

Effects of Warning Lamp Color and Intensity on Driver Vision

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EFFECTS OF WARNING LAMP COLOR AND
INTENSITY ON DRIVER VISION

Report of work on Non-Blinding Emergency Vehicle Lighting (NBEVL)

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EXECUTIVE SUMMARY

The work reported here was part of a program of research on how warning lamps affect driver vision, and how those lamps can be designed to provide the most benefit for the safety of emergency vehicle operations. In order to understand the overall effects of lamps on safety, it is necessary to know about the positive (intended) effects of the lamps on vehicle conspicuity, as well as any negative (unintended) effects that the lamps may have on factors such as glare and driver distraction. This research was designed to provide information about how the colors and intensities of warning lamps influence both positive and negative effects of such lamps, in both daytime and nighttime lighting conditions. Color and intensity have received considerable attention in standards covering warning lamps (e.g., SAE, 2004, 2005), and interest in these variables has recently increased because of the new options provided by the growing use of LED sources in warning lamps.

Participants in this study were selected to be reasonably representative of the driving public. Two groups, based on age, were chosen to insure that some estimate could be made of how warning lamp effects might change with driver age. A static field setting was used to simulate the most important visual circumstances of situations in which drivers respond to warning lamps in actual traffic. Two vehicles with experimental warning lamps were placed so that they would appear 90 degrees apart in a simulated traffic scene as viewed by an experimental participant who was seated in a third vehicle. Four lamp colors were used (white, yellow, red, blue), and all four colors were presented at two levels of intensity. All intensity levels were high relative to current minimum requirements, since the greatest interest was in measuring potential benefits of high intensity lamps in the day, and possible problems with high intensity lamps at night. Participants performed three tasks, under both day and night conditions:

1. Lamp search, in which the participant had to indicate as quickly as possible whether a flashing lamp was present on the right or left simulated emergency vehicle. This task was designed to capture the kind of visual performance that would be important when a driver tries to locate an emergency vehicle approaching an intersection on one of two possible paths. Faster performance for a certain type of lamp can be taken to mean that the lamp provides better conspicuity.
2. Pedestrian responder search, in which the participant had to indicate as quickly as possible whether a pedestrian responder wearing turnout gear was present near the right or left simulated emergency vehicle. This was designed to capture negative effects of the warning

lamps on seeing pedestrian responders near an emergency vehicle. Slower performance for a certain type of lamp can be taken to mean that the lamp causes more interference with driver vision (e.g., glare or distraction).

3. Numerical rating of the subjective conspicuity of warning lamps. This task was designed to provide a subjective measure of the visual effects of lamps, which may or may not show the same effects of color and intensity that are provided by the objective search tasks.

As would be expected, the results of all three tasks showed major differences between day and night conditions. Search for lamps was easier during the night, and search for pedestrians was easier during the day. The large differences in performance between night and day add support, and some level of quantification, to the idea that the most significant improvements that can be made in warning lamps may be in adopting different light levels for night and day.

Over the range of lamp intensity that was used, there were improvements with higher intensity for the lamp search task during the day, but performance on lamp search at night was uniformly very good, and did not improve with greater intensity. The lamps showed little effect on the pedestrian search task during either day or night.

Color affected both the objective lamp search task during the day, and the rating of subjective conspicuity during both day and night. The different photopic photometric values for different colors that are currently specified by the SAE are approximately consistent with these findings, but there appear to be some discrepancies, particularly at night. More data on color may be useful in reviewing those specifications.

Based on the results of the experiment, and on previous results in the literature, we offer three major recommendations for the use of warning lamps:

1. use different intensity levels for day and night,
2. make more use of blue overall, day and night, and
3. use color coding to indicate whether or not vehicles are blocking the path of traffic.

In future research, we recommend that the following issues be addressed:

1. better definition of, and measures for “effective” intensity of flashing lamps,
2. the relationship between subjective conspicuity and objective search performance,
3. further development and validation of search tasks for evaluating warning lamps, and
4. more comprehensive data on color effects in daytime and nighttime.

CONTENTS

EXECUTIVE SUMMARY	i
CONTENTS	iii
INTRODUCTION	1
Overview of research issues	3
Special issues related to blue warning lamps	4
Overview of the experimental approach.....	7
METHOD	9
Participants	9
Tasks.....	9
Test site and materials	12
Experimental design.....	19
Procedure	20
RESULTS.....	21
Reaction time	21
Errors	26
Modeling effects of color and intensity.....	28
Conspicuity ratings.....	34
Summary of findings.....	38
Recommendations	40
Possibilities for future research.....	44
REFERENCES	46
ABOUT THE AUTHORS.....	47
APPENDIX	48

INTRODUCTION

The research reported here was designed to build on the results of several previous projects, all of which were aimed at identifying possible improvements in emergency vehicle lighting that might lead to better safety. We first examined crash data for emergency vehicles to determine what inferences could be made about the possible roles of warning lamps (Flannagan & Blower, 2005). We then investigated the visual effects of unusually intense experimental warning lamps on driver vision and driving at night in a test track situation (Flannagan & Devonshire, 2007). The current project extends the visual performance results in two main directions: (1) by incorporating new measures of the objective visual effects of warning lamps based on visual search tasks, and (2) by directly comparing the effects of warning lamps in nighttime and daytime using otherwise identical procedures.

The development of objective measures was an extension of work by Howett and his colleagues (Howett, Kelly, & Pierce, 1978; Howett, 1979). Further development of objective measures was particularly important because of a finding in our earlier work that the effects of lamp color were different for an important subjective variable (rating of conspicuity) compared to the effects of color on an important objective variable (the undesirable effect of warning lamps in which they cause visual masking of a nearby pedestrian at night). Specifically, the participants in the previous study rated the subjective conspicuity of blue relative to red much higher than would be expected based on the corresponding relative effects of blue and red lamps in masking a pedestrian emergency responder.

Main new aspects of method in this work:

1. Development of objective measures
2. Direct comparison of day and night

The work described in this report had both relatively short-term, substantive objectives and more long-term, methodological objectives. Substantively, it was designed to provide information about the effects of warning lamp intensity and color that could be used to develop new recommendations to improve the safety effectiveness of warning lamps. Methodologically, it was designed to develop more objective measures of the effects of warning lamps on driver vision, including both positive effects (e.g., alerting drivers to the presence and location of an emergency vehicle) and negative effects (e.g., unnecessarily distracting drivers or impairing their

ability to detect other important things, such as pedestrian emergency responders). The motives for the work included the general need to better understand the effects of warning lamps in order to make possible improvements in the safety of emergency vehicle operations, and also a specific need to understand the visual effects of LED light sources, which are fast growing in popularity for warning lamps. LEDs have many advantages outside of their visual effects, such as reliability and electrical efficiency, but they may also have important visual advantages for warning lamps because they can provide strong colors, flexible spatial patterns, rapid onsets and offsets, and variable flash patterns.

The work reported here is primarily based on assessing visual effects, using an experimental setting to simulate as well as possible the perceptual and attentional factors that seem likely to be important for warning lamp effectiveness in the real world of traffic. However, we also considered previous results from analyses of crash data designed to better understand the importance of various mechanisms in crashes that involve emergency vehicles of various kinds—including fire, police, and emergency medical services. One specific goal was to generate new proposals for how the use of warning lamps might be improved. This was intended to help maintain the focus of the entire effort on practical issues that could lead to change on at least some medium scale of time. Emergency vehicle operations are inherently risky and much more complex than other aspects of traffic. Furthermore, policies with regard to emergency vehicle warning lamps are based on strong and varied traditions. Because of these circumstances, almost any proposals must be considered tentative and subject to many possible criticisms and modifications. However, the recommendations developed here were meant to be at least innovative and thought provoking, and to embody as well as possible the best current knowledge with regard to visual effects of lamps.

For flashing colored lamps, LEDs provide much more flexibility than filtered bulbs.

Increased use of LED light sources makes it more important to understand color and intensity.

Overview of research issues

The present study was designed to address questions in three primary areas:

1. *Development of objective measures of the visual effects of warning lamps.* Much of the past work on warning lamps has been based on subjective assessments of the conspicuity of various lamps. Mortimer (1970) provided useful data on the effects of color of automotive signal lamps, but the work was largely based on subjective ratings. Howett (1979) used both subjective and objective methods, and included an interesting but unsystematic treatment of color. The present work is in several ways an extension of Howett's approach.
2. *Direct comparison of the effects of warning lamps in daytime and nighttime.* The differences in ambient light between night and day are so large that the effects of warning lamps are likely to be quite different. The conspicuity of lamps at night, against a generally dark background, is certainly much higher than it would be in daytime. In addition, changes in human vision from relatively cone-based vision in daytime to relatively rod-based (and blue-sensitive) vision at night could strongly affect the influence of color. The substantial change in spectral sensitivity that exists between cone and rod vision is illustrated in Figure 1.
3. *The effects of color and intensity of warning lamps, with a particular emphasis on blue.* Color has always been important in the design of warning lamps, although the use of color has not always been consistent. A careful use of color appears to be one way to obtain the best combination of high conspicuity (the desirable effects of warning lamps) and limited distraction or masking effects (the undesirable effects of warning lamps). In particular, our recent findings about the relative effects of red and blue seem worth extending to other colors. In the present study, we compared the effects of white, yellow, blue, and red lamps—using lamps that were constructed to allow each of the four colors to be presented while keeping all other lamp characteristics the same.

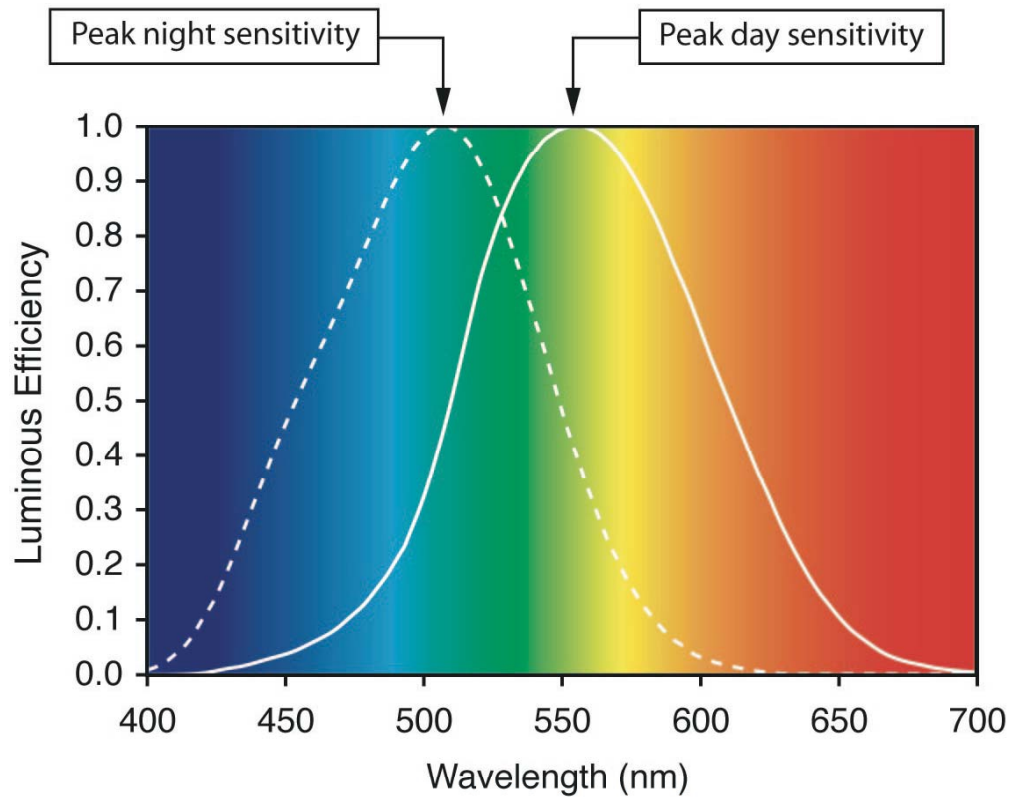


Figure 1. The scotopic (dashed line) and photopic (solid line) luminous efficiency functions, describing the spectral sensitivities of night and day vision, respectively.

Special issues related to blue warning lamps

Blue warning lamps have always had an ambiguous status. Consistent with the basic changes in human visual sensitivity between bright daylight and dim night conditions, as illustrated in Figure 1, most people have asserted that blue lamps are highly effective at night. However, it has also been claimed that blue lamps are weak, or even ineffective, in daylight conditions. For example, the 1999 version of SAE J2498, one of the major standards of the Society of Automotive Engineers (SAE) covering emergency warning lamps, stated in the Rationale section of the document:

Because of the change in human vision from the cones during the day to the rods at night, combinations of red and blue may be desirable to obtain maximum performance under both day and night viewing conditions.

Similarly, Oyler (as cited in Post, 1978) recommended a high minimum intensity during daytime for a particular application of blue warning lamps:

. . . to overcome, as far as possible the extreme tendency of blue to fade out in bright sunlight. For improved effectiveness blue, if used, should not be used exclusively, but with a signal of another color.

And in a study of emergency vehicle beacons of various colors, Rumar (1974) concluded with regard to blue that:

The blue beacons are almost too good in nighttime conditions in the respect that they cause discomfort but they are poorly visible in bright daylight conditions.

