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Predicting Components of Closed Road Driving Performance From Vision Tests

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ABSTRACT: *Purpose.* Mild cataracts can interfere with visually dependent everyday activities, although they only minimally affect static visual acuity. This study compared the effects of simulated cataracts with that of optical blur on driving performance and determined the extent to which acuity could account for variations in driving performance either alone or in combination with supplementary vision tests. *Methods.* Closed road driving performance was measured in 24 young, normally sighted subjects under five binocular acuity levels, four produced by different levels of optical blur (6/4.5, 6/12, 6/30, 6/60) and one by frosted lenses simulating mild cataracts (6/12c). Driving measures included gap perception, total driving time, sign recognition, road hazard avoidance, maneuvering time, and errors. Subjects were also tested with the Pelli-Robson chart, SKILL card, and Berkeley Glare Test under comparable acuity levels. *Results.* Total driving time, sign recognition, and hazard avoidance were linearly related to the acuity degradation produced by blur; performance in the 6/12c condition was similar to that in the 6/60 blur condition. Static acuity predicted 30% to 60% of the variance in these driving measures when the 6/12c condition was excluded from analysis; this proportion was reduced by a factor of two to three when the 6/12c condition was included. However, using any one of the three supplementary tests with visual acuity in a multiple regression analysis recaptured much of the lost variance. *Conclusions.* Static acuity can only predict variations in closed road driving performance measured under degraded conditions that include simulated mild cataracts when it is combined with supplementary vision tests. (Optom Vis Sci 2005;82:647–656)

Key Words: driving performance, vision, visual acuity, contrast sensitivity, SKILL score, Disability Glare Index (DGI)

A continuing issue confronting motor vehicle licensing agencies concerns the selection of a vision test (or test battery) that will enable the accurate prediction of driving safety.[1,2] Numerous researchers, following the lead of Albert Burg, attempted to address this issue by correlating measured visual characteristics of licensed drivers (e.g., visual acuity) with some index of driver performance.[3–7] Typically, traffic accident records were used as the measure of driving performance, and with large samples, significant correlations between vision test results and driving record were obtained. However, the magnitude of the correlations, approximately 0.1, indicated that little of the variance in the crash database could be attributed to variations in visual characteristics within the driving sample.

At various times, it has been suggested that this apparent failure of vision tests to predict significant aspects of driver performance may, in part, be the result of limitations inherent in the methodological approach used by Burg and his successors.[8,9] First, the use of licensed drivers is likely to have eliminated most, if not all, of those with generally poor vision, thereby biasing the sample toward individuals with generally good vision. Second, real-world crashes are statistically rare events[10] and, for that reason, are unlikely to provide a fine-grained measure of differences in driving performance among the sample of drivers.

One noteworthy attempt to improve the sensitivity of the Burg et al.[3] approach is represented by the more recent work of Ball et al.[11] These investigators examined the relationship between vision test results and crashes in a sample of elderly drivers that were selected to represent different frequencies of crash involvement (0, 1, and 3 or more "at-fault" crashes) during the previous 5 years. This approach ensured that crash record would, in principle, provide a finer-grained discrimination among drivers. In addition, by selecting a group of elderly drivers, Ball et al. ensured that their sample would manifest a greater range of performance on vision tests (e.g., visual acuity, contrast sensitivity) than would occur in the general population. However, notwithstanding these improvements, Ball et al.[11] found that although there were significant correlations between vision test performance and crash frequency, the magnitude of the relationships remained relatively weak. They noted that "no single value of acuity, contrast sensitivity, or peripheral vision could be adopted that would place persons in the high-risk category without including a significant number of crash-free drivers in this category as well."[11] The most significant predictor of crash involvement was the Useful Field of View (UFOV), a test that provides a measure of higher-order processing of visual information under conditions requiring divided and selective attention but is not particularly demanding in terms of its acuity and visual field size requirements.

Closed road driving assessments provide another approach for attempting to improve the sensitivity of the paradigm used to investigate the effect of different levels of simulated[12] and real[13] visual impairments on driving performance. We used the same approach to investigate the effect of different kinds (blur vs. simulated cataract) and amounts (6/4.5 to 6/60) of visual acuity degradation on closed road driving performance.[9,14] We reported that some, but not all, measures of driving performance were significantly and linearly related to the level of acuity degradation when the acuity degradation was produced by optical blur.[9] In addition, acuity degradation could explain as much as 50% to 60% of the variance in sign recognition and road hazard avoidance measures of driving performance.

In this article, we consider the effect of optical blur and simulated cataracts[14] on driving performance and, further, the need for supplementing high contrast acuity measurements with results from at least one additional test to account for the effects of different mechanisms (e.g., uncorrected refractive error vs. cataract) by which visual acuity may be degraded. Conceptually, the approach represented by this research on driving is similar to studies by Elliott et al.[15] and Anand et al.[16] regarding the effects of simulated cataracts on pedestrian mobility and postural stability.

METHODS

Experimental Design

A repeated-measures experimental design was used to test young visually normal subjects on two different closed road driving circuits and on each of four vision tests (static acuity plus three supplementary tests) under each of five binocular visual acuity levels. One level represented normal viewing, and the remaining four represented differing kinds and amounts of simulated acuity loss.

Subjects

Twenty-four young, visually normal adults (15 males, 9 females), ages 20 to 35 years (mean 23.1 ± 3.8 years) participated in this research. Subjects were recruited from the staff and students at the School of Optometry, Queensland University of Technology. All were in good health, free of eye disease, and had a distance visual acuity of 6/6 or better. All held a currently valid driver's license and reported that they drove regularly.

The study was conducted in accordance with the requirements of the Queensland University of Technology Human Research Ethics Committee. All subjects were given a full explanation of the experimental procedures, and written informed consent was obtained with the option to withdraw from the study at any time.

