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16. Abstract

This experiment evaluated potential benefits of hydrophobic coating of windshields under simulated conditions of use. The main independent variables were hydrophobic treatment, participant age, and time of day. The dependent measures were minimum visual angle resolved and response time. The results indicate that the hydrophobic coating improved visual performance, decreasing the minimum visual angle resolved by almost 34% and reducing the response time by more than one second. In practical terms, visual acuity improved in the treated-nighttime condition to approximately the level of acuity in the untreated-daytime condition.

This experiment showed that hydrophobic coatings can result in significantly improved driver visual performance without negatively affecting response time. However, this experiment did not address the durability or longevity of these products, as the hydrophobic coating was only tested when it was newly applied (and therefore could be expected to be near peak performance). Benefits associated with hydrophobic coatings are likely to diminish with time and wear (more or less slowly depending on durability), unless the coating is reapplied.

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CONTENTS

INTRODUCTION

Several hydrophobic coating products for motor vehicle windows are commercially available. Hydrophobic coatings are generally liquid polymers that bind with motor vehicle glazing. These transparent coatings act as water repellents, causing rain, and other accumulated moisture, to bead up. Aided by airflow caused by wind and vehicle motion, the resulting beads of water run off the vehicle's windshield and other windows. The beading and ease with which the beads are cleared are thought to lead to improved driver visual performance due to reduced optical distortion. In other words, not having to look through a sheet of moisture should result in a clearer image.

Most, if not all, of the commercially available hydrophobic coating products claim to aid drivers' visual performance. Yet, there exists no research in the open literature to substantiate the claims of improved visual performance, or any other benefits for that matter, associated with the use of hydrophobic coatings on the windshields of motor vehicles. While there are instances of specific product evaluations in popular magazines, these evaluations only provide anecdotal support for improved visual performance. The anecdotal support is largely in the form of improved visibility through the windshield, even without the use of windshield wipers, as well as visibility benefits when applied to the side and rear windows (which generally lack wiper mechanisms).

The purpose of this experiment was to quantify the effects of this class of products on visual performance under simulated conditions of use. More specifically, this experiment examines the minimum visual angle resolved and response time to targets viewed through a motor vehicle windshield for the following main independent variables:

- hydrophobic treatment (treated versus untreated),
- time of day (daytime versus nighttime), and
- participant age.

This experiment was performed under conditions of simulated rain and simulated wind effects associated with vehicle motion. Although the effects under real driving/raining conditions may differ from those obtained under the simulated conditions, the directions of the effects can be expected to be the same. Visual acuity is one of several possible measures of visual performance that could have been investigated in this study. Other measures include low-luminance detection, visual comfort, and visual scanning efficiency. However, the distortions typical of water film on window glass suggested that visual acuity is particularly likely to show a benefit of hydrophobic coatings. While there may be other benefits as well, visual acuity seemed a good candidate for the first, rather exploratory study.

Although the specific task used in this experiment is probably a relatively pure measure of visual acuity, participants were not given time limits for individual trials. Because of the dynamic character of the stimulus situation (including simulated wind and rain, as well as the action of windshield wipers) it is probably possible for participants to improve their performance by allocating more observation time to each trial. Therefore response time was measured, as well as minimum visual angle resolved, to insure that we had a comprehensive measure of relative visual performance across conditions.

This experiment did not address the durability or longevity of these products, as the hydrophobic coating was only tested when it was newly applied (and therefore could be expected to be near peak performance). The effects of hydrophobic coatings on driver visual acuity are likely to diminish with time and wear (more or less slowly, depending on durability).

METHOD

Participants

Thirty-two individuals participated in the study, 16 participants each in a younger group and an older group. The younger participants were between the ages of 20 and 30, and the older participants were between the ages of 60 and 70. Each group consisted of eight men and eight women. While taking part in the study, all participants wore the same corrective lenses, if any, that they would normally wear when driving. Measures of participant visual acuity (corrected acuity for those with corrective lenses) were recorded using an OPTEC 2000 vision tester. Measures of visual acuity ranged from 20/13 to 20/40 for the younger participant group (median = 20/19), and 20/13 to 20/50 for the older participant group (median = 20/22.5).

Apparatus

Stimuli. Participants viewed a series of 12 Landolt C targets from a distance of 38.1 m (125 ft) across an asphalt-paved lot (Figure 1). The Landolt C recognition task is a common measure of visual acuity. Performance on the Landolt C task is determined by the smallest gap size in the letter "C" a participant can detect when the gap is presented in one of four possible locations, separated by 90 degrees (up, down, left, or right). The stroke width of the character is kept equal to the gap size, and the height of the character is five times the gap size/stroke width. The range of gap sizes, and the associated subtended visual angles, of the targets are presented in Table 1. The target gap size, and stroke width, ranged from 4 to 33.5 mm (0.36 to 3.02 minutes of arc).

Table 1
Stimulus gap size and associated subtended visual angle.