Nevertheless, the belief that blue lamps are ineffective in daytime has not been universal. The SAE document J595, which does not distinguish between photometric levels for day versus night use, specifies that when blue is used the minimum photometric requirements are only 25%, of those for white, implying that blue light is 4 times as effective as white light under the same circumstances. The SAE J595 relative requirements for white, yellow, red, and blue warning lamps are illustrated in Figure 2. Similarly, Mortimer (1970) had the participants in an experiment make subjective judgments about the conspicuity of automotive lamps of various colors, and obtained the data that we have summarized in Figure 3. The intensities of blue stimuli that were matched to white were slightly less than 25% of the corresponding white values. Given the substantial ambiguities about the status of blue lamps, this appears to be an issue on which it might be especially useful to obtain new, more objectively based data in the hope of reaching some resolution.

Some people have considered blue lamps ineffective in daytime, especially compared to red.

That view is qualitatively consistent with photometry for day and night vision

But the issue of blue in daytime is not simple.

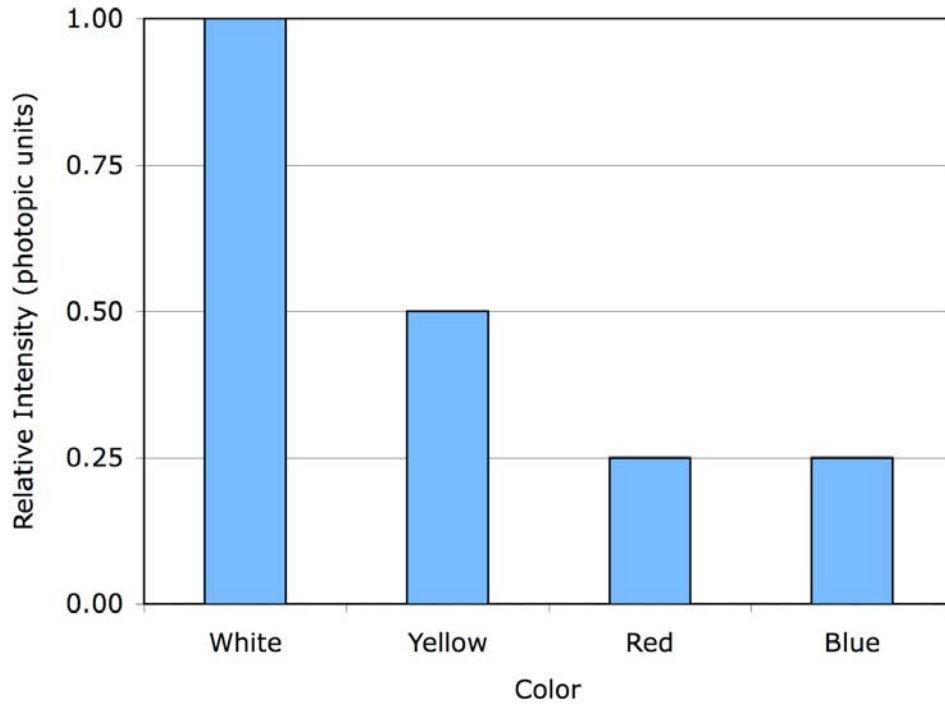


Figure 2. Requirements for relative intensities of four lamp colors (SAE, 2005).

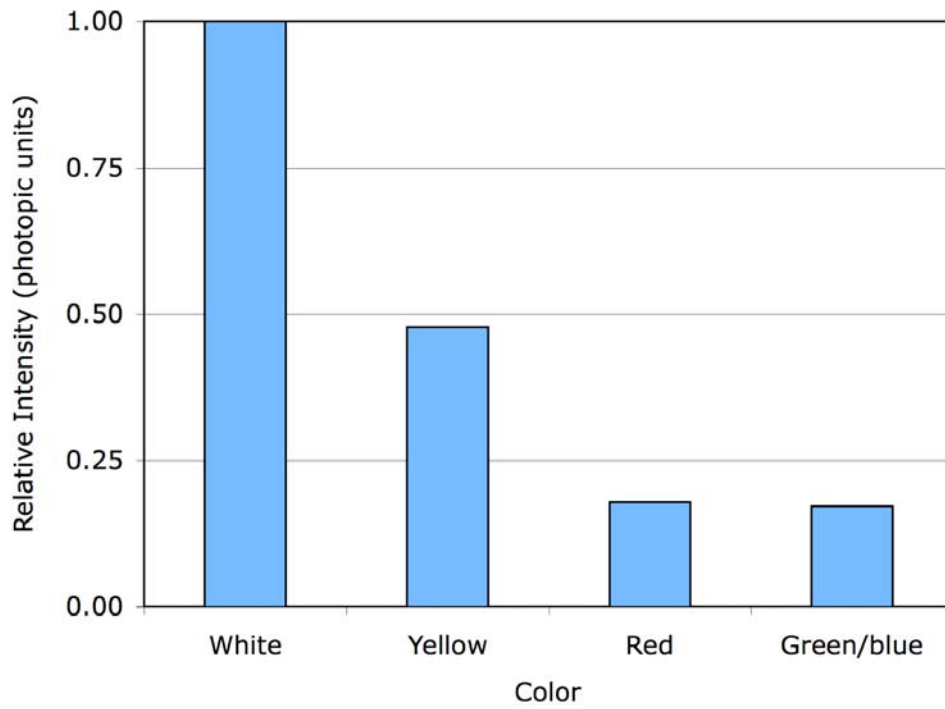


Figure 3. Equivalent relative intensities for four colors in daytime, based on subjective ratings of conspicuity (Mortimer, 1970).

Overview of the experimental approach

We had participants in this study perform three tasks: visual search for warning lamps, visual search for pedestrian emergency responders in the vicinity of warning lamps, and subjective ratings of the conspicuity of the warning lamps. The subjective ratings were similar to tasks that we and others had used before. The search tasks were used to obtain data on the objective visual performance associated with warning lamps that varied in intensity and color. The rationale for this was that, in many of the encounters that drivers have with warning lamps in normal traffic, the drivers are essentially performing search tasks, under strong time pressure.

One important real-world task that drivers face is to locate an approaching emergency vehicle as quickly as possible when the uncertainty about the location of the vehicle is high. For example, an ambulance could be approaching from any of several streets at an intersection. Another

The experimental setting was static, but was intended to simulate the most important visual conditions in real traffic.

The procedure was the same for night and day sessions. Same participants too.

Participants had to be fast and accurate in the search tasks; their performance could be scored objectively.

kind of task that a driver might face is to locate and avoid a pedestrian emergency responder who may be standing very close to an emergency vehicle parked at the scene of an emergency. In the first case, warning lamps would presumably help the driver locate the vehicle, whereas in the second case warning lamps might distract the driver from searching for possible pedestrians, or even mask their presence in the darkness of night.

In our experimental field situation, we tried to incorporate the essential parts of these types of real-world tasks. While it is not possible to capture all of the uncertainty of real traffic in any experimental procedure, we tried to create a high level of spatial uncertainty by requiring the participants in the experiment to respond to stimuli (flashing lamps or pedestrians) in widely separated locations. The participants sat in stationary vehicles and had to respond to lamps or pedestrians that could be located 90° apart—approximately as far left as a typical left exterior rearview mirror and as far right as a typical interior rearview mirror. We measured the time it took them determine in which location the lamps or pedestrian appeared.

Warning lamps can affect driver performance in ways that are determined by both perceptual mechanisms (e.g., how sensitive are the eyes to different colors) and more cognitive mechanisms (e.g., how efficient is the driver in executing a search strategy, or how resistant is the driver to the distracting influences of warning lamps). Such perceptual and cognitive abilities are known to vary markedly with age. We therefore sampled the participants from the normal driving population, but to provide a variety of visual abilities and driving styles we selected them from young and old ranges of driver age. We also balanced the groups by gender.

We used a field experimental situation in which the photometric levels throughout the scene would be realistic, and we used exactly the same procedure for day and night conditions in order to make comparisons of the results across those conditions as simple as possible.

We selected a range of warning lamp intensities that were high relative to current minimum standards (e.g., SAE, 2004). This was so that the results would be useful in addressing questions related to high light levels: Can we quantify negative effects of warning lamps (masking, distraction, etc.) for light levels at or above current levels? And is there evidence for possible benefits (increased conspicuity) at such levels of light?

In selecting a flash pattern for the experimental warning lamps, we made the flash rate high enough that multiple onsets and offsets would normally occur before participants responded. The rate was 5 Hz, which is just slightly higher than the 4 Hz upper limit specified in SAE J595, (SAE, 2005). The high flash rate was intended to reduce variability in response times that may have occurred because of when in the flash phase a participant began their search. (The signal to begin searching was always exactly coincident with the first lamp onset, but there may have been delays in when participants actually began their searches.)

METHOD

Participants

Eight people participated in the study. In order to allow a rough assessment of the effect of age, the participants were chosen from relatively young and old ranges of the overall driving population. Four were in a younger age group (between 18 and 28 years old with a mean age of 23.8 years) and four were in an older age group (between 62 and 79 years old with a mean age of 70.5 years). Each age group had two men and two women. The participants were recruited from a list of volunteers maintained at UMTRI, and were paid a nominal amount for their participation. All participants were licensed drivers with visual acuity that fell within legal driving limits and normal color vision based on testing with pseudoisochromatic plates (Ichikawa, Hukami, Tanabe, & Kawakami, 1978).

Tasks

During the course of the study, all participants performed three tasks: search for emergency vehicle warning lamps, search for a pedestrian emergency responder, and rating of the conspicuity of emergency vehicle warning lamps. All participants performed the three tasks in the same order (lamp search, pedestrian responder search, conspicuity rating) in each of two sessions (daytime and nighttime). All of the important aspects of the procedure, and all of the nominal requirements of the three tasks, were the same for daytime and nighttime sessions. However, as will be evident in the results, the actual task demands were strongly influenced by differences in ambient light between the day and night sessions.

All participants did the same three tasks (in both day and night):

Lamp search

Pedestrian responder search

Conspicuity rating

For all tasks, participants were seated in the driver's seat of a stationary passenger car in an open, paved area. In front of them there were two other stationary vehicles, each with experimental emergency warning lamps mounted on their roofs. During the pedestrian search task, experimenters wearing turnout gear could also be present, one at a time, in any one of four positions just to the left or right of either of the two forward vehicles. Figure 4 illustrates the field setup, showing the positions of the three vehicles

and the four potential positions in which a pedestrian might be present for the pedestrian responder search task.

In the lamp search task, the participant experienced a series of trials, each of which began with the participant looking down into his or her lap so that the exterior scene was not visible. A computer in the car emitted a brief tone to signal the onset of the trial, and, simultaneously, one of the warning lamps on the forward vehicles began to flash at 5 Hz (except for a small proportion of catch trials for which no lamp was presented). The flashing lamp could be any of four colors, each at either of two intensities (see Table 1). The participants' task was to indicate, as quickly as possible, which vehicle's lamp was flashing by pushing one of two buttons on a small response box that they held in their hands. They were permitted to use any scanning strategy—including head movements and eye movements—that they believed would allow them to respond as quickly as possible. They were permitted to look up from their laps, and to scan the scene however they wished. They were given no advice or requirements about looking directly at the forward vehicles, the lamps, or any other part of the scene. The response buttons were marked "left" and "right" and were mounted on the left and right sides of the hand-held box, respectively. For those trials on which there was no flashing lamp, they were instructed not to respond at all. The lamps flashed for four seconds, or until a button was pressed. The computer recorded which button was pressed and the elapsed time, in milliseconds, from the onset of the tone (which, except for catch trials, was also the onset of the flashing light) until the button was pressed. If no button was pressed within four seconds of the tone, the computer recorded that fact (which would be a correct response if there had been no flashing light, and otherwise would be considered a miss) and ended the trial. After each trial, the participant looked back down into his or her lap and awaited the next tone from the computer. An experimenter in the back seat of the participant's car initiated each trial after checking that everything was ready. Trials occurred at about four per minute for the lamp search task.

In the pedestrian responder search task, participants experienced a similar series of trials. They again began each trial looking down in their laps, and trials began with a brief tone from the computer. On most trials, one of the lamps began to flash simultaneously with the tone. As in the lamp search task, the flashing lamp could be any of four colors, at either of two intensities, and could be on either of the two forward vehicles. Also as in the lamp search task, there were some trials on which no lamp was flashing. However, for the pedestrian responder search task

the participant was to ignore the lamps and, instead, to indicate as quickly as possible which vehicle had a pedestrian responder standing by it. This was done using the same two buttons that were used for the lamp search task. On a small number of catch trials, no pedestrian was present. For those trials, the participant was instructed not to respond at all. As before, the lamps flashed for four seconds or until a button was pressed. The computer awaited a response for those four seconds, after which, if no response had occurred, it recorded that fact and ended the trial. At most, only one pedestrian responder was present at a time. When present, the pedestrian responder could be in any of the four positions shown in Figure 4. The pedestrian could be wearing either black or yellow turnout gear, equipped with standard retroreflective markings and with a background material having one of the spectral reflectances shown in Figure 9. (For a comparison of visual performance with turnout gear such as that used in this study to ANSI 207 garments, see Tuttle, Sayer, & Buonarosa, 2008.) As for the lamp search task, the participants were given no advice or restrictions about how they should scan to locate the pedestrian responder. As soon as the tone sounded, they were free to look up from their laps and use any pattern of head or eye movements that they believed would help them to respond quickly and accurately. With regard to the correct response, it made no difference if the pedestrian was immediately to the left or right of a vehicle; the only thing that mattered was which of the two vehicles, if either, had a pedestrian next to it. It also did not matter which color of turnout gear the pedestrian was wearing. All levels of the lamp variables (color, side, intensity, and whether or not a lamp was flashed at all) were fully combined with the pedestrian variables (color, which vehicle the pedestrian was adjacent to, which side of that vehicle the pedestrian was on, and whether or not a pedestrian was present at all) so that the presence or nature of the flashing lamps was in fact not predictive in any way of whether a pedestrian was present, or where the pedestrian would be. The best strategy for the participants was therefore to ignore the lamps as much as possible.