Binocular Distance Acuity Levels

The driving performance of each participant was measured under each of five binocular distance acuity levels, one representing their normal acuity and the remaining four representing degraded acuity levels. Distance acuity was determined for each subject under the outdoor illumination conditions (shade, not direct sunlight) present at the test track using a standard high-contrast Bailey-Lovie Chart (Australian Vision Chart no. 5). This chart is designed for a working distance of 4 meters and visual acuity was scored on a letter-by-letter basis. For each condition, subjects wore a pair of modified swimming goggles that provided a field of view equivalent to that provided by standard 38-mm diameter trial lenses. For the normal acuity condition, subjects drove while wearing the goggles but without any additional optical device other than their normal distance spectacle correction, which was incorporated into the goggles using standard wide-aperture trial lenses. The average normal visual acuity of the 24 subjects was 6/4.5.

Plus lens blur was used to produce three of the four degraded distance acuity levels. Specifically, binocular plus lenses were used to reduce each subject's binocular distance acuity to each of three levels: 6/12, 6/30, and 6/60. (These are equivalent to 20/40, 20/100, and 20/200, respectively, in the U.S. notation.) The average amounts of plus lens blur necessary to reduce the subjects' average distance acuity to each of these levels were 1.82 (± 0.85), 3.13 (±0.90), and 4.85 (±0.99) D, respectively.

The cataract simulators described previously[17] were used to produce the fourth degraded acuity level. These cataract simulators reduced Bailey-Lovie distance acuity to an average level of approximately 6/12 (6/11.4 to be exact). Most of the subjects (80%) were still able to meet the minimum 6/12 acuity level required for driver licensure. To distinguish this 6/12 viewing condition from the 6/12 condition produced by optical blur, it will hereafter be referred to as the 6/12c acuity level, the "c" referring to the cataract simulators.

To characterize the difference between the two 6/12 acuity conditions, the Vistech Chart[18] was used to measure spatial contrast sensitivity of all subjects under normal viewing conditions and under the 6/12 optical blur and 6/12c simulated cataract conditions. These measurements were undertaken in the laboratory. The test distance was 3 meters and the chart background luminance was approximately 90 cd/m^2, with a variation of approximately 5% across the surface of the chart. The degraded acuity levels were tested first, and the normal viewing condition was tested last.

Figure 1 illustrates the difference between the simulated cataract (6/12c) and 6/12 optical blur conditions compared with normal binocular viewing. This figure compares the mean contrast sensitivity of the subjects under each of the three conditions measured using the Vistech chart. Compared with normal binocular viewing (6/4.5), the 6/12 optical blur condition produced a predominantly high spatial frequency loss in sensitivity. The cataract simulator produced a similar magnitude of loss in high spatial frequency sensitivity plus an additional loss at low spatial frequencies. The magnitude of the loss at 1.5 c/deg was approximately 0.5 log unit. One of the authors (JW) has more recently found a similar magnitude of low frequency loss using the cataract simulator with a CRT-based contrast sensitivity test system.

The order of testing was balanced across the four degraded acu-

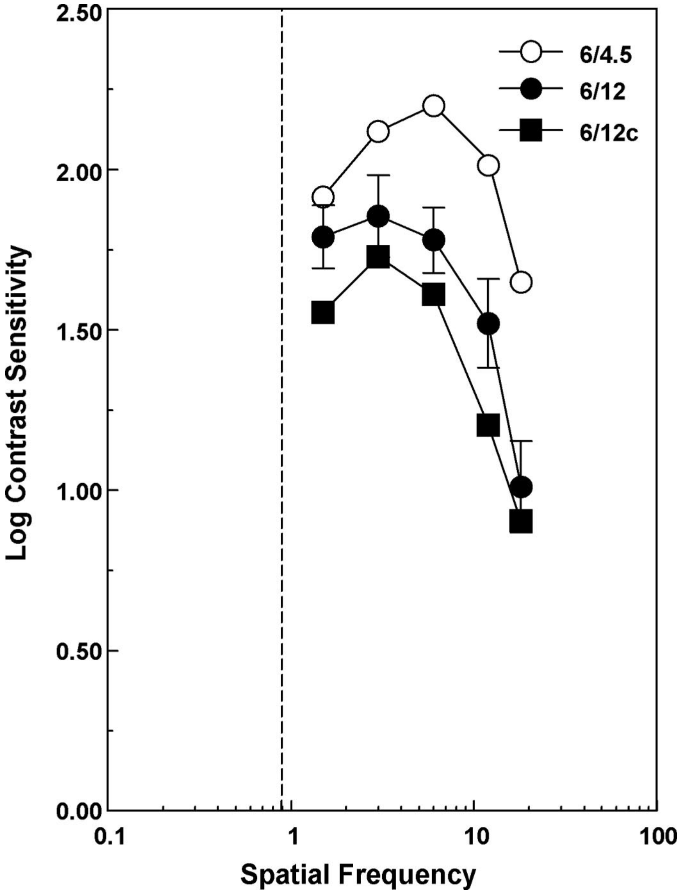

FIGURE 1.
Comparison of Vistech spatial contrast sensitivity measured under normal binocular acuity (6/4.5) conditions with that obtained under the 6/12 optical blur and simulated cataract (6/12c) conditions. Error bars represent ± 1 standard deviation. The vertical dashed lines represent the predominant spatial frequency of the letters on the Pelli-Robson Chart when viewed at a 1-meter test distance.[27]

ity conditions using a Latin square design. This design was used in an attempt to distribute any learning (memorization) effects across the four degraded acuity conditions. The normal acuity condition was always tested last to minimize the possibility that subjects would memorize the numerous signs and obstacles along the roadway.

Closed Road Driving Circuits and Measures of Driving Performance

Each subject's driving performance was assessed using two test circuits.

Main test circuit

The main test circuit consisted of a 5.1-km closed bitumen roadway with hills, curves, straightaways, intersections, and an abundance of roadway signage. The roadways were bordered by a series of large trees that produced numerous shadows. In addition, a number of additional roadway objects were introduced to obtain some of the measures of driving performance described subsequently.

Total driving time: The total time required to complete the 5.1-km course was recorded for each subject and acuity condition.