Stimulus	Gap Size (mm)	Visual Angle (min)
1	4.0	0.36
2	5.4	0.49
3	6.6	0.60
4	8.1	0.73
5	10.0	0.90
6	11.6	1.05
7	14.3	1.29
8	16.9	1.52
9	20.0	1.80
10	24.6	2.22
11	29.4	2.65
12	33.5	3.02

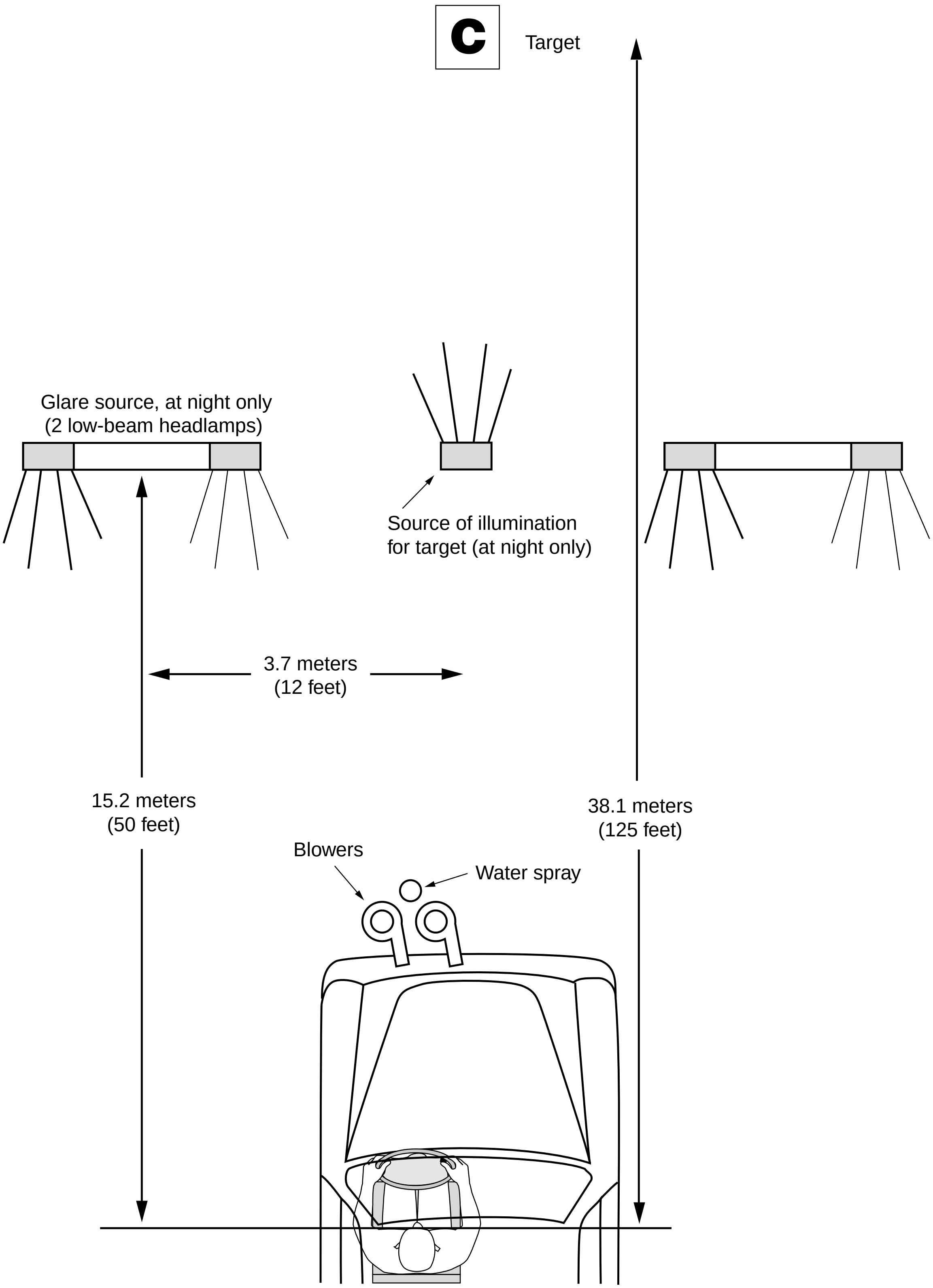

Figure 1. Overhead diagram of the experimental setup (distances are not to scale).

Participants viewed the targets while seated in either the driver's or the passenger's seat of a research vehicle, a 1992 compact with 36,000 km on the odometer. The center of the target was 1200 mm above the asphalt surface, and in line with the center of the vehicle. The target was therefore approximately 0.5 degrees to the right of straight ahead when the participant was seated on the driver's side, and 0.5 degrees to the left of straight ahead when the participant was seated on the passenger's side. The targets were constructed of retroreflective sheeting affixed to square aluminum plates that were 305 mm on each side. The "C" was made of white retroreflective sheeting and the background was made of green retroreflective sheeting. These materials were selected in order to simulate the appearance of roadway signs.

Simulated Rain and Wind. Rain and wind were simulated in this experiment. Rain was simulated by spraying water onto the vehicle's windshield. The resulting coverage was uniform over the area of the windshield through which participants could view the target. The rate at which water was applied could be varied (either 10 or 12 L/min), and the patterns of coverage were similar for the two rates. Both levels of water flow appeared to be comparable to that experienced while driving in a natural, moderate-to-heavy rainfall.