In the conspicuity rating task, the participant was instructed to look at the lamp on the left vehicle while each combination of color and intensity was presented, and to rate the subjective conspicuity of that stimulus by saying a number. The low intensity white lamp was presented at the beginning of the task and assigned a value of 100 to use as a standard. Participants were allowed to use any positive real number for each stimulus. Each color and intensity combination

was presented as a steady light for three seconds. The combinations were presented in random order.

Test site and materials

The test was conducted on a flat, unmarked, 40x40-meter, asphalt-paved area on the UMTRI grounds. Sessions were conducted during the day and at night, with dry pavement. For half of the participants, the area was lighted during the night sessions with pole-mounted luminaires; for the other half of the participants, all fixed lighting in the immediate area was turned off. The high-beam headlamps of the participants' vehicle were always on for the night sessions. This provided a reasonably bright area of pavement immediately in front of that vehicle (peaking at about 5 cd/m² from the participant's point of view), and provided illumination on the retroreflective markings of the turnout gear worn by the pedestrian responders. Illumination values from the high beams on vertical surfaces at the four potential pedestrian positions were (from left to right, from the participant's point of view) 0.58, 0.42, 0.60, and 0.56 lux, for an average of 0.54 lux. Background illuminance levels at the same positions, with the headlamps off, averaged 0.34 lux. That light was mostly from distant road lighting that was not directly behind the participant and which therefore had no discernible effect on the retroreflective markings on the turnout gear. When the pole-mounted luminaires were on, illuminance from those sources on vertical surfaces, facing the participants, at the four pedestrian positions were (from left to right) 1.60, 1.61, 7.91, and 9.85 lux.

The participants' vehicle faced directly north, so that in daytime the sun would be behind it and would provide high illumination on the rears of the other two vehicles, and on the scene in general as viewed by the participants. Daytime conditions were mostly sunny, but there were occasional clouds during some experimental sessions. Sun illumination, measured for a south-facing vertical surface at the center of the experimental site, ranged from 86,000 to 10,000 lux, with an average of 48,000 lux.

Figure 4 shows the placement of the stationary vehicles and the four locations where pedestrian responders could appear during the pedestrian responder search task. Experimental emergency warning lamps were mounted on the roofs of the two forward vehicles, at positions 25 m from the eyes of the subjects as they were seated in the rear vehicle. As shown in Figure 4, the forward vehicles were located 45° to the right or left of the main axis of the subject vehicle. From the subject's point of view, this meant that the left vehicle was visible through the left-

front side window, just wide of the A-pillar and at approximately the lateral angular position of the left-side rearview mirror. The right vehicle was visible through the windshield, at approximately the lateral angular position of the center rearview mirror. Because of the vertical positions of the rearview mirrors, the left vehicle appeared above the left-side mirror and the right vehicle appeared below the center mirror. All of the vehicles were typical, late model passenger cars. The two forward vehicles were identical to each other.

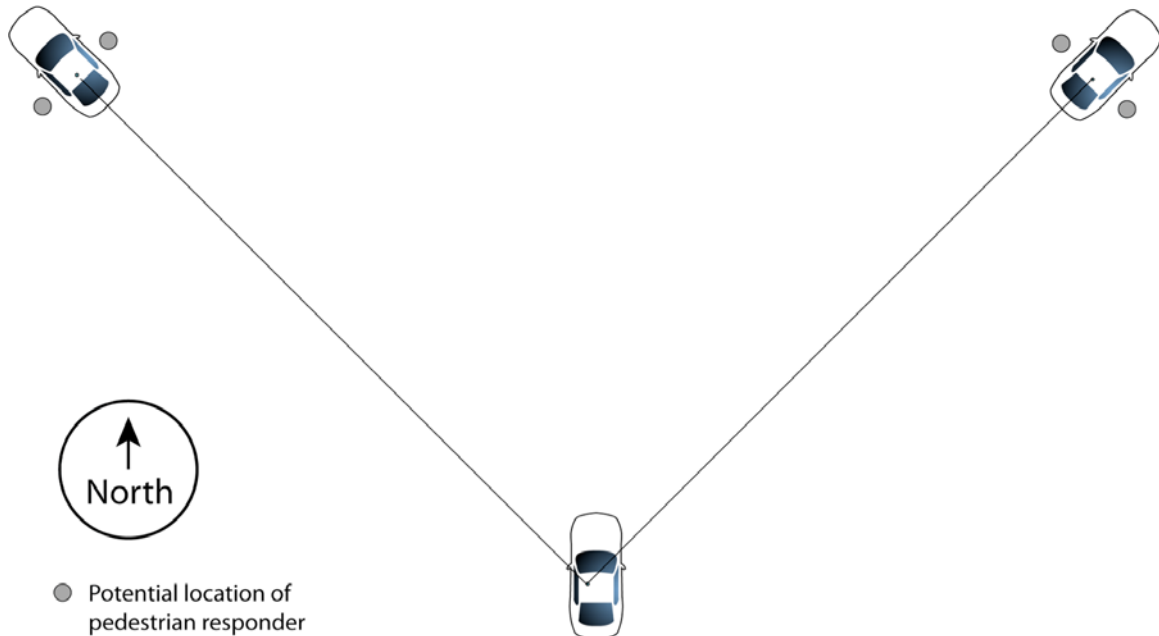


Figure 4. Diagram of the test site, showing the locations of the stationary vehicles and the four potential locations of pedestrian responders (scale is approximate).

The background areas that could be seen beyond the two forward vehicles from the participant's point of view included parts of the UMTRI building and grounds. The background scenes were primarily gray in color, and included an assortment of other vehicles behind the experimental vehicles. Those vehicles included the personal vehicles of UMTRI employees and an assortment of University vehicles. These vehicles varied from day to day, and to some extent within experimental days.

There were two identical experimental warning lamps, one of which is shown in Figure 5. They were constructed for the purposes of this study, and were designed to allow the presentation of any of four colors (white, yellow, red, and blue) at various intensities. These specially constructed lamps were used instead of commercially available lamps so that color and

intensity could be varied while all other aspects of the lamps were held constant (such as the shape, number, and spacing of individual light emitters in the lamps). The experimental lamps were also designed to provide higher intensity levels at a single point than is typical of current emergency warning lamps. This design was appropriate for the purposes of the study because the lamps would be viewed only from a single fixed angle; although it would not work for real lamps, which have to be viewable from a range of angles.

Each lamp contained 16 LEDs, four of each color. Each LED was fitted with a reflector that produced a narrow beam, so that a high intensity could be achieved immediately on the axis of the lamp. This meant that it was necessary to control the aim of the lamps accurately to reliably produce high levels of light at the eye positions of the participants, but it was reasonably easy to do that because of the static nature of the experimental setup. The lamps were fitted with lasers parallel to their main axes for ease of aiming in the field. During experimental sessions, participants were free to make normal head and eye movements, but because they always were in the driver's seat of the rear vehicle those movements could not result in substantial shifts within the beam patterns of the experimental lamps. For example, at the 25-m viewing distance, if participants moved their heads laterally 25 cm, that would change their angular position within the beam pattern by only about 0.6°.

The arrangement of colors within each lamp is illustrated in Figure 6. As viewed by the participant, the order of colors from left to right was: white, yellow, blue, and red. That pattern was repeated twice on each side of the lamp, with a clear space in between two sets of 8 LEDs. The light-emitting face of each component was round and 25 mm in diameter; spacing within each set of 8 was 35 mm (center-to-center). The entire width of the light-emitting portion of the lamp, between the outer edges of the outermost individual reflectors, was 1 m. Because of the way the colors were arranged—in a pattern that repeated left to right rather than symmetrically around the center of the lamps—there was a slight correlation between color and location (e.g., the white LEDs would be slightly closer than the red LEDs to a pedestrian on the left of one of the forward vehicles as viewed by the participants). But such biases were balanced by the multiple locations of vehicles, lamps, and pedestrians used in the study.

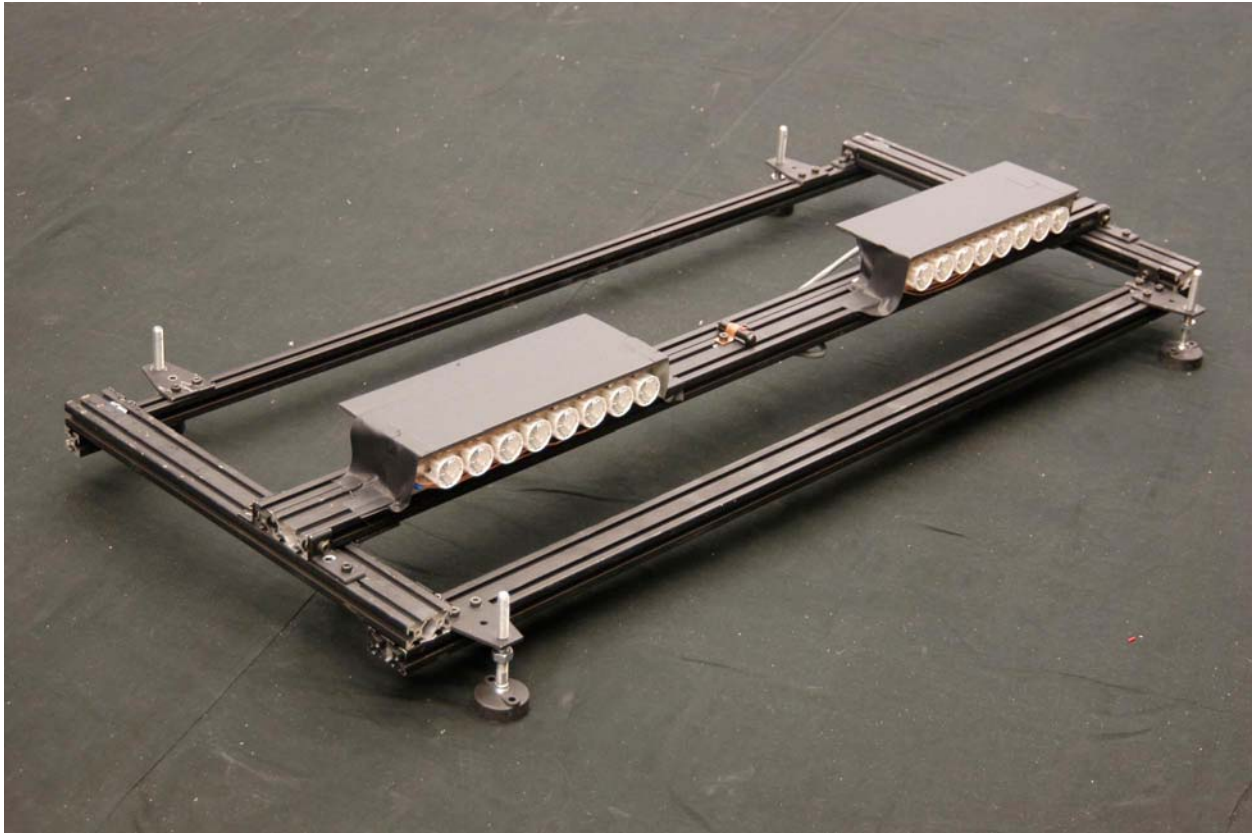


Figure 5. One of the experimental LED lamps that were used on top of the parked vehicles.



Figure 6. Schematic diagram of one of the experimental LED lamps, showing the layout of colors (white, yellow, blue, red) as viewed by a subject.

The spectral output of the LEDs is shown in Figure 7. The peak beam intensities of the lamps (which were aimed at the participants’ eye position) are given in Table 1. These intensities represent the combined output of the four LEDs of each color that made up each lamp. Table 1 also gives scotopic/photopic (S/P) ratios for these spectra (see Figure 1 for the scotopic and photopic luminous efficiency functions), and peak wavelengths for the three colored LEDs. The lamps were operated with computer control of current to produce two levels of intensity for each of the four colors, with ratios of about 2:1 between the levels within each color.

