a tendency toward greater night myopia for bright targets when viewed through dirty as compared to clean windshields, but there was no effect of windshield transmittance on night myopia. Though suggesting possible effects of windshield variables on night myopia, this inference is tentative because the present subjects exhibited only small levels of night myopia. Clarification of the possible effects of light transmittance and scatter of windshields on night myopia awaits future experimentation with subjects who suffer more substantial levels of night myopia.

Visual performance in night driving is subject to the combined effects of all of variables listed in Table 1 and, insofar as possible, each variable should be optimized in the interest of safety. From this standpoint, our results suggest that control of dirt might be more cost-beneficial than control of transmittance.

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APPENDIX I

The effects of rake angle on transmittance of windshields used in the present study are shown in Figure 12.

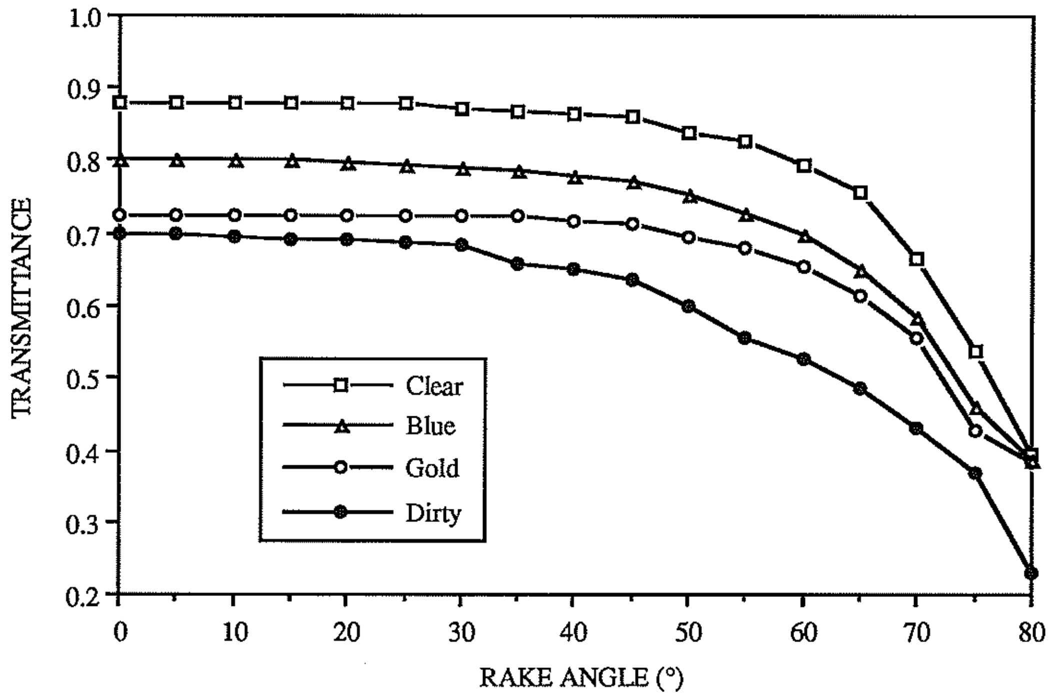

Figure 12. The effects of rake angle on transmittance of windshields used in the present study.

APPENDIX II

Light scattering characteristics of the experimental windshields were measured according to the technique devised by Helmers and Lundkvist (1988, Appendix 1). The measurements were taken with the glare source at an eccentricity ("dazzling angle") of 2.0° as used for the present psychophysical tests and with two glare intensities: 0.7 lux as used in the present experiments and 115 lux for comparison with the measures of Helmers and Lundkvist (1988). Table 2 provides a summary of the light-scatter coefficients (Lv) of the five windshields in the present study at both glare levels. Also shown are data for two windshields from Helmers and Lundkvist, which were described as "new clean" (H&L#1) and "very worn washed" (H&L#3), evaluated at the 115 lux level. The magnitude of light-scatter introduced by each windshield was then compared with level of intraocular light-scatter (Ls), which was estimated using the following formula: Ls = 10 * lux at the eye / glare angle^2.

Table 2. Light-scatter coefficients (Lv) for the five experimental windshields used in the present experiment as measured at two levels of glare. The level of light-scatter by the windshield glass (Ls) relative to magnitude of light-scatter within the eye is given in the columns labelled 'Lv vs. Ls.' Data from two windshields reported by Helmers and Lundkvist (H&L #1 and #3) are also included for the 115 lux glare level.

Windshield	Glare = 0.7 lux		Glare = 115 lux	
	Lv	Lv vs. Ls	Lv	Lv vs. Ls
Clear	0.03	2%	2.71	1%
Blue	0.06	3%	3.27	1%
Gold	0.17	10%	8.33	3%
Dirty 45°	3.63	207%	420	146%
Dirty 75°	3.66	209%	353	123%
H&L #1	—	—	4.6	2%
H&L #3	—	—	132	46%