In order to simulate the wind, which normally aids in removing the beaded water from the windshield of a vehicle in motion, two leaf blowers were mounted on the front of the vehicle. These blowers produced a wind speed of about 58 km/h (36 mph), as measured on the exterior of the windshield at the participant's line of sight to the target. The apparatus for the simulated rain and wind could be positioned on either the driver's or passenger's side of the vehicle. It was positioned low on the hood in order not to obstruct the participant's view of the target or of the glare from headlamps in the nighttime testing.

Independent Variables

Hydrophobic Treatment. Hydrophobic treatment of the windshield was a within-subject variable. The windshield of the research vehicle was thoroughly cleaned with isopropyl alcohol, and new windshield wiper blades were installed. One half of the windshield was then treated with a commercially available hydrophobic coating, following the manufacturer's directions for application. Additional treatments were applied after every 4 - 6 hours of testing in order to maintain the hydrophobicity at near peak performance. The manufacturer's directions were also followed for additional applications. One half of the participant group received the hydrophobic treatment on the driver's side of the windshield, and the other half received the hydrophobic treatment on the passenger's side. When the treated side of the windshield was changed, the hydrophobic treatment was thoroughly removed (in accordance with the manufacturer's recommendations), and the windshield was examined to ensure that no residual treatment remained.

Participant Age. There were two age groups, younger and older. Sixteen participants were between the ages of 20 and 30 (mean = 25.8 years), and 16 were between the ages of 60 and 70 (mean = 65.6 years).

Flow Rate. Flow rate was a between-subjects variable. Sixteen participants performed the Landolt C task while water was sprayed onto the windshield at a rate of 10 L/min, and the remaining 16 participants received a flow rate of 12 L/min. The two rates of simulated rain are believed to be appropriate amounts of water for the selected windshield wiper setting (low). Both levels of flow rate appeared as a "moderate to heavy rainfall." All testing was performed without active natural precipitation. The vehicle's windshield wipers ran continuously during the experiment at the rate of 1.5 s for a complete cycle (i.e., bottom of the windshield to full extension and back to the bottom).

Time of Day. Time of day was a between-subjects variable. Sixteen individuals participated in the experiment during the daytime, under partly cloudy to cloudy conditions, and the remaining 16 participated at night. The targets were illuminated by a standard U.S. low-beam headlamp during the nighttime condition, energized by a voltage-regulated power supply set at 12.8 V. This headlamp was located 22.8 m from the target, 0.6 m above the pavement, and positioned in line with the centerlines of the target and the research vehicle. The luminance of the target for the nighttime condition, as viewed from the position of the participants (through the research vehicle windshield) was approximately 2.5 cd/m^2 for the green background and 6.4 cd/m^2 for the white letter C. Luminance measurements were taken using the 38.1 m viewing distance and oversized samples of the same retroreflective material used in producing the stimuli.

Glare. Within the nighttime condition, the presence or absence of glare was an additional within-subject variable. The glare sources consisted of two pairs of standard U.S. low-beam headlamps. The two sets of headlamps were located 3.7 m (centerline of headlamp set to centerline of vehicle) on either side of the research vehicle, at a distance of 15.2 m, and 0.6 m above the pavement. The center-to-center separation between headlamps in a set was 1.2 m. Only one set of headlamps, those located on the side closest to the participant, was energized at a time. These headlamps were energized by voltage-regulated power supplies set at 12.8 V. The level of illumination reaching the participants' eyes was maintained at approximately 1 lux.

Dependent Variables

The purpose of this experiment was to quantify the effects of hydrophobic treatment on visual performance under simulated conditions of use. It was believed a priori that the hydrophobic treatment would influence visual performance, more specifically affecting the minimum visual angle resolved. However, the visual acuity task used here is likely to be affected both by the participants fundamental visual acuity, and the amount of time devoted to the task. By measuring the response time to targets, in both treated and untreated conditions, it was possible to evaluate whether any apparent differences in acuity could be attributed to differences in subjects' self-imposed time limits.

Visual Acuity - Landolt C Recognition. Performance on the Landolt C task is determined by the smallest gap size (minimum visual angle) in the letter "C" a participant can detect when the gap is presented in one of four possible locations, separated by 90 degrees (up, down, left, or right). The range of gap sizes, and the associated subtended visual angles used, were previously presented in Table 1.

Response Time. Response time in the Landolt C task was defined as the time from when the stimulus was first exposed to when the participant reported the orientation of the gap (up, down, left, or right). Response times were collected manually for each trial by a researcher located in the seat behind the participant. Participants were not aware that response times were being recorded.

Design

Daytime Condition. Participants in the daytime condition took part in two blocks of trials, one seated on the driver's side and one seated on the passenger's side. Each block consisted of 32 trials, excluding practice trials. The total time it took one participant to complete the two daytime blocks (64 trials, plus practice trials) was approximately 25 minutes. There was an equal number of participants (2) for each combination of hydrophobic treatment, participant age group and flow rate. The sex of participants was also balanced over these conditions (one male and one female in each combination).