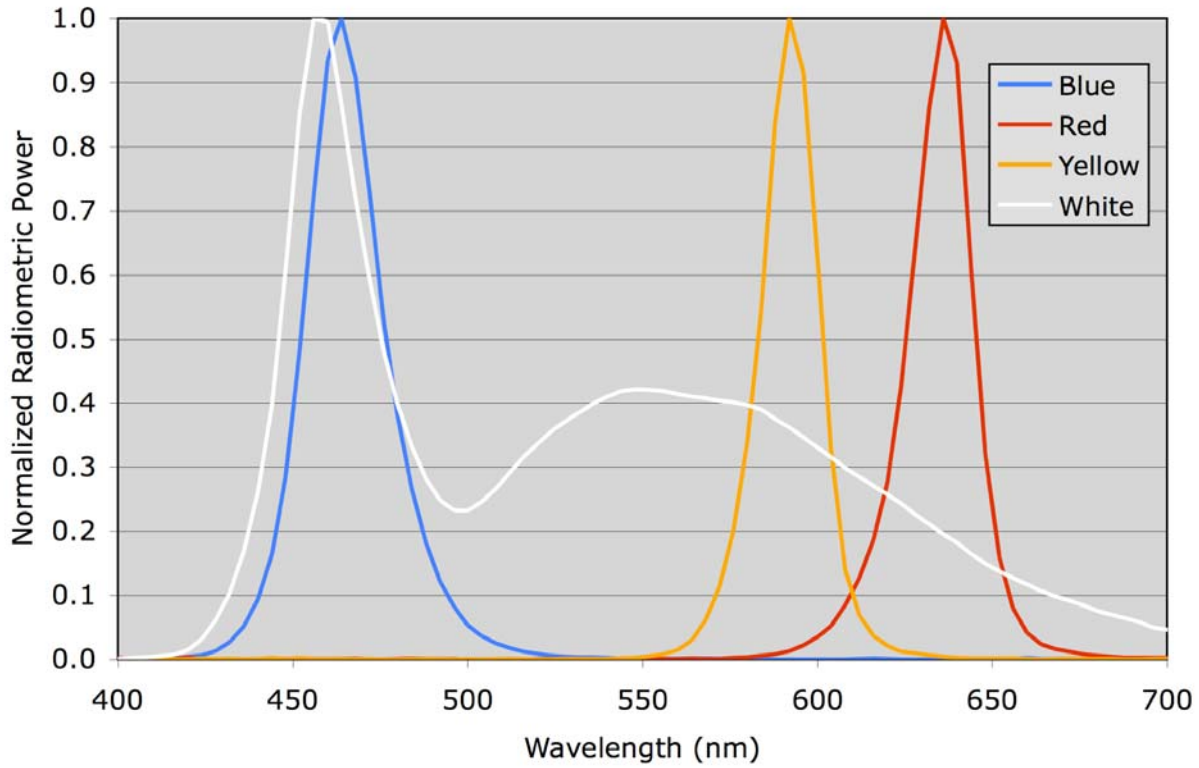


Figure 7. Spectral power distributions for the four LED colors.

Table 1. Photometric values for the LED lamps

LED color	S/P ratio	Peak wavelength (nm)	Nominal intensity level	Luminous intensity	
				Photopic cd	Scotopic cd
Blue	16.4	464	High	1,444	23,617
			Low	604	9,878
Red	0.069	636	High	4,260	295
			Low	2,112	146
Yellow	0.246	592	High	2,060	507
			Low	1,276	314
White	2.52	Not applicable	High	5,988	15,107
			Low	2,320	5,853

The overall range of intensities was chosen to be high relative to current standards for warning lamps. For example, in SAE J2498 (SAE, 2004) the minimum photometric value at any one point in front of a large emergency vehicle, operating in the mode of clearing the right-of-way, for all lamps (combining upper and lower lamps) is 13,750 candela-seconds per minute (cd-s/min). Because the lamps in the current study were always flashed with a 50% duty cycle, the candela values in Table 1 can be converted to cd-s/min by multiplying by 30. Thus, the minimum value used in the study (the lower blue level) was $604 \times 30 = 18,120$ cd-s/min. The maximum value used in the study (the higher white level) was $5,988 \times 30 = 179,640$ cd-s/min. (Because the SAE standard uses photopic photometric units, the photopic candela values from Table 1 are most relevant. However, it is worth noting that, because the effect of color was a major issue in this study, and because the study involved both day and night conditions, neither the photopic nor the scotopic values in Table 1 should be expected to be fully predictive of visual performance.)

The ranges for the individual colors were chosen on the basis of pilot testing and previous results to yield approximately equal levels of performance on the experimental tasks. We did this so that, in the analysis of results, we would be able to find photometric levels across colors that corresponded to equal levels of performance by interpolation (or, to some extent, by extrapolation).

During the lamp and pedestrian search tasks, the LEDs were always flashed at 5 Hz, with a 50% duty cycle. This is slightly above the range of 1 to 4 Hz specified for flashing warning lamps in SAE J595 (SAE, 2005), but for the reaction time tasks used in this study a relatively high flash rate may produce less variable performance by reducing the degree to which a participants' search for a flashing lamp may be delayed by a long off cycle. An important assumption behind the use of a single flash rate in this study was that the effects of color, which were of primary interest, do not vary with flash rate.

The two sets of turnout gear worn by pedestrians had standard retroreflective markings. The background material on one was black and on the other was yellow, as illustrated in Figure 8. The spectral reflectance of those materials is shown in Figure 9.



Figure 8. The two colors of turnout gear (black and yellow) worn by the pedestrian responders.

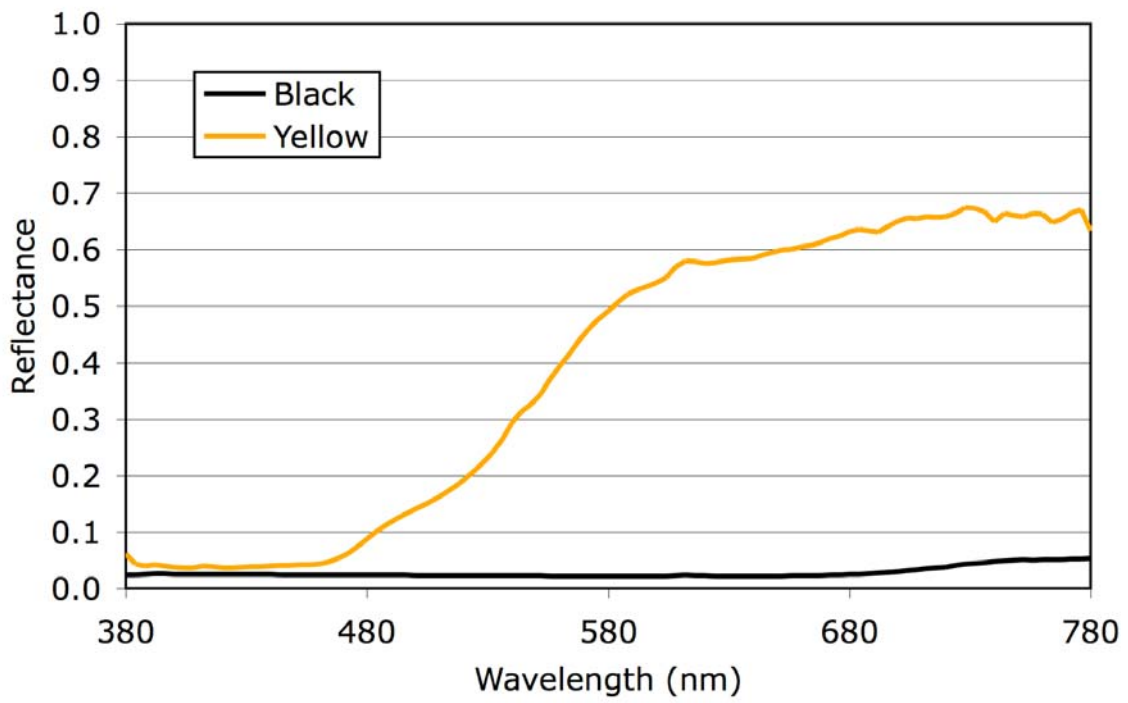


Figure 9. Spectral reflectance of the two colors of turnout gear.

Experimental design

There were three tasks in the experiment: lamp search, pedestrian responder search, and conspicuity rating. All three tasks were performed by all participants in each of two sessions (day and night). The order of sessions and tasks was the same for all participants. The day session was always first, followed by the night session. Within each session, the order of tasks was: lamp search, pedestrian search, and conspicuity rating. The lamp search task and the conspicuity rating task used full factorial designs, and the pedestrian search task used a fractional factorial design. The order of trials was randomized individually for each subject in each task.

In the lamp search task, the independent variables were warning lamp color (white, yellow, red, blue), warning lamp intensity (low, high), vehicle location (left, right), and ambient light (day, night). The combinations of those variables yield $4 \times 2 \times 2 \times 2 = 32$ conditions. Those conditions were repeated 5 times per participant. In addition, 40 trials per participant were run with the warning lamps off, yielding 200 trials per participant in the lamp search task.

In the pedestrian responder search task, the independent variables were turnout gear color (black, yellow), pedestrian location in the scene (by the left or right car), pedestrian location relative to the car (left or right of the car), warning lamp color (white, yellow, red, blue), warning lamp intensity (low, high), vehicle location for the warning lamp (left, right), and ambient light (day, night). The combinations of those variable yield $2 \times 2 \times 2 \times 4 \times 2 \times 2 \times 2 = 256$ conditions. A half-fraction of those (128 conditions) was used for each participant, with each of the complementary half-fractions being used for half of the participants. In addition, for each participant, 32 trials were run with the warning lamps on and the pedestrian absent, 32 trials were run with the warning lamps off and the pedestrian present, and 8 trials were run with the warning lamps off and the pedestrian absent, yielding 200 trials per participant in the pedestrian search task.

In the conspicuity rating task, the independent variables were warning lamp color (white, yellow, red, blue), warning lamp intensity (low, high), and ambient light (day, night). The factorial combination of those variables produced $4 \times 2 \times 2 = 16$ conditions. Each of those was repeated 3 times per participant, yielding 48 trials per participant in the conspicuity rating task.

Within each task, trials were presented in random order, so that participants could not anticipate the nature of upcoming trials. For example, all colors and intensities of the warning lamps were randomly mixed.

Procedure

Each participant took part in two experimental sessions, one in the daytime and one at night. The night sessions always began after the end of civil twilight (when the sun is six degrees below the horizon). For each participant, the night session was conducted during the evening of the day in which the day session took place. After arriving at UMTRI, each participant completed visual acuity and color vision screening tests and was led to the outdoor area where the experiment was conducted. He or she was seated in the test vehicle, and an experimenter read instructions for the experiment and answered any questions. The full text of the instructions that were read to the participants is given in the Appendix.

Three experimenters were involved in each session. One sat in the back seat of the participant's car. He was primarily responsible for giving instructions, answering questions, and supervising the overall progress of the session. The two other experimenters served as pedestrian responders during the pedestrian search task. For all three tasks, the experimenter in the participant's car initiated each trial when it was clear that everything was ready. For the lamp search and conspicuity rating tasks there was little delay between trials, and trials were run at about 4 per minute. In the pedestrian responder search task, the pedestrian experimenters had to move quickly into position, or out of sight, before each trial. The experimenter in the participant's car monitored their progress and initiated a trial when they were ready. All three experimenters had lists of trial numbers and the order of experimental conditions, and were in radio contact with each other so that they could help each other keep track. In the pedestrian responder search task, trials were run at about 3 per minute.

RESULTS

We present the results here first in terms of overall summaries of reactions times and error rates, and then we present a more detailed description of the effects of warning lamp color and intensity on both reaction time and errors, followed by description of the results from subjective conspicuity ratings. Preliminary analyses indicated that there were no differences between the night conditions in which the pole-mounted lighting was on or off. All results are reported here for day versus night, without distinguishing between the two night lighting conditions.

Reaction time

Figure 10 gives an overall summary of the reaction times in both of the search tasks. These results serve to illustrate some of the main characteristics of the tasks, and how they are affected by ambient light. First, it is clear that under the range of conditions used in this experiment the lamp search task is considerably easier than the pedestrian responder search task. The overall average reaction time for the lamp search task is 635 ms, while the overall average reaction time for the pedestrian search task is 1409 ms. The effect of ambient light is opposite for the two tasks, as one might expect. The lamp search task becomes substantially easier at night, with average reaction time falling from 853 ms in the day to 473 ms at night, $F(1,4) = 31.2$, $p = .0051$. Even at the high intensity levels used for these experimental warning lamps, the lamps are much harder to locate against the background of daylight than at night. In contrast, and also as expected, the pedestrian search task becomes substantially more difficult at night, with average reaction time rising from 1243 ms in the day to 1608 ms at night, $F(1,4) = 23.1$, $p = .0086$. Even with retroreflective markings, the pedestrians are considerably harder to locate at night than during the day. However, even though these results are probably broadly applicable to day and night situations in the real world, it is important to keep in mind that many real-world circumstances may modify them considerably.

Lamp search was harder in daytime;
pedestrian search was harder at night.

Lamp search was better with higher intensities
in the day, but was uniformly fast at night.

The lamps had little if any effect on pedestrian
search, day or night.

For example, because the nature of the search task used in this experiment required the main targets to be 90° apart (45° to each side of the straight ahead), the geometry was unfavorable to the retroreflective functioning of the turnout gear. Even with the high-beam lamps on, there was far less light on the pedestrian locations than there would be in many situations in which a vehicle is approaching an emergency scene at night. Also, the observation angles (the angles formed by the headlamps, the retroreflective markings, and the participants' eyes) were larger than they would usually be for more distant retroreflective stimuli, thereby reducing the retroreflective efficiency of the markings.