Sign recognition/peripheral awareness: Subjects were instructed to identify each sign that they saw while they drove around the main test circuit under each of the five different acuity levels. Of the 65 signs along the main test course, 10 were primarily informational (e.g., street names, road curvature information) and the remainder were regulatory (e.g., stop and speed limit signs). The total number correctly detected was recorded for each test drive. It is important to note that none of the participants were able to report all of the signs, even when driving with their normal vision.

Road hazard recognition/avoidance: Subjects were informed that there would be a number of "road hazards" positioned throughout the main test course. These consisted of nine 1 m x 2.2-m sheets of 8-cm thick gray foam rubber "speedbumps" placed at different locations throughout the course. One subject described them as resembling blocks of concrete lying across the roadway. These obstacles did not interfere with vehicle control when struck, although participants could "feel" when they ran over them. Participants were told to indicate verbally when they saw one of the hazards and to avoid it by steering around it. Interestingly, when driving with degraded acuity, there were a number of occasions on which subjects mistook the shadows of trees on the roadway for the hazards and steered around them. On each test drive, subjects received a score for the number of hazards seen, the number seen too late to avoid hitting, and the total number hit (irrespective of whether they were seen or not).

Gap clearance measures: This task was patterned after the one described by Betts et al.[19] Pairs of high-contrast orange traffic cones, with variable lateral separation, were positioned in the driving lane at nine different locations throughout the main test course. The lateral separation between cones was set at one of nine values relative to the outer width of the vehicle's wheelbase (tires). The specific separations used were -20, -10, -5, 5, 10, 20, and 40 cm, with negative numbers representing separations that were smaller than the width of the vehicle's wheelbase.

As they approached each pair of high-contrast cones, subjects were instructed to indicate verbally whether the gap clearance was sufficient to drive between them and, if so, to attempt to do so. If, however, they perceived the cone separation to be too narrow, they were instructed to drive around the cones. Cone separations were varied from one test run to the next. Each subject received three scores for this task: the number of reported correct perceptions of gap clearance, the number of attempts to make a safe passage between a cone pair because the gap was correctly perceived to be sufficiently wide, and the number of such attempts on which the subject was successful in maneuvering between the cones without hitting them.

Maneuvering test circuit

After completing the main test circuit, subjects were required to slalom twice through a series of nine traffic cones, with successive cones separated by approximately 1.5 car lengths. The normally high-contrast orange cones were covered with three different shades of gray cloth to reduce their contrast and make this task more visually dependent. In addition, an element of uncertainty was introduced by adding a randomly determined lateral offset to the positioning of successive cones. The two measures recorded for each subject were the total time it took to drive through the course and the total number of cones hit during two passes (once in each direction) through the course.

Test vehicle

The test vehicle used for this research was a full-sized (Australian) Ford station wagon. Two experimenters, one beside the driver and a second in the rear seat, scored the subject's driving performance. A third experimenter, driving a "chase" car, followed the research vehicle for the purpose of resetting any of the test track objects that may have been hit during passage of the test vehicle and to randomize the cone separations between successive runs for the gap clearance task.

Supplementary Vision Tests

The three supplementary tests described subsequently were administered in the laboratory both for practical reasons and to ensure that testing conditions were standardized. Each of the supplementary tests was administered under each of the five binocular acuity conditions. The four degraded acuity levels were tested in the same order that was used at the test track for the driving tests and was balanced across the four degraded acuity conditions using the aforementioned Latin square design.

Pelli-Robson Contrast Sensitivity Test:[20] Contrast sensitivity was determined using the Pelli-Robson chart at a working distance of 1 meter. Subjects were instructed to look at a line of letters and forced to guess the letter when they were not sure. The test was scored letter by letter as suggested by Elliott et al.,[21] and the results were expressed in terms of log contrast sensitivity. Two versions of the chart were used, and subjects alternated between the two versions in an attempt to minimize chart memorization. The background luminance of the chart was approximately 90 cd/m^2. To ensure that the level of optical blur when viewing this test at 1 meter would be equivalent to that used for the driving tests, a +1.0-D lens was added to the distance correction required to produce the different acuity levels at the test track.

*S*mith-*K*ettlewell *I*nstitute *L*ow *L*uminance (SKILL) Card:[22] One side of the SKILL card represents a conventional high-contrast/high-luminance acuity test. The other side contains low-contrast (14%) letters against a dark gray (low luminance) background. The effective luminance of the two sides differs by approximately 1 log unit.[22] The test was administered at the recommended distance of 40 cm and illuminated to ensure that the background luminance of the light side of the card was 100 cd/m^2. To correct for the near distance of this test, a +2.5-D plus lens was added to the distance corrections used to produce the different acuity levels at the test track. Each side of the SKILL Card was scored letter by letter. The difference, or SKILL, score was calculated as the difference between the numbers of letters correctly identified on the two sides.

Berkeley Glare Test:[23] This test consists of opaque, triangular acuity charts similar in design to the high reflectance side of the SKILL Card except that the letters are low (10%) in contrast. The test distance was 1 meter. Like in the case of the Pelli-Robson test, a +1.0-D lens was added to the distance corrections used to produce the different acuity levels at the test track. The charts were front-illuminated at a luminance of 80 cd/m^2, and the effect of glare was measured by comparing the measurement of low-contrast acuity without the glare source and with the surrounding opal Plexiglas "glare" screen back-illuminated at the maximum level of 3000 cd/m^2. Two different but equivalent low-contrast charts were used for the glare versus no-glare measurements to minimize the effects of memory on test performance. In addition, the glare condition was always tested before the no-glare condition. Acuity was scored letter by letter for the glare and no-glare conditions. The difference score, or Disability Glare Index (DGI), was calculated by subtracting the number of letters correct in the glare condition from the number correct in the no-glare condition.