Nighttime Condition. Participants in the nighttime condition took part in four blocks of trials, two seated on the driver's side and two seated on the passenger's side (once each with and without oncoming glare). Each block consisted of 32 trials, excluding practice trials. The total time it took one participant to complete the four nighttime blocks (128 trials, plus practice trials) was approximately 40 minutes. As in the daytime condition, there was an equal number of participants (2) for each combination of hydrophobic treatment, participant age group and flow rate, and there was one male and one female for each combination of these variables. The order of glare treatment was partially counterbalanced across participants.

Procedure

The staircase method, a psychophysical method used to determine absolute and difference thresholds, was employed. Each condition began by presenting the largest stimulus gap size, 33.5 mm. When the orientation of the target was correctly identified, then the subsequent stimulus was 40% smaller. This process of reductions, in step size by 40%, continued until a participant incorrectly identified the orientation of the target (a reversal). The first trial after this reversal always began with the stimulus that was one level of gap size (20 %) larger than the incorrectly identified target. Starting with the first trial after the initial reversal, a series of 32 trials was presented with gap size increasing by one step (20%) after each trial on which a participant's response was incorrect, and decreasing by one step (20%) after each correct response. The reversals, the points at which the order of increasing or decreasing stimulus size changed, were considered estimates of the participant's threshold. The average of these transition points over the 32 trials was considered the participant's threshold for a given condition.

One experimenter placed the stimuli in a frame, mounted on a tripod. A second experimenter recorded the stimuli presented, whether the participant correctly identified the stimulus orientation (communicating via CB radio with the participant), and instructed the first experimenter as to which stimulus to present next. A third experimenter, seated behind the participant, provided instructions for the task, recorded response times, and ensured that the prescribed protocol was followed. The specific instructions to participants were as follows:

> *In this study you will be seated in a car and asked to look at targets located across a parking lot. The targets are always the letter "C," but vary in orientation and size. You will be asked to state which direction the opening in the letter "C" is pointed; up, down, left, or right. Even if you can not accurately judge the orientation of the target, you must still guess.*
>
> *Example:*

> *Water will be sprayed on the windshield to simulate rain, and blowers will be turned on to simulate wind. You will be asked to report the orientation of the targets to the experimenters using a hand-held CB radio. Please respond as rapidly as possible after the experimenter has stepped out from in front of the target.*
>
> *We recognize that this is a difficult task, but we ask you to try as hard as possible to correctly identify the orientation of the targets presented.*

RESULTS

Glare Conditions

The glare condition, examined only during nighttime testing, was found in preliminary analyses not to influence performance on either dependent measure, either as a main effect or as part of any higher order interactions. Consequently, the data were collapsed across glare conditions, thereby eliminating glare as a variable, but retaining time of day as an independent variable.

Analyses of Covariance

Two analyses of covariance (ANCOVA) were performed, one each for the two dependent measures of visual acuity and response time. ANCOVA is a procedure that uses statistical control to remove the effects of a variable, also known as a covariate, that is believed to be correlated with an independent measure, particularly where strict experimental control of the covariate is difficult or impractical. ANCOVA determines whether there are differences among groups or conditions observed in the experiment, over and above those differences that could be accounted for by the covariate. The covariate in these analyses was the standardized score (z) of visual acuity obtained with the OPTEC 2000 vision tester, as it was expected to be correlated with participant age, and may affect the measure of visual acuity used in the experimental task (Landolt C recognition). All means reported here are adjusted means from the ANCOVAs.

Response Time. Of the four main-effects (hydrophobic treatment, participant age, flow rate, and time of day), and all possible interactions, only the main effect of hydrophobic treatment was statistically significant, $F(1,16) = 29.8$, $p \leq 0.0001$. Specifically, the response times of participants to the Landolt C recognition task were shorter when performed with a hydrophobically treated windshield (mean = 3.0 s) than for the same task in the untreated condition (mean = 4.2 s). This result is illustrated in Figure 2.

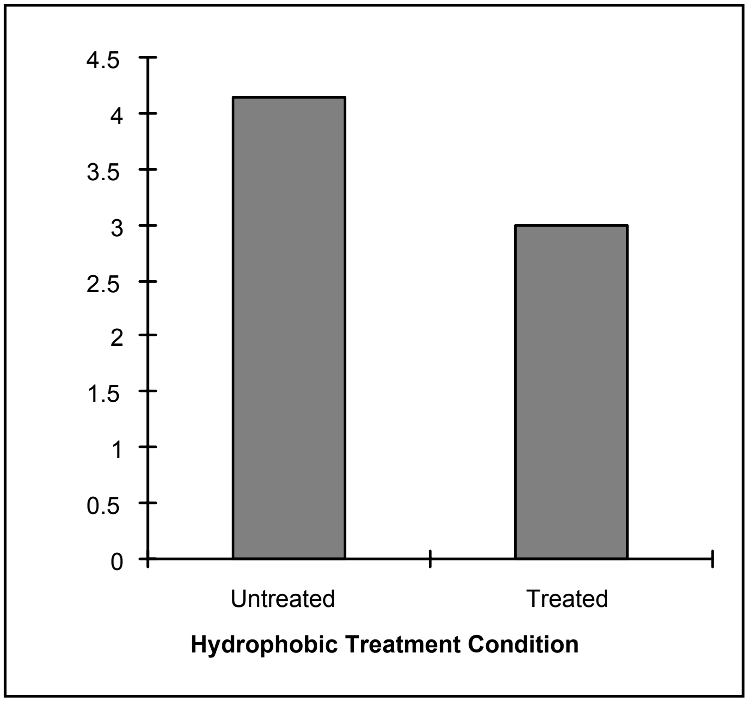

Figure 2. Response time by hydrophobic treatment condition.