Figure 11 and Figure 12 show reaction times broken down by age group for the lamp search task and the pedestrian search task, respectively. These figures further illustrate differences in the effect of ambient light on the two search tasks, by showing how the two age groups differ in their responses. Although the effects of age on reaction time were not statistically significant, we present them here for comparison to the error data to be presented later, for which age did have statistically significant effects. As would be expected for many visual tasks involved in driving, the older group tended to be slower than the younger group for most comparable conditions. There is one interesting exception to that pattern, which is that the older group was slightly faster than the younger group on the lamp search task at night. As can be seen in Figure 11, even though the older group was considerably slower on this task than the younger group during the day—the pattern that one usually sees for visual performance—they improved their reaction times so much at night that they became slightly faster than the younger group. We will return to this unusual outcome in the following section, in which we present an overview of error rates on the two search tasks.

Figure 13 and Figure 14 show how the intensity of the warning lamps affected reaction time for the lamp search task and pedestrian search task, respectively, under day and night ambient light conditions. (These figures show results in terms of *nominal* intensity levels. Actual levels were different for each color, as shown in Table 1.) In Figure 14, we have included the condition with the warning lamps off. (For the pedestrian search task, reaction times with the warning lamps off were a meaningful baseline for how hard it was to find the pedestrian with no distracting or masking effects of the lamps, whereas in the lamp search task the only responses that occurred with the warning lamps off were a few errors.) The same main effects of ambient light on the two search tasks that were seen in Figure 10 are also evident in Figure 13 and Figure

14 (i.e., the lamp search task is easier at night, whereas the pedestrian search task is harder at night). In addition to those effects, the intensity of the warning lamps has a significant main effect on reaction time for the lamp search task, $F(1,4) = 57.6, p = .0016$. It is clear from Figure 13 that this effect occurs entirely within the daytime condition, with daytime performance being faster with higher lamp intensity. Consistent with that pattern of effects, the interaction between lamp intensity and ambient light is also significant, $F(1,4) = 17.6, p = .014$. As can be seen in Figure 14, lamp intensity (including zero intensity) had little if any effect on reaction time for pedestrian search during the day or at night. Neither the main effect of lamp intensity, $F(2,8) = 0.75$, nor the interaction of lamp intensity with ambient light, $F(2,8) = 0.07$, were significant.

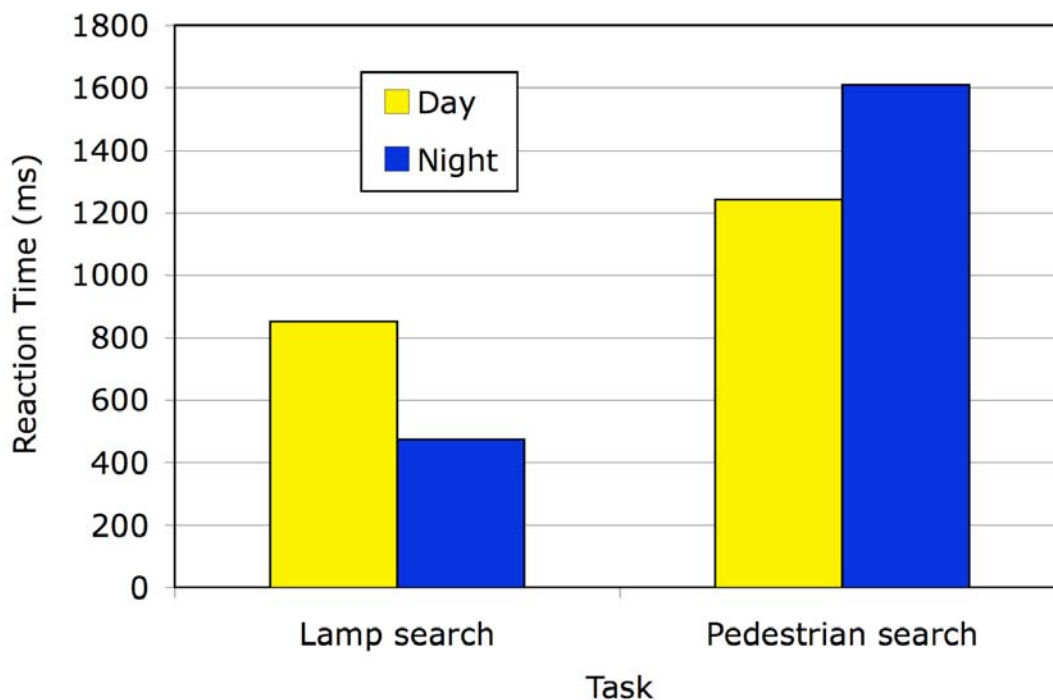


Figure 10. Reaction times for both search tasks by day/night.

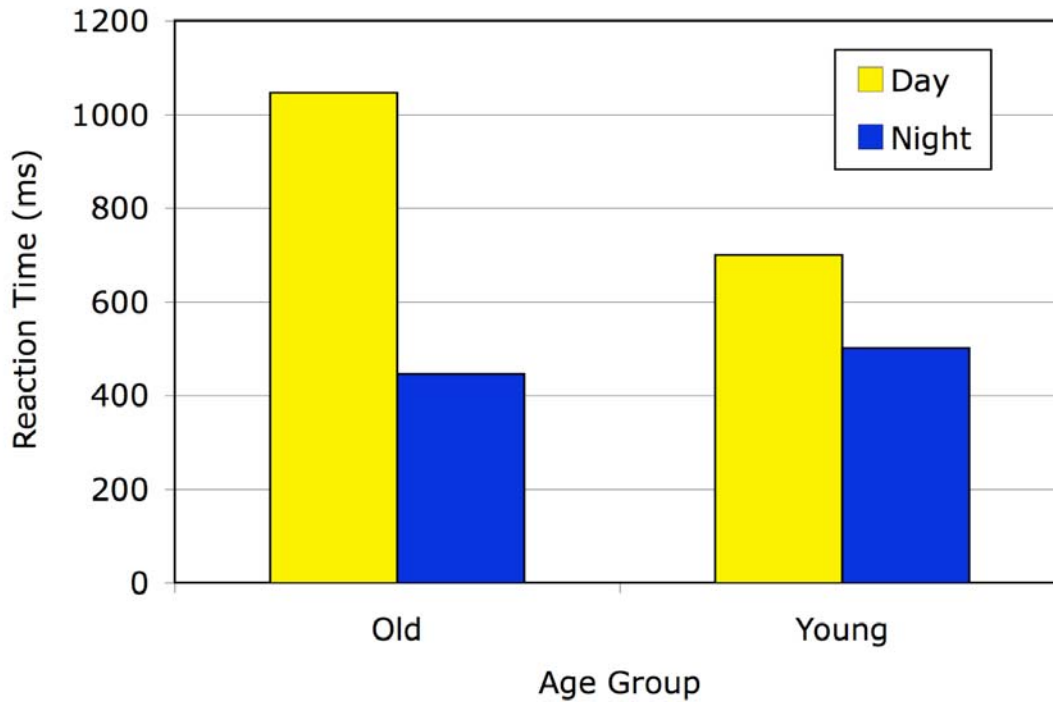


Figure 11. Reaction times for the lamp search task by age group and day/night.

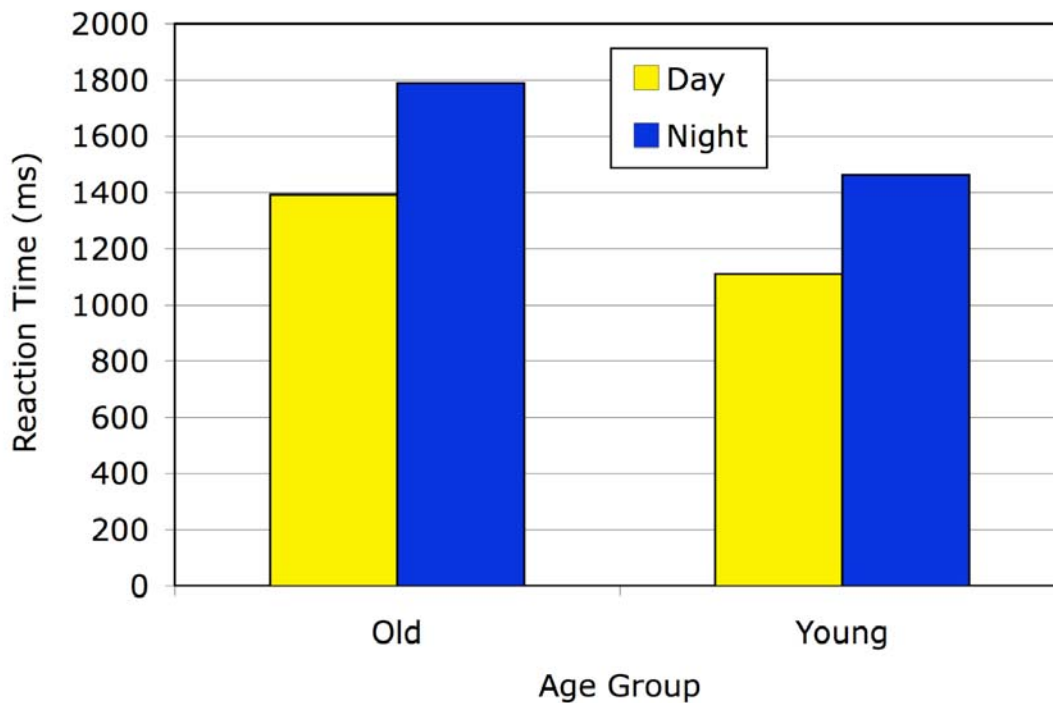


Figure 12. Reaction times for the pedestrian responder search task by age group and day/night.

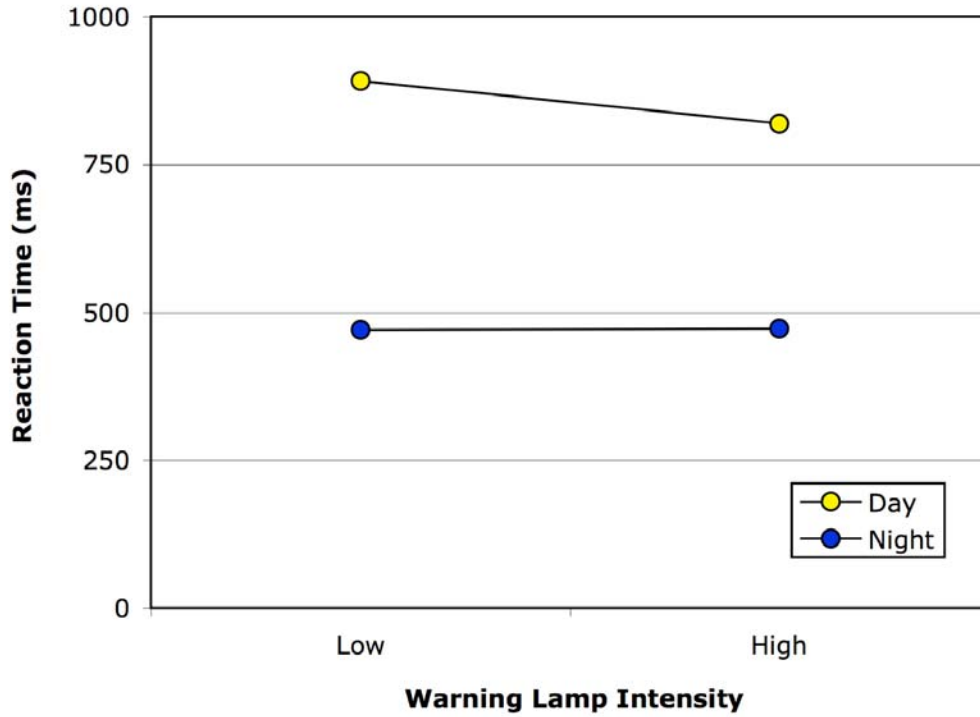


Figure 13. Effects of warning lamp intensity and ambient light on reaction time for the lamp search task.