RESULTS

Closed Road Driving Measures

Preliminary analyses revealed that a number of measures of driving performance needed to be excluded, either because they were highly correlated with another measure or evidenced zero variance. For example, there was a high negative correlation between the number of road hazards seen and the number hit. When driving with normal acuity, all of the subjects saw all of the road hazards, thereby resulting in a zero-variance measure. However, although they saw all of the hazards, there were a number of instances in which subjects hit them because they saw them too late to avoid them. Because, in the final analysis, hitting the hazards was deemed more significant to driving safely than simply seeing them, only the number hit was used in the data analysis. To further minimize the zero- or near-zero-variance problem for this single measure, all driving performance measures for the four degraded acuity conditions were normalized with respect to the scores for the normal 6/4.5 acuity level. Thus, the number of driving measures was reduced to six for a repeated-measures multivariate analysis of variance (MANOVA). Four were from the main test course (total driving time, number of signs read, number of hazards hit, number of correct gap perceptions) and two were from the maneuvering course (number of cones hit and total driving time).

A preliminary 2 gender by 4 (normalized) acuity level by 6 driving measure MANOVA indicated that acuity level was the only significant factor. Gender was not significant and did not interact with acuity level for any of the driving measures. A corresponding analysis of the vision test scores produced a similar result. Accordingly, to simplify description of the results, both MANOVAs were recalculated with gender excluded. These analyses indicated that acuity level was significant for the driving measures (Wilkes $\lambda = 0.045$; $F[6,18] = 7.08$, $p < 0.011$) and for the supplementary vision test scores (Wilkes $\lambda = 0.033$; $F[9,15] = 49.01$, $p < 0.001$). For the latter analysis, scores of the four degraded acuity levels were also normalized with respect to scores obtained in the normal (6/4.5) acuity condition.

Main Test Course

Table 1 shows the results of the univariate analyses of variance (ANOVAs) for the effect of acuity degradation on the normalized driving performance measures across the 6/12, 6/12c, 6/30, and 6/60 acuity conditions. Acuity degradation did not have a signifi-

TABLE 1.
Summary of statistical analysis of driving performance and supplementary vision test measures

Driving measures	F	df	p
Main test course			
Sign recognition	35.35	3, 69	< 0.001
Road hazard hit	36.91	3, 69	< 0.001
Driving time	15.889	3, 69	< 0.001
Gap perception	0.582	3, 69	0.629
Maneuvering test course			
Errors (number of cones hit)	0.256	3, 69	0.857
Driving time	5.347	3, 69	0.002
Supplementary vision measures			
Pelli-Robson CS	158.8	3, 69	< 0.001
SKILL score	64.9	3, 69	< 0.001
Disability Glare Index	34.0	3, 69	< 0.001

F, F-radio from the analysis of variance; df, degrees of freedom for the numerator and denominator of the associated F-ratio; p, probability of the F-ratio occuring by chance.

cant effect on either gap perception or errors on the shorter maneuvering course. Acuity degradation did, however, have a significant effect on the remaining three measures derived from the main test course (sign recognition, road hazard avoidance, total driving time) and total driving time from the maneuvering course (see Table 1).

Figures 2A-C show the dependence of total driving time (main course), sign recognition, and road hazard avoidance on acuity level expressed in terms of minimum angle of resolution (MAR). Corresponding Snellen fractions are shown across the top of each figure. The open circles in these three figures represent the average performance of the 24 subjects when tested with their normal acuity level (mean = 6/4.5, MAR = 0.77) and when tested under each of the three degraded levels that were produced by optical blur and plotted at MARs of 2, 5, and 10 arcmin. The filled circle in each figure represents the average results for the same individuals when tested under the 6/12c condition. Error bars represent ± 1 standard deviation.

Figure 2A shows the significant effect of acuity degradation on driving time across the 6/12, 6/12c, 6/30, and 6/60 acuity conditions. From Figure 2A, it is clear that subjects took longer to complete the main test course because acuity was degraded by increasing amounts of optical blur. The increase in driving time for the 6/12c condition was more similar to the increase produced by the 6/60 optical blur condition than the 6/12 optical blur condition. When results of the 6/12c condition were excluded from the analysis, there was a significant linear trend across the 6/12, 6/30, and 6/60 optical blur conditions ($F[1,23] = 25.56$, $p < 0.001$). This trend is represented by the solid line in Figure 2A, which has been extrapolated to include the average performance obtained under the normal viewing condition. When the 6/12c condition was included, the cubic ($F[1,23] = 28,84$, $p < 0.001$) and linear ($F[1,23] = 7.08$, $p = 0.014$) components were both significant, indicating that there was no longer a simple linear relationship between acuity level and driving time. Further pairwise comparisons indicated that the means of the 6/12, 6/30, and 6/60 conditions varied significantly from one another ($p < 0.003$). However, the 6/12c condition did not differ significantly from the 6/60 optical blur condition ($p = 0.142$).

Figure 2B indicates that increased acuity degradation produced increasingly poorer sign recognition performance, with performance in the 6/12c condition being more similar to that in the 6/60 optical blur condition than the 6/12 optical blur condition. From Table 1, it is clear that the effect of acuity on sign recognition was significant when results for all four degraded acuity conditions were included in the analysis. The effect of acuity degradation was also significant when the three degraded conditions produced by optical blur were considered separately ($F[2,44] = 53.7$, $p < 0.05$). Furthermore, for the latter three conditions, there was a significant linear trend ($F[1,23] = 90.61$, $p < 0.001$), which is represented by the solid line in Figure 2B. Including the 6/12c condition in the analysis produced significant linear ($F[1,23] = 44.30$, $p < 0.001$) and cubic ($F[1,23] = 41.19$, $p < 0.001$) trend components. Pairwise comparisons indicated that although the means of the 6/12, 6/30, and 6/60 conditions differed significantly from one another ($p < 0.002$), the mean of the 6/12 c condition did not differ from the 6/60 condition ($p = 0.081$).