*Visual Acuity***.** Hydrophobic treatment and time of day had statistically significant effects on visual acuity, $F(1,16) = 85.5$, $p \leq 0.0001$ and $F(1,16) = 17.4$, $p = 0.0007$, respectively. Participants were able to detect targets of smaller subtended visual angle through a hydrophobically treated windshield (mean = 1.0 min) than through one that was untreated (mean = 1.5 min) (Figure 3), and also detect targets of smaller subtended visual angle in the daytime condition (mean = 0.9 min) as opposed to nighttime (mean = 1.5 min) (Figure 4).

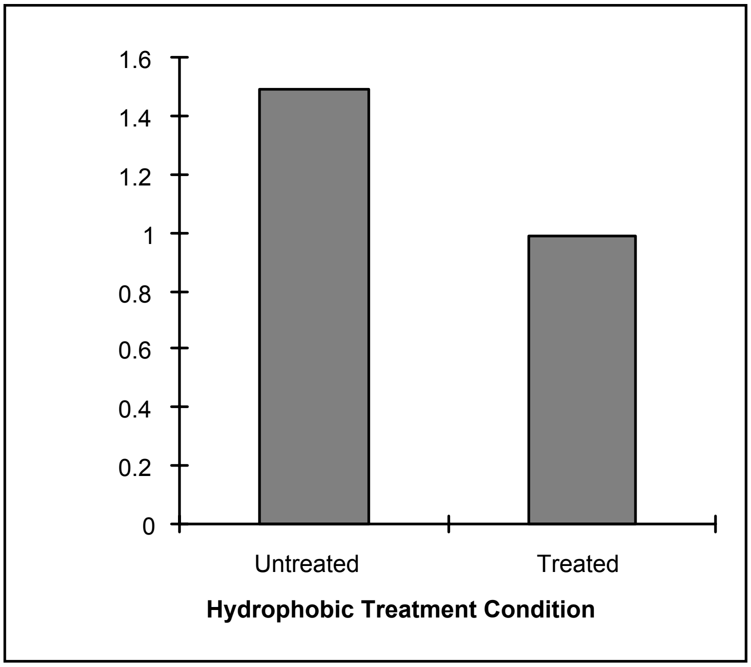

Figure 3. Visual acuity by hydrophobic treatment condition.

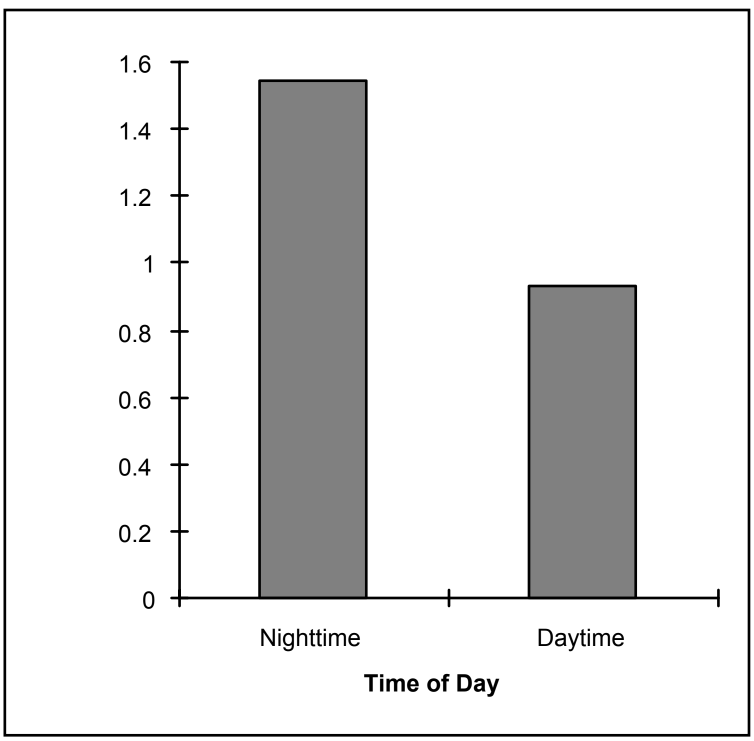

Figure 4. Visual acuity by time of day.

Several two-way interactions were statistically significant. Figure 5 illustrates the interaction of hydrophobic treatment condition and time of day, $F(1,16) = 21.8$, $p = 0.0003$. A Student-Newman-Keuls post-hoc analysis of the results showed participants were better at detecting targets of smaller subtended visual angle in the treated-daytime condition than in the remaining three conditions. The treated-nighttime condition was not statistically different from the untreated-daytime condition ($\alpha = 0.05$). The untreated-nighttime condition was statistically different from the other three conditions and resulted in the poorest overall performance.