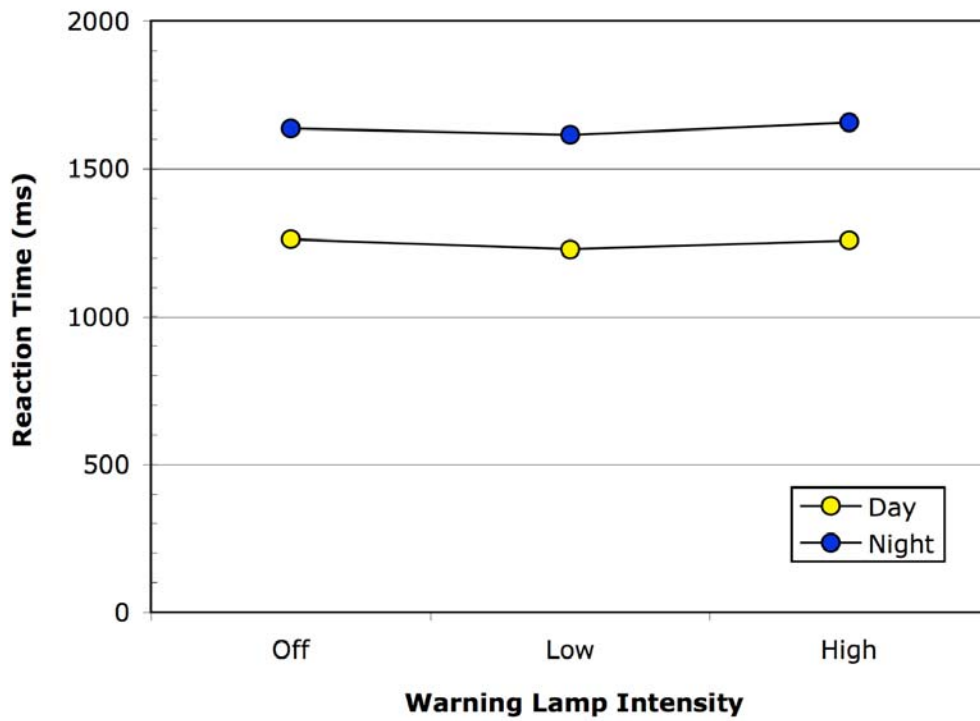


Figure 14. Effects of warning lamp intensity and ambient light on reaction time for the pedestrian responder search task.

Errors

Figure 15 shows the overall proportions of correct trials for the two search tasks in daytime and nighttime. In contrast to the findings for reaction times, in which ambient light appeared to have different effects on the difficulty of the two tasks, in terms of error rates both of the tasks tended to have lower performance at night (although the main effect of ambient light was not quite significant at the conventional 0.05 level, $F(1,4) = 7.16, p = .056$). However, when these data are broken down by age group, as they are in Figure 16 and Figure 17, it appears that this pattern is largely due to the older group, which showed remarkably faster (and, in that sense, better) performance on the lamp search task at night (see Figure 11). Overall, the older group had a significantly higher error rate than the younger group, $F(1,4) = 18.5, p = .013$. Figure 16 shows that the large improvement in speed that the older group displayed on the lamp search task at night was accompanied by a dramatic reduction in proportion correct. In contrast to the older group, the younger group—which also showed a substantial, if more modest, improvement in lamp search speed at night—has a slightly higher proportion correct for lamp search at night.

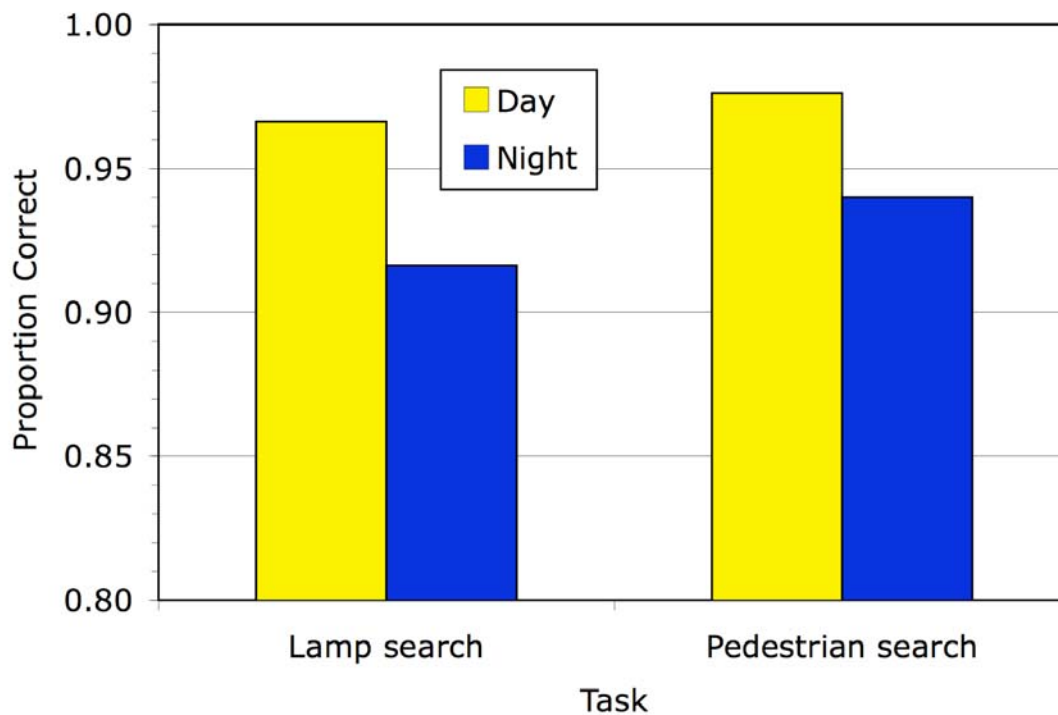


Figure 15. Proportion correct for both search tasks by day/night.

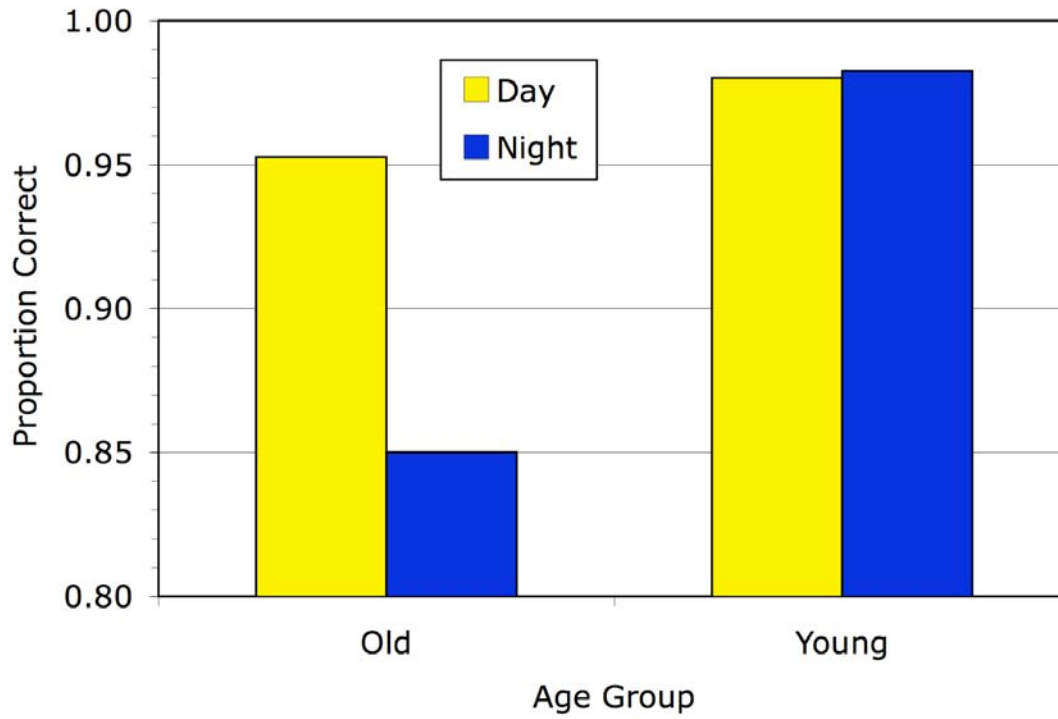


Figure 16. Proportion correct for the lamp search task by age group and day/night.

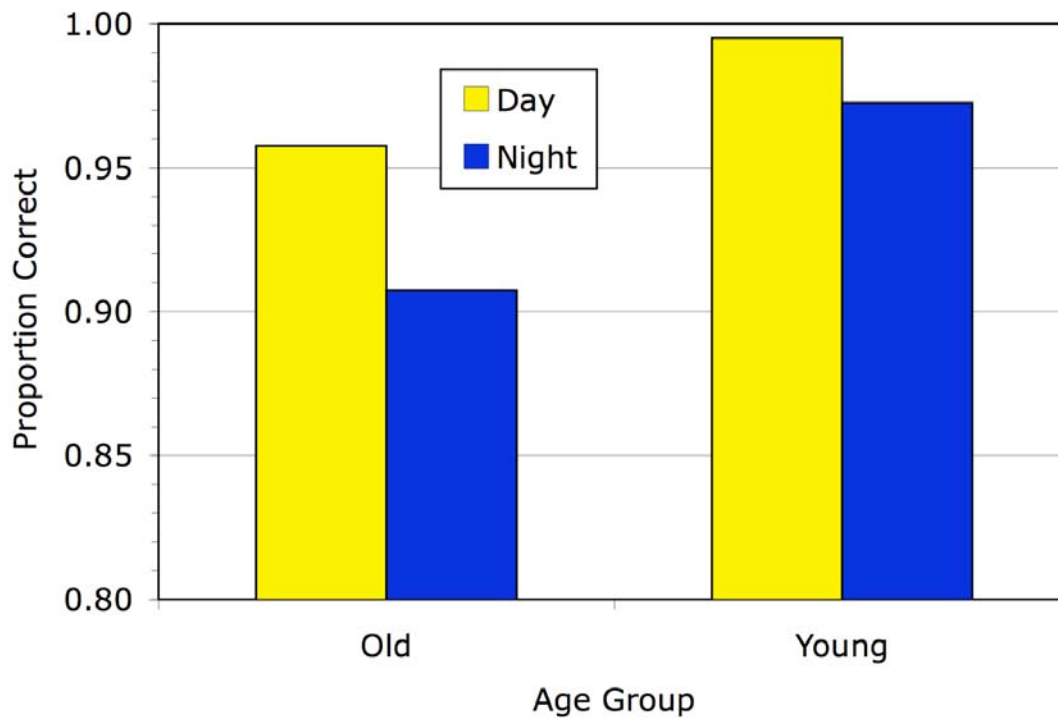


Figure 17. Proportion correct for the pedestrian responder search task by age group and day/night.

In summary, it seems that the older group may be displaying a difference in strategy from the younger group. Both are actually better able to perform the lamp search at night, but the older group has chosen to increase the speed of their responding so much at night that they have paid for part of that increase in higher error rates. This is therefore an example of the kind of speed-accuracy tradeoff that can occur in many areas of human performance data because of shifts in strategy. Very broadly speaking, faster performance is usually associated with fewer errors, rather than more errors, when comparisons are being made across conditions in which human performance differs (e.g., Posner, 1978). When they perform under two conditions that differ in difficulty, people usually take advantage of their fundamentally better abilities in the easier condition to go a bit faster, but also to achieve somewhat higher accuracy. It is difficult to completely sort out the effects of such possible strategic factors, but one practical result for the current study is that reaction times on the lamp search task at night are uniformly fast, and it is therefore difficult to use them to estimate how changes in lamp intensity might affect performance. However, the light intensities for this experiment were chosen to be high enough that performance on the lamp search task at night was expected to be very high, and possibly subject to a ceiling effect. The more interesting effects of lamp intensity at night were expected to be negative effects on the pedestrian responder search task.

Modeling effects of color and intensity

Figure 18 shows a breakdown of the data in Figure 13 by color, presenting reaction time on the lamp search task for each combination of the four colors and the two intensity levels, for both day and night conditions. The horizontal axis of this figure is luminous intensity in photopic candelas, plotted on a logarithmic scale. As was already shown in Figure 10, search times are dramatically lower at night. Also, at night there are no discernible effects of intensity and color on reaction time, as if performance is constrained by a ceiling effect. In contrast, in the daytime the higher intensity levels within each color have shorter reaction times than the lower levels.

However, in spite of the fact that higher intensity led to shorter reaction times in the daytime, it is clear that intensity does not capture all of the differences among the lamp conditions. At any level of intensity, there are offsets in performance for the different colors. We have modeled this effect of color by choosing the overall average reaction time for daytime, 853 ms, and interpolating for each color the intensity that would be associated with that common

level of performance according to the data in Figure 18. The results of this modeling yield estimates of intensity levels for each color that are equivalent to each other in terms of at least one performance measure (search time under daytime conditions). These results are shown in Figure 19 in a form that is directly comparable to the current SAE requirements for these colors as shown in Figure 2, and to the equivalent intensities derived from Mortimer's (1970) results for subjective ratings of conspicuity in the daytime as shown in Figure 3.