Finally, from Figure 2C and Table 1, it is evident that acuity degradation had a significant effect on subjects' ability to avoid hitting the large low-contrast road hazards. Like with the preceding two measures, pairwise comparisons indicated that although the means of the 6/12, 6/30, and 6/60 conditions differed significantly from one another ($p < 0.001$), performance in the 6/12c condition was essentially identical to that in the 6/60 optical blur condition ($p = 0.632$), and performance in both of these conditions was poorer than that in the 6/12 optical blur condition. Including results of the 6/12c condition again produced significant linear ($F[1,23] = 32.25$, $p < 0.001$) and cubic ($F[1,23] = 67.03$, $p < 0.001$) trend components. When the results of the 6/12c condition were excluded from the analysis, there was a significant linear trend ($F[1,23] = 116.43$, $p < 0.001$) across the remaining three degraded conditions (solid line in Fig. 2C) produced by different amounts of optical blur.

Maneuvering Test Course

As Table 1 indicates, acuity degradation had a significant effect on the total time required to complete the test course. Although statistically significant, the effect of acuity degradation across conditions was relatively small, although there was a significant linear trend across the three degraded acuity conditions produced by optical blur ($F[1,23] = 5.17$, $p < 0.033$).

Supplementary Vision Test Results

Figures 3A-C show the effect of the different acuity levels on Pelli-Robson contrast sensitivity, the SKILL score, and DGI score. Results are plotted using the same conventions as used to plot the driving performance results. Open circles represent individual data obtained under the four conditions differing in optical blur and the filled circles represent results obtained for the same individuals when tested in the simulated cataract condition.

Pelli-Robson contrast sensitivity: Variations in Pelli-Robson contrast sensitivity across the five conditions are shown in Figure 3A. The effect of acuity level on contrast sensitivity was significant

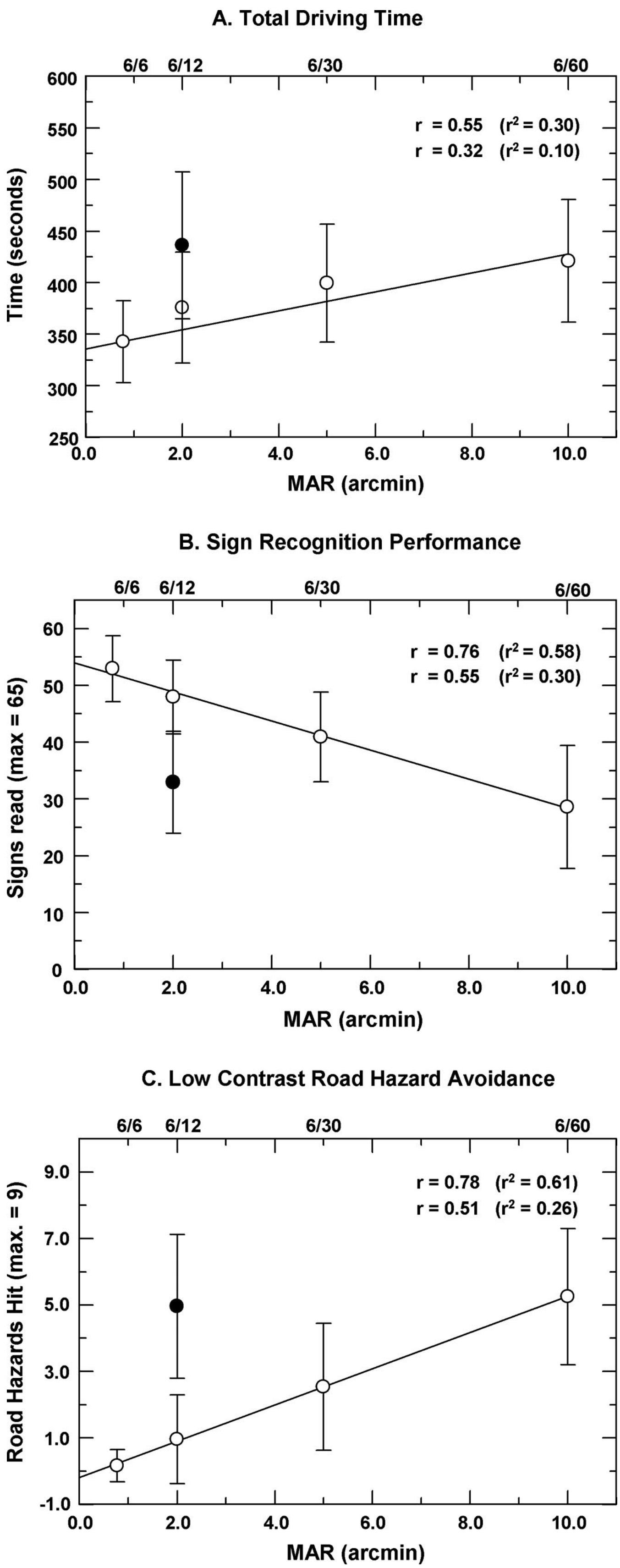

FIGURE 2.

Variations in total driving time (A), sign recognition (B), and road hazard avoidance (C) on the main test circuit as a function of binocular acuity level, expressed in minimum angle of resolution (lower axis) and Snellen notation (top axis). Open symbols represent mean performance for normal viewing (leftmost symbol) and for the three conditions (6/12, 6/30, and 6/60) produced by increasing amounts of plus lens blur. The filled symbol represents the mean performance obtained under the simulated cataract (6/12c) condition. Error bars represent ± 1 standard deviation. Note that performance on these driving tasks under the simulated cataract condition was more similar to performance under the 6/60 optical blur condition than to performance under the 6/12 optical blur condition. The solid line in each figure represents the regression line fit to the individual (not mean) results of the 6/4.5, 6/12, 6/30, and 6/60 conditions only. The top row or r and r^2 values indicate the correlation coefficient and proportion of explained variance, respectively. The bottom row of values indicates the magnitude by which both values were decreased by including results from the simulated cataract (6/12c) condition.