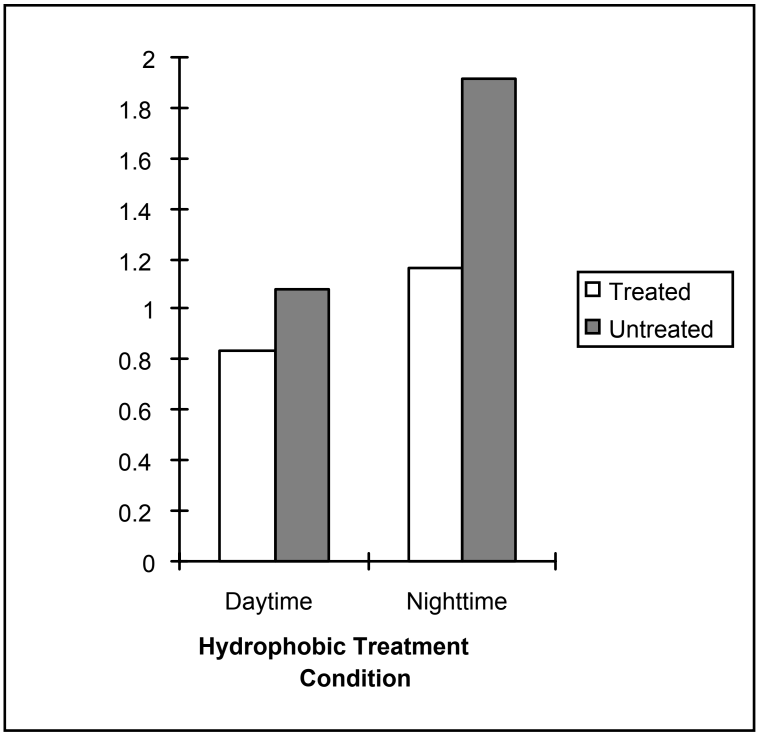

Figure 5. Visual acuity by hydrophobic treatment condition and time of day.

Figure 6 shows the interaction of participant age and time of day $F(1,16) = 7.0$, $p = 0.018$. A Student-Newman-Keuls post-hoc analysis of the results showed that both younger and older participants were better at detecting targets in the daytime condition than in the nighttime condition, and that, in the nighttime condition, younger participants were better than older individuals. The difference between younger and older participants in the daytime condition was not significant.

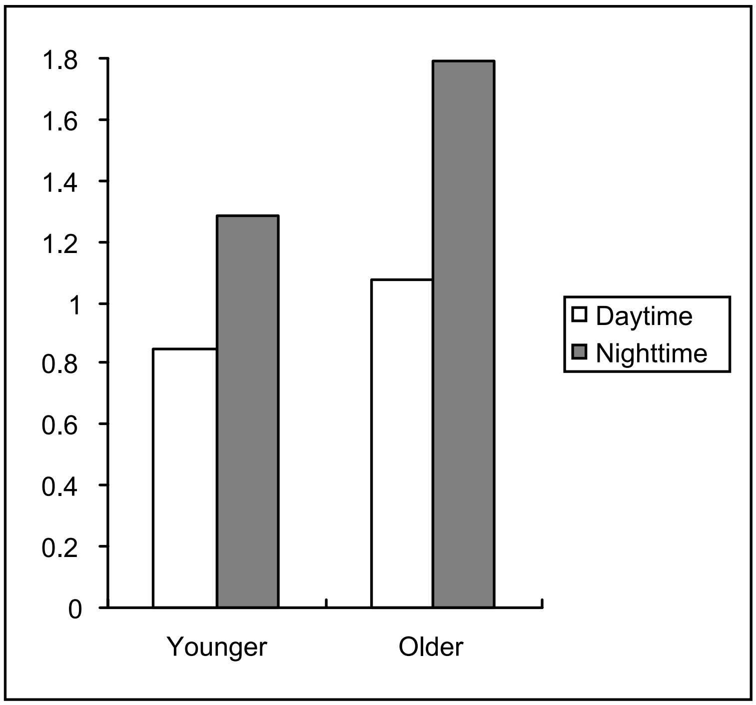

Figure 6. Visual acuity by age and time of day.

Figure 7 shows the interaction of water flow rate and time of day, $F(1,16) = 6.5$, $p = 0.022$. A Student-Newman-Keuls post-hoc analysis of the results showed that the pairwise comparison between the daytime and nighttime treatments with high flow rate (12 L/min) were not significantly different from one another. The three remaining pairwise comparisons between treatments were significant.