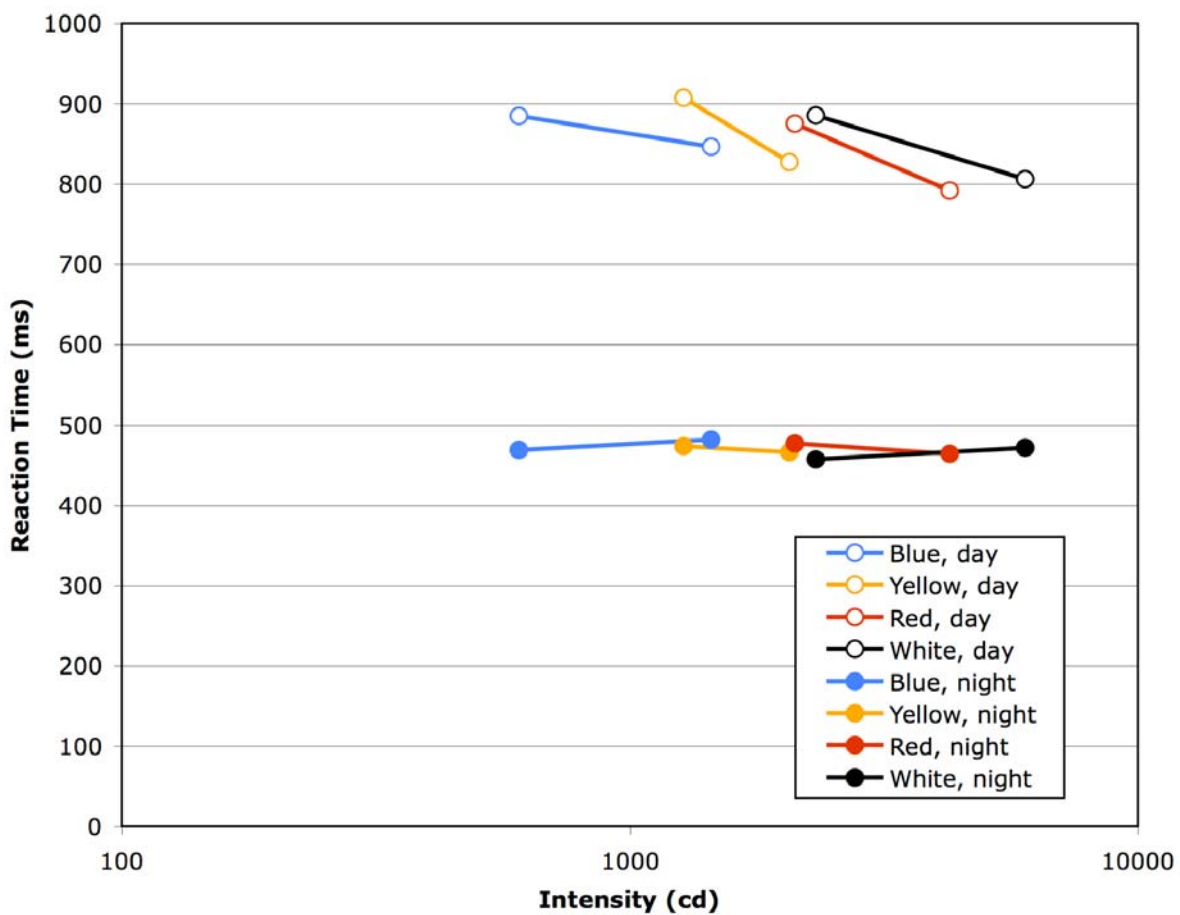


Figure 18. Reaction time in the lamp search task for each color, by intensity and day/night.

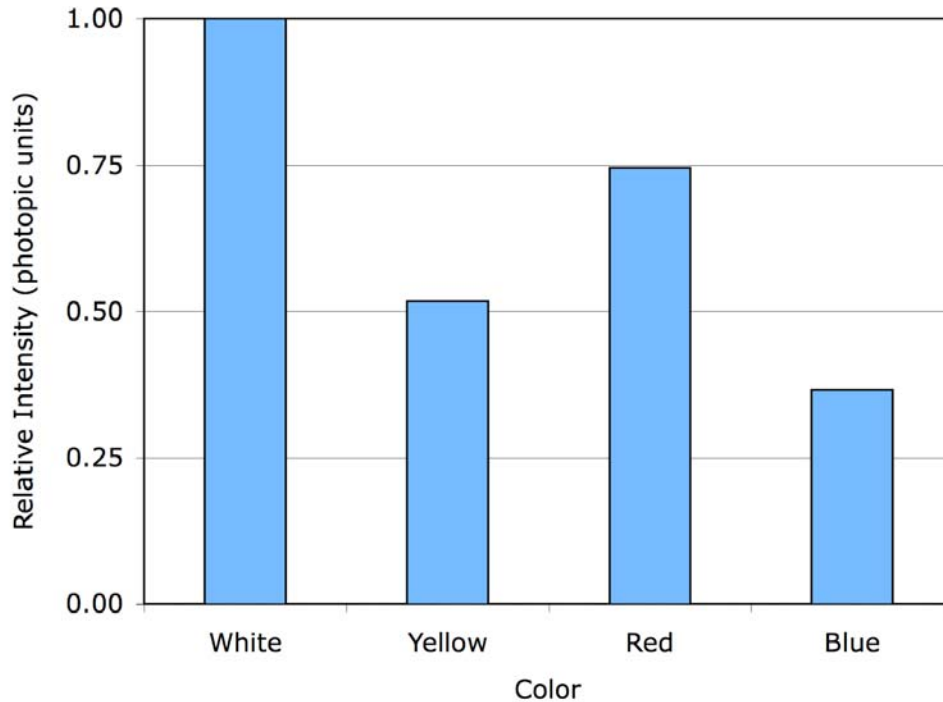


Figure 19. Equivalent relative intensities for four lamp colors in daytime, based on reaction times for the lamp search task in the current study.

The correspondence between the current results, derived from objective visual performance data, and the earlier results is reasonably good. White is still the least effective color, and thus requires the highest intensity to reach the common performance level. Blue appears very effective in the new performance-based data, requiring the lowest intensity to reach that performance level. The largest discrepancy between the new and old values appears to be for red, which was about as effective as blue in Mortimer’s subjective data (Figure 3) and in the SAE requirements (Figure 2), but is less effective than yellow in the new results.

Because warning lamp intensity had no effect on the lamp search task at night, the modeling of the effect of color that we applied to the daytime data could not be applied to the nighttime data. Similarly, because intensity had no effects on the pedestrian responder search task in daytime or nighttime (see Figure 14), we could not model the effect of color on the pedestrian task for either situation. However, there were some suggestions that the warning lamps did affect performance for pedestrian search in terms of error rates at night. In the

remainder of this section, we present the details of trends in the reaction time and error data for the pedestrian search task, including the effects of color.

Figure 20 shows reaction times for the pedestrian responder search task for the young and old subject groups, day and night conditions, and by whether or not a flashing warning lamp was activated. There is little evidence that reaction times are affected by the presence of the active warning lamps under any of these conditions. It might be expected that there would be no effect in daytime conditions, or for younger participants, but the stimuli were designed to make it likely to observe a negative effect for at least the older participants at night. Figure 21 shows the same data for each lamp color separately, and, again, there is little evidence of an elevation of reaction time because of the presence of the flashing warning lamps for any subcondition. However, it is important to consider both reaction time and error rate in an overall determination of how performance may be affected.

Figure 22 and Figure 23 show proportion correct for the same sets of conditions that were used for reaction time data in Figure 20 and Figure 21. It appears that the presence of a flashing warning lamp may have at least a modest effect on pedestrian search performance in one subcondition, i.e., the older subjects at night. In Figure 23 it also appears that this effect occurs for all four lamp colors, although white appears to have the strongest effect.

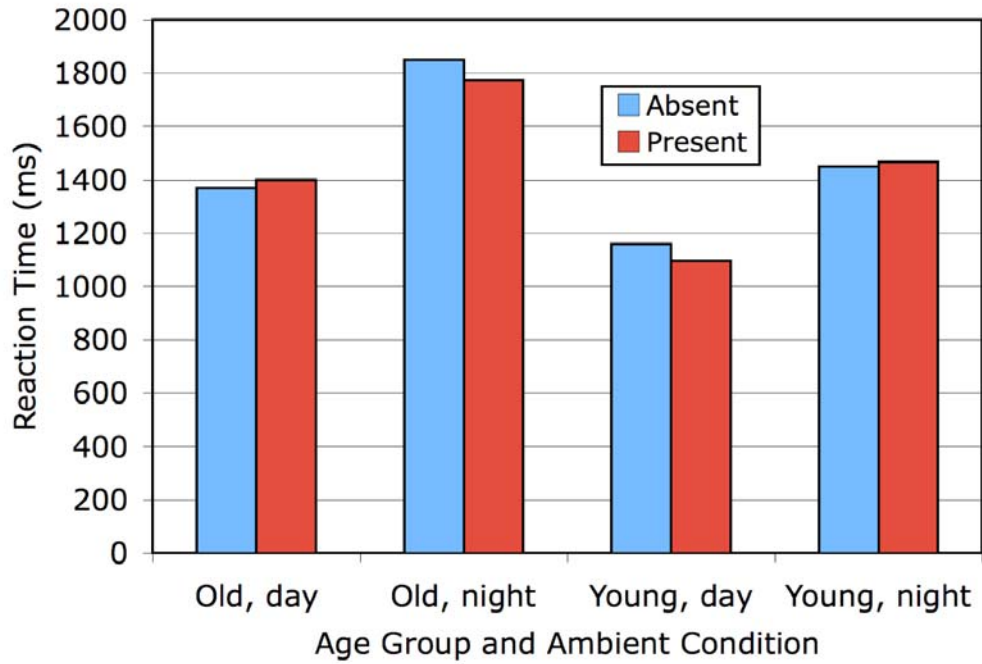


Figure 20. Reaction time for the pedestrian responder search task by age group, day/night, and presence or absence of a flashing warning lamp.

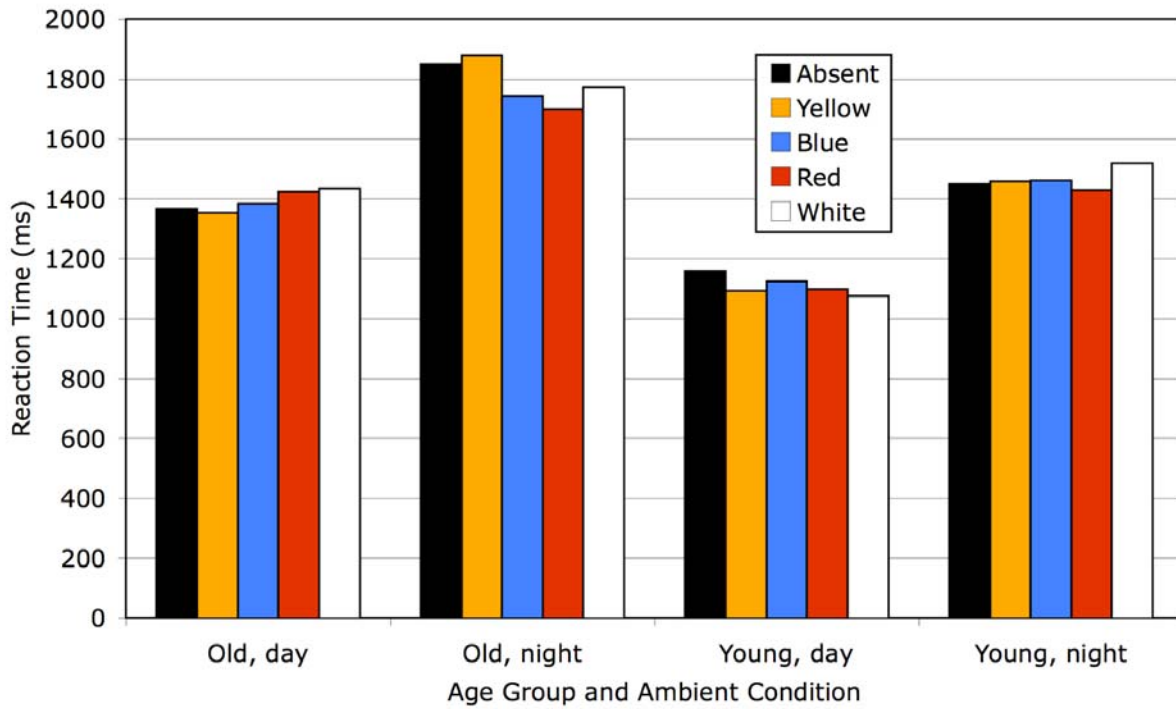


Figure 21. Reaction time for the pedestrian responder search task by age group, day/night, and color of warning lamp.

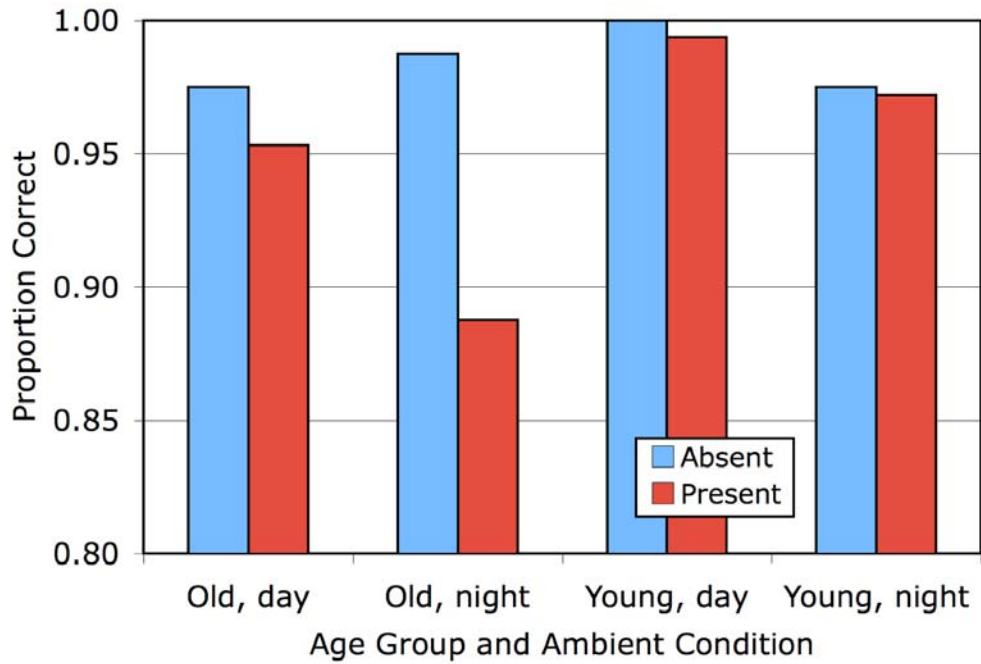


Figure 22. Proportion correct for the pedestrian responder search task by age group, day/night, and presence or absence of a flashing warning lamp.