(Table 1). Note also that the simulated cataract condition, 6/12c, produced a loss in contrast sensitivity greater than that observed in the 6/60 optical blur condition. A further analysis, excluding the results of the 6/12c condition, revealed a significant linear decline, albeit small, in Pelli-Robson contrast sensitivity with increasing optical blur ($F[1,23] = 200.39$, $p < 0.001$); the rate of decline was 0.09 log units/D.

SKILL score: Figure 3B illustrates the effect of the five acuity levels on the SKILL score. Variations in the SKILL score across the four degraded acuity conditions were significant (Table 1). However, as is evident from Figure 3B, the effect was largely the result of the inclusion of the 6/12c condition. When the latter was excluded from the analysis, there remained a small, but significant, variation in SKILL score across the 6/12, 6/30, and 6/60 conditions ($F[2,46] = 4.33$, $p = 0.019$). Further analysis revealed the variation to consist of a small linear trend ($F[1,23] = 10.26$, $p = 0.004$) that is, as Figure 3B shows, barely discernible across the three conditions. In other words, the SKILL score was relatively insensitive to the level of optical blur. Parenthetically, it may be noted that, for the high luminance side of the SKILL card (effectively a near-distance version of the Bailey-Lovie acuity chart) performance in the 6/12c condition was comparable to that of the 6/12 optical blur level measured with the Bailey-Lovie chart at the test track. For the low-luminance/low-contrast side of the test, the 6/12c condition produced a selective decrement in performance, producing a SKILL score roughly 2.5 times greater than that for any of the optical blur conditions.

DGI score: Figure 3C shows the variation in the DGI obtained using the Berkeley Glare Test. The effect of acuity level on DGI was significant across the four degraded conditions (Table 1). However, this difference was largely the result of the inclusion of the 6/12c condition. When the latter condition was excluded from the analysis, there was no effect of acuity level on DGI across the three degraded acuity conditions produced by different amounts of optical blur ($F[2,46] = 0.6$, $p = 0.58$). Thus, the DGI was also relatively independent of optical blur.

Relationship Between Driving and Vision Test Performance

The results described in the preceding sections indicated that some measures of driving performance were linearly related to acuity level when, that is, the acuity levels were produced by different amounts of optical blur. However, the simulated mild cataract degraded performance by an amount that was disproportionate considering the relatively minor effect it had on visual acuity. In addition, results of the supplementary vision tests indicated that although some vision test scores were either relatively independent of (the SKILL and DGI scores) or only modestly affected by (Pelli-Robson contrast sensitivity, different levels of optical blur, they were disproportionately degraded by the simulated cataract. The remainder of this section considers the implications of the results in the preceding two sections for screening the visual acuity of driver applicants by licensing agencies that do not distinguish between mild acuity losses resulting from uncorrected refractive error and similar magnitudes of acuity loss resulting from, for example, mild cataracts.

More specifically, licensing agencies record a single datum for each prospective driver, an acuity level. Individuals having the same visual acuity are treated equally. Thus, two individuals, both having 6/12 acuity, would be treated equally and both would meet the minimum acuity criterion required by most states and provinces for an unrestricted driver's license, although both evidenced a small loss in acuity. However, the preceding results indicated that not all individuals with 6/12 acuity drive equally well. Rather, the performance of drivers with 6/12 acuity depended significantly on the cause of the mild acuity loss (optical blur vs. simulated cataract).

Accordingly, a number of regression analyses were performed to determine the proportion of variance in driving time, sign recognition, hazard avoidance, and maneuvering time that could be explained either by high-contrast Bailey-Lovie distance acuity alone or by Bailey-Lovie acuity combined with each of the three supplementary vision test scores in a multiple regression format, both with and without results from the simulated cataract, 6/12c, condition. For the multiple regression analyses, distance acuity was entered as the first variable and the supplementary vision measure was entered second, the assumption being that licensing agencies are unlikely to question the primary importance of the acuity standard.

The solid lines in Figures 2A-C represent the linear regression lines fit to the individual (not mean) data obtained under the 6/4.5, 6/12, 6/30, and 6/60 conditions for each of the driving performance measures. In each figure, two rows of values are listed. Values listed in the top row indicate the correlation coefficient (r) between acuity and the driving performance measure and the proportion of variance (r^2) in the driving measure attributable to acuity variations. Thus, the low correlation with acuity is for the driving time measure (0.55) and the highest correlations are for sign recognition (0.76) and hazard avoidance (0.78). The proportions of variance in the three driving measures explained by acuity