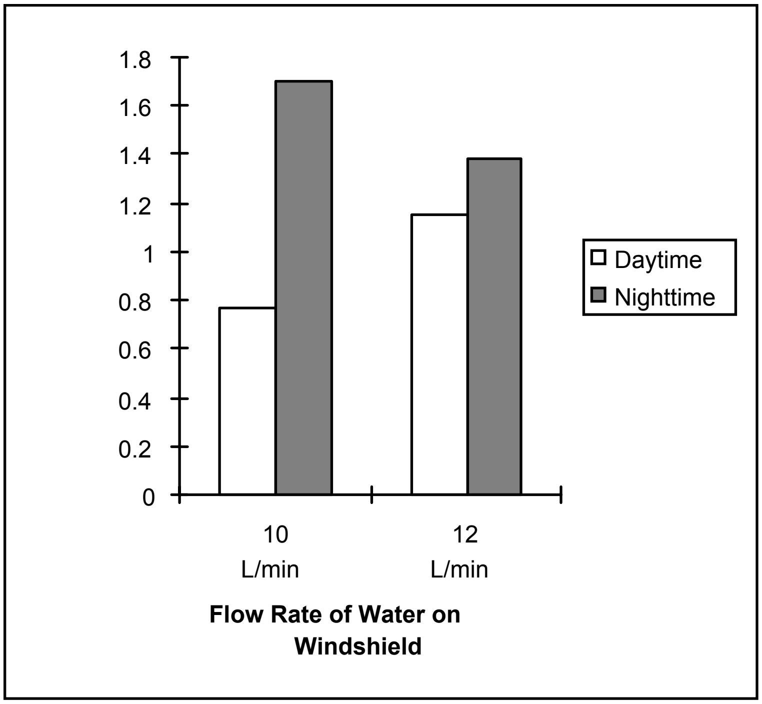

Figure 7. Visual acuity by flow rate and time of day.

In addition, two three-way interactions were statistically significant. Figure 8 shows the interaction of hydrophobic treatment, time of day, and participant age, $F(1,8) = 6.2$, $p = 0.024$, and Figure 9 shows the interaction of hydrophobic treatment, time of day, and flow rate, $F(1,8) = 6.2$, $p = 0.024$. It should be noted, particularly in Figure 8, that the benefit of hydrophobic treatment appears to be proportional (18% - 42% improvement) to visual performance without hydrophobic treatment.

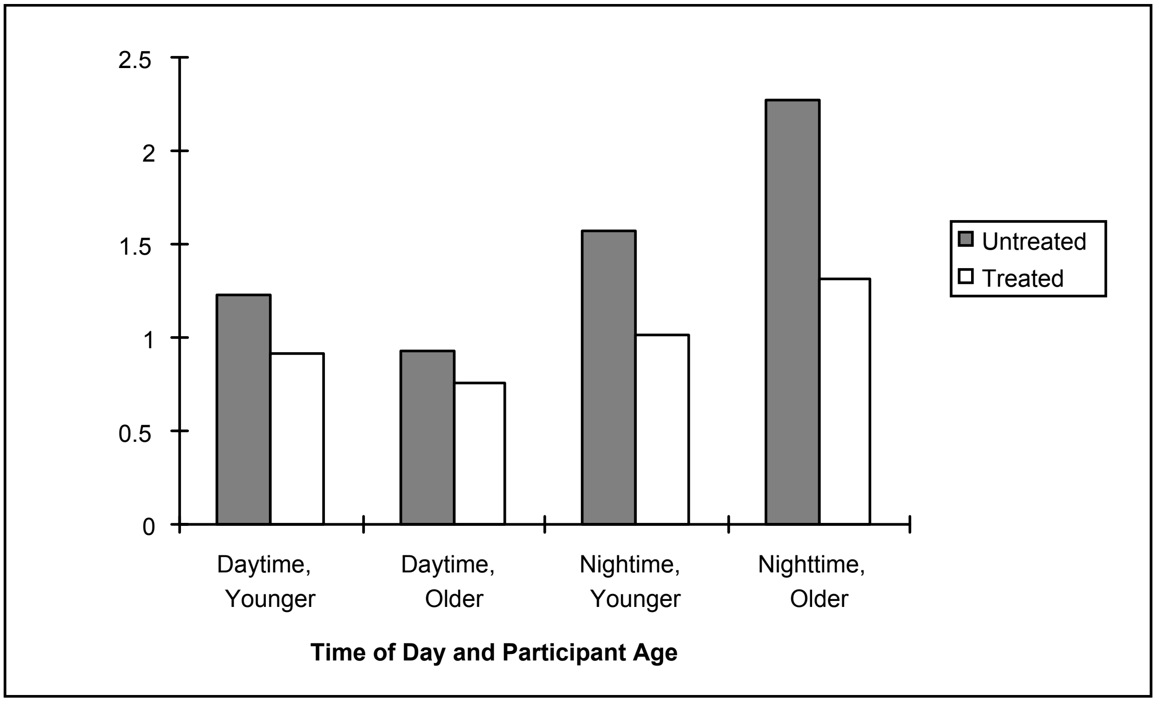

Figure 8. Visual acuity by treatment condition, age, and time of day.