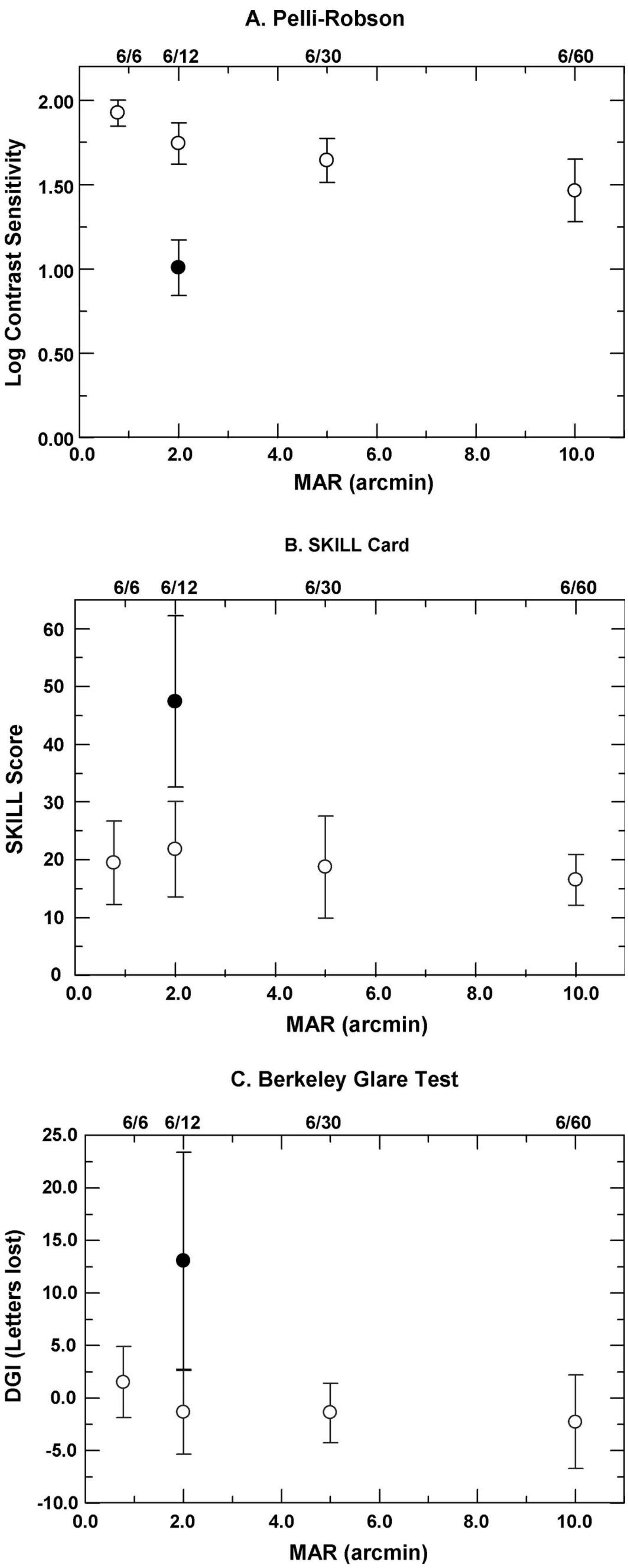

FIGURE 3.
Variations in the three supplemental vision test scores as a function of binocular acuity level, expressed in minimum angle of resolution (lower axis) and Snellen notation (top axis). In each figure, open symbols represent mean performance for normal viewing (left-most symbol in each figure) and for the three conditions (6/12, 6/30, and 6/60) produced by increasing amounts of binocular plus lens blur. Filled symbols represent the mean performance obtained under the simulated cataract (6/12c) condition. Error bars represent ± 1 standard deviation. The open indicate that Pelli-Robson contrast sensitivity (A) was moderately reduced by the increased amounts of optical blur required to produce the 6/12, 6/30, and 6/60 acuity levels, whereas the SKILL Score (B) and Disability Glare Index (C) were relatively insensitive to optical blur. In all three cases, the filled symbol indicates that the simulated cataract condition degraded performance on these vision tests by an amount that was disproportionately large, considering the mild acuity (6/12) loss associated with this viewing condition.

variations are 0.30, 0.58, and 0.61, respectively. These proportions (times 100) are listed in column 1 of Table 2. It should be noted that adding each of the three supplemental vision measures did not produce any significant increment (or decrement) in the proportion of explained variance. Thus, if the only cause of acuity loss was optical blur (uncorrected refractive error), acuity would explain significant percentages of variation in these three driving measures, and there would be no need for a supplemental vision measure.

The second row of values in Figures 2A-C indicates that when results from the 6/12c condition were included in the regression analysis, there were still significant correlations between acuity and the driving measures. However, the magnitude of the correlations between acuity and each of the driving measures decreased, as did the proportion of variation in the driving measures attributable to acuity alone. Thus, for the hazard avoidance measure (Fig. 2C), the proportion of explained variance dropped from 0.61 to 0.26 with the inclusion of the 6/12c results. The smaller proportions of explained variance (times 100) for each driving measure resulting from inclusion of the 6/12c condition are shown in the second column of Table 2.

Columns 3 to 5 of Table 2, however, indicate that significant proportions of the variance lost as a result of inclusion of the 6/12c results can be recovered by using each of the supplementary vision test scores with Bailey-Lovie acuity in a multiple regression format. Including the 6/12c results decreased the percentage of explained variance in driving time, sign recognition, and hazard avoidance from 30%, 58%, and 61% to 10%, 30%, and 26%, respectively. As column 3 (Table 2) indicates, using Pelli-Robson contrast sensitivity in addition to Bailey-Lovie acuity, increased the percentage of explained variation to 26%, 57%, and 58% for the respective measures. Columns 4 and 5 indicate that using the SKILL and DGI scores also produced significant increments in explained variance, albeit the magnitude of the increments were, on average, somewhat smaller than for Pelli-Robson contrast sensitivity.

Effect of Test Order

To evaluate the possibility that testing order, not acuity level, may have had a significant effect, results for the four driving measures and the three supplementary vision measures were analyzed as a function of test order. For the driving measures, there was a significant effect of test order (Wilkes $\lambda = 0.086$; $F[12,12] = 10.62$, $p < 0.001$a), but only for total driving time measured on the main test course ($F[3,69] = 13.42$, $p < 0.001$). Briefly, subjects drove more slowly on the first test drive than on any of the remaining test drives, irrespective of the acuity condition. For the supplementary vision measure, the effect of test order was not significant (Wilkes $\lambda = 0.853$; $F[9,15] = 0.29$, $p = 0.97$). These analyses confirmed that acuity level, not test order, was the significant factor determining performance in the present study.

DISCUSSION

The results indicate that the sudden imposition of acuity degradation on otherwise normal subjects had a selective effect on the different driving tasks measured on the main driving circuit. Clearly, the sudden imposition of such visual restrictions is an artificial situation and is likely to produce a greater impairment of performance than if the visual impairment had been introduced (or developed) slowly so that the individual had time to adapt. The study was done, without a period of adaptation, to isolate the effects of visual impairment on driving performance without introducing contaminating factors such as differences in experience and risk-taking.

However, even without a period of adaptation, driving performance on the maneuvering test course was, at most, minimally affected and showed no significant relationship with either static acuity or any of the supplementary vision measures. One possible explanation for this finding is that the close spacing of the traffic cones forced the subjects to drive so slowly that they were effectively able to compensate for their acuity degradation and the degradation of the traffic cones' visibility. If so, a higher speed version of the maneuvering task might evidence a greater dependence on visual degradation. Slow driving speed cannot, however, easily explain the failure of acuity degradation to affect performance on the gap clearance task on the main test course. A more likely explanation is that the orange cones were of sufficiently high contrast to provide adequate visibility under all of the degraded acuity conditions. Owens and Tyrrell,[24] for example, have shown that optical blur and severe reductions in luminance level produce significant losses in focal visual ability (e.g., acuity) but have little affect on the steering ability and accuracy of young subjects, a

TABLE 2.
Percent of total variance in driving time (main circuit), sign recognition, and hazard avoidance measures attributable to minimum angle of resolution (Bailey-Lovie acuity) alone for the four conditions differing in optical blur (column 1), for the same four conditions plus the simulated cataract (6/12c) condition, both without any supplemental vision test score (column 2) and with each of the indicated supplemental vision test scores (columns 3-5)

	1, 2, 5, 10 MAR levels	1, 2, 5, 10, 2C[a] MAR levels			
Driving measure	MAR (Bailey-Lovie alone)	MAR (Bailey-Lovie alone)	MAR + Pelli-Robson	MAR + SKILL glare	MAR + disability glare
Driving time	30[b]	10[b]	26[c]	31[c]	22[c]
Sign recognition	58[b]	30[b]	57[c]	44[c]	40[c]
Road hazards hit	61[b]	26[b]	58[c]	42[c]	37[c]

[a]$p < 0.001$.
[b]$p < 0.0015$ for increment in percent variance.
[c]MAR 2C = the 6/12c acuity condition.MAR, minimal angle of resolution; SKILL, *S*mith-*K*ettlewell *I*nstitute *L*ow *L*uminance.

finding they interpreted as indicating that steering is mediated by ambient, not focal, visual abilities. It is also possible that the results for this task may have been different if the contrast of the cones had been degraded to approximate the contrast of the road hazards, or more likely that these tasks tap higher-order processes that are only minimally affected by visual degradation.

Acuity degradation did, however, affect time to complete the course, sign recognition, and hazard avoidance measures from the main test course. In particular, when acuity was degraded by optical blur, these three measures were linearly related to acuity degradation with acuity variations alone accounting for 30%, 58%, and 61% of the variance in driving time, sign recognition, and hazard avoidance, respectively.

The dependence of total driving time on acuity variations produced by optical blur suggests that the subjects, to some extent, were aware of, and attempted to compensate for, their degraded vision by driving slower. This was not unexpected because many but not all of the subjects represented staff and students of an optometry school. However, even visually knowledgeable individuals overestimated their ability to see and compensate for their degraded vision. Although they drove more slowly because their acuity was decreased by larger levels of optical blur, they did not slow down enough to eliminate errors in sign recognition and road hazard avoidance. In this respect, their behavior provides a partial parallel to real-world drivers who drive as fast at night as they do during the daytime, although their vision is partially degraded at night.[25]

A strong relationship between sign recognition and acuity under the optical blur conditions was expected because road signs contain small, high-contrast detail when viewed at the long distances associated with normal driving. Indeed, as noted by Bailey and Sheedy,[1] the current rule for road sign design requires that the letter height should be 1 inch for every 50 feet of the required recognition distance, corresponding roughly to an acuity of approximately 6/6.9.

The finding of an equally strong linear relationship between road hazard avoidance and acuity under the same conditions was particularly interesting, because the spatial dimensions of the hazards were quite large relative to the angular dimensions of the detail of common roadway signage and the detail of optotypes on standard acuity charts. However, the task was included for this very reason; the road hazards were included to represent real-world objects that can be large relative to the spatial resolution limits of the normal eye, yet be low in contrast. Some of these "objects" have little significance for a driver. One example would be newly repaired roadway areas that have only a small difference in reflectance relative to the original roadway surface. Other real-world objects (e.g., potholes, real-world speed bumps, roadside pedestrians, and vehicles at night) are significant in that they require the driver to take some kind of evasive action to avoid an accident.

Overall, these results provide partial empirical support for the continuing reliance of licensing agencies on static acuity measurements as an indicator of the integrity of central visual function. If the only cause of acuity loss was uncorrected refractive error, static visual acuity would, by itself, suffice to explain much of the variance in an attentive driver's daytime performance in sign recognition and road hazard avoidance tasks.

When, however, other potential sources of acuity reduction are considered (e.g., mild cataracts), other vision tests provide an important supplement to the conventional static acuity test. Including results from the 6/12c condition in the analysis decreased the proportion of variance in the driving measures that could be explained by acuity alone. Although the cataract simulators produced only a mild loss in visual acuity, their effect on sign recognition, road hazard avoidance, and total driving time were more similar to the 6/60 condition than to the 6/12 optical blur condition. This finding is in agreement with previous studies that looked at the effect of simulated[17] and real cataracts[13,26] on driving performance; both studies found that driving performance was significantly impaired, although the visual acuity of all drivers was equal to or better than the 6/12 licensing standard.

Importantly, the present results indicate that Pelli-Robson contrast sensitivity, the SKILL score, and the DGI are each capable of measuring the component of visual disability introduced by the cataract simulators that cannot be detected by static acuity alone. In addition, our results suggest that Pelli-Robson contrast sensitivity may be slightly more sensitive to this component of disability than are the SKILL and DGI scores. It is also likely that all three measures are effective because they are relatively independent of optical blur but extremely sensitive to the light-scattering/contrast-reducing properties of the cataract simulators. The resistance of these three indices of visual function to optical blur has also been noted by previous investigators. [22,27-30]

Cataracts have recently been shown to be a risk factor in at-fault accidents,[31] and cataract surgery[26,32] has been shown to mitigate this risk factor and improve driving performance, very likely by reducing the severe contrast sensitivity impairment that drivers experience resulting from cataracts.[33] Finally, the present results suggest that licensing agencies can more effectively detect vision problems resulting from cataracts by supplementing the standard static acuity test with one of the three tests used in this study.

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