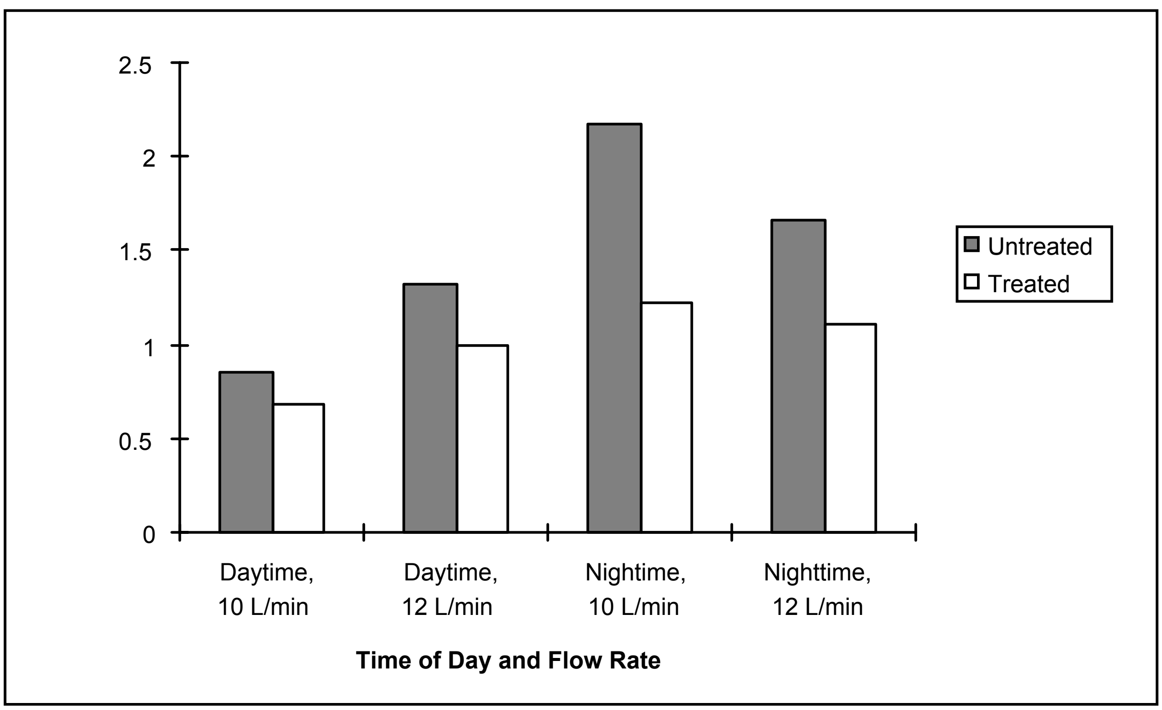

Figure 9. Visual acuity by treatment condition, time of day, and flow rate.

DISCUSSION

The application of hydrophobic treatment to the windshield of an automobile, under simulated rainy-driving conditions, resulted in significantly improved visual acuity and decreased response time to recognize a simple target. The improvement in response time was, on average, greater than one second: equivalent to more than 27 m of travel at 100 km/h. The improvement in visual acuity was also rather large (approximately 34% in terms of the minimum visual angle resolved). By way of comparison, visual acuity improved in the treated-nighttime condition to a level that was not significantly different from performance in the untreated-daytime condition (Figure 5). Although these findings require validation under conditions of actual rain, and in real-world driving conditions, the preliminary indications are that the introduction of hydrophobic coatings to automotive windshields can substantially improve driver visual acuity and response time (Figures 2 and 3).

Despite the illumination of the target by a headlamp in the nighttime condition, visual acuity in the daytime condition was significantly better than at night (Figure 4). It is in the nighttime condition, particularly for older participants, that the hydrophobic treatment appears to provide the greatest benefit in terms of comparison with an untreated condition (Figures 5 and 8). Performance by both age groups was influenced by the time of day and treatment conditions. However, younger participants consistently showed better performance than older participants (Figures 6 and 8).

Although there was no main effect of flow rate, the interaction of time of day and flow rate produced an unexpected result. Participants were able to detect targets of smaller subtended visual angle in the nighttime condition with the higher level of water flow (Figure 7). The reason for this result is unclear. The remaining statistically significant effects, three-way interactions, all showed improved visual acuity resulting from the hydrophobic treatment (Figures 8 and 9).

The experimental conditions in the present study simulated moderate to heavy amounts of rainfall, windshield wipers on at all times, and a moderate traveling speed. This experiment did not examine the scenario of very light rainfall, windshield wipers off, and a low traveling speed. In the later scenario, increased nighttime glare may result from water beading that is not rapidly removed. In addition, the current study was only performed under circumstances where the hydrophobic coating was applied as specified by the manufacturer, and believed to be near peak performance. Similar levels of improvement in visual acuity may not be observed with worn, or less effective, applications of hydrophobic coating. The durability of these treatments, and the resulting effects on visual acuity, remain to be investigated.

CONCLUSION

This experiment evaluated potential visual acuity benefits of hydrophobic coating products under simulated conditions of use. In general, this experiment showed that these products appear to significantly improve driver visual acuity and response time. However, this experiment did not address the durability or longevity of these products, as the hydrophobic coating was only tested when it was expected to be near peak performance. Therefore the benefits associated with hydrophobic coatings that were demonstrated here may diminish with time and wear, more or less slowly, depending on the durability of different hydrophobic treatments. Additional testing, under real-world driving conditions, where actual precipitation and durability are examined, would be desirable.