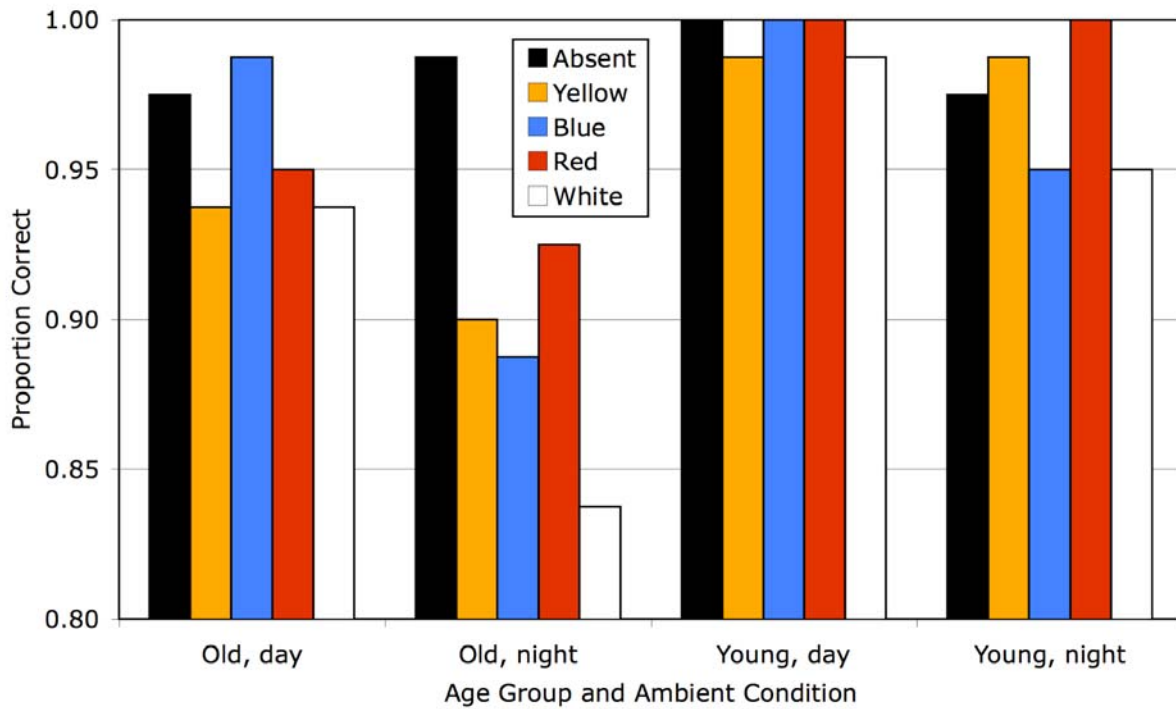


Figure 23. Proportion correct for the pedestrian responder search task by age group, day/night, and color of warning lamp.

Conspicuity ratings

Figure 24 shows average conspicuity ratings for each color and intensity, under both day and night conditions. Within each color, higher intensities lead to higher subjective ratings, but there are also effects of color, and those effects appear to change between day and night. As with the reaction time data for the lamp search task in daytime, we have modeled the effects of color in Figure 24 by choosing the overall average response variable, which in this case was a subjective rating of 116. We then interpolated or extrapolated from the intensity values that were actually used for each color, to determine the intensity value for each color—in both night and day conditions—that corresponds to that rating value. The results are presented in Figure 25 and Figure 26, in formats that are directly comparable to both the new results from objective reaction time data that are shown in Figure 19, and the earlier criteria for color effects shown in Figure 2 and Figure 3.

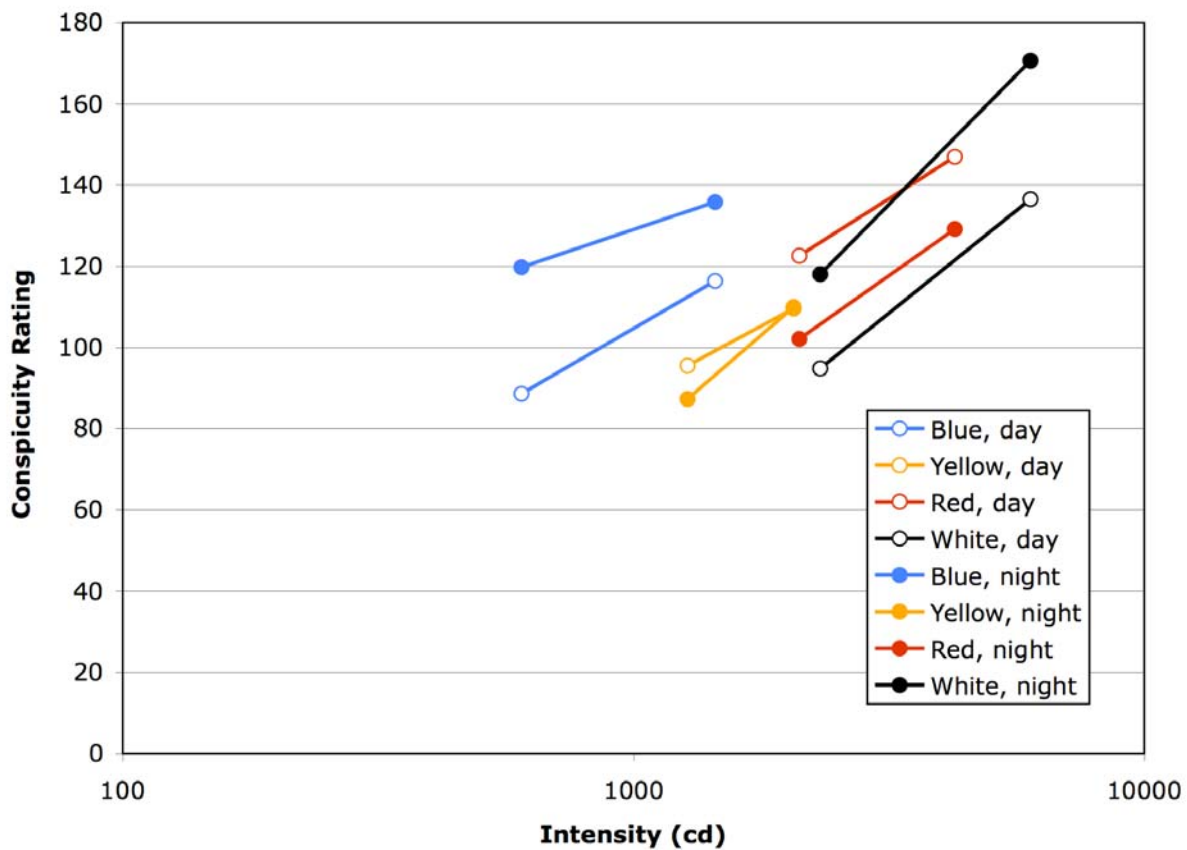


Figure 24. Conspicuity ratings for each lamp color, by intensity and day/night.

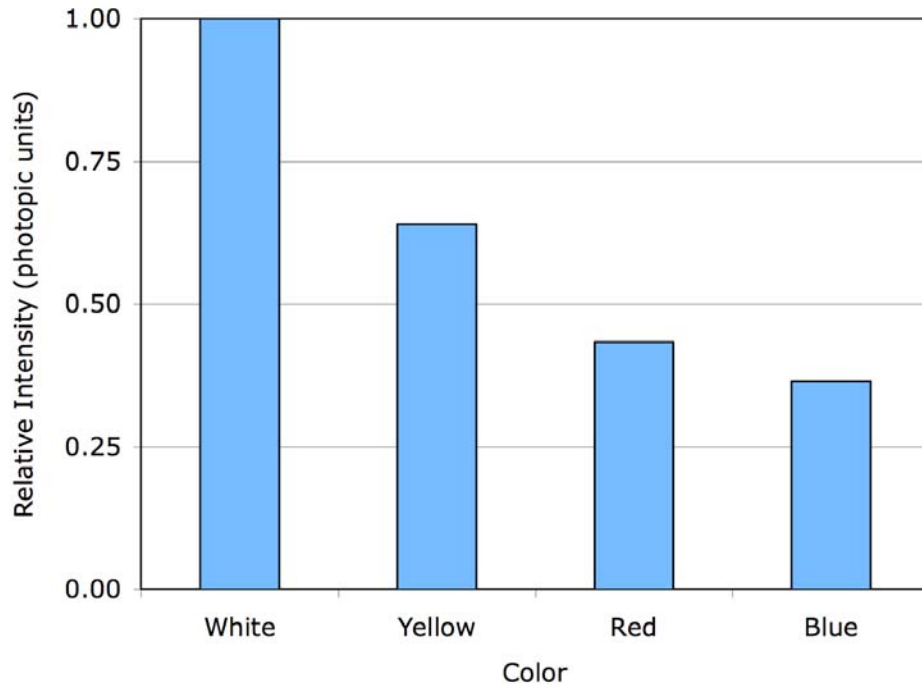


Figure 25. Equivalent relative intensities for four lamp colors in daytime, based on subjective conspicuity ratings in the current study.

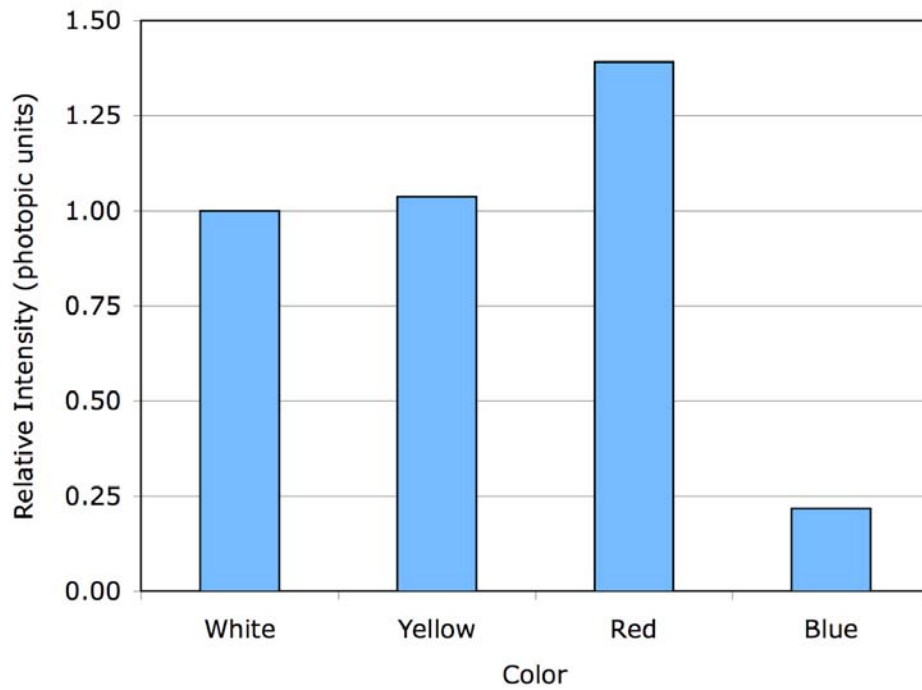


Figure 26. Equivalent relative intensities for four lamp colors in nighttime, based on subjective conspicuity ratings in the current study.

The results for daytime in Figure 25 are quite similar to the results from Mortimer's (1970) subjective ratings, as might be expected because the tasks were similar, at least in that they both involved subjective ratings of conspicuity. It is interesting that the circumstances of this experiment, which did differ in many ways, produced such similar results for subjective ratings of conspicuity and yet the equivalent intensities based on objective search performance (Figure 19) were markedly different from both the new and the old results based on subjective ratings. Although all of the currently available results should still be considered provisional, there appears to be highly suggestive evidence for systematic discrepancies between the colors that people consider subjectively conspicuous and the colors that are easier to find in a search task.

The results for nighttime in Figure 26 indicate that people believe that red and yellow both diminish in conspicuity relative to white at night. One possible explanation for this is that white lamps tend to blend in with the many other bright objects that are visible in the day, and which are primarily neutral in color (e.g., sun reflections from glossy vehicle surfaces, or even diffusely reflecting surfaces that are illuminated by strong sunlight). In contrast, at night white lamps are better able to stand out against the low ambient background by virtue of their brightness alone. Figure 26 also shows that, in terms of subjective conspicuity, blue becomes stronger at night relative to any of the other colors, as would be expected from a Purkinje shift caused by greater involvement of rod photoreceptors at night.

Although we have suggested that there may be discrepancies between subjective ratings of conspicuity and objective performance on search tasks, it is clear that over all eight combinations of lamp color and intensity that were used in this experiment there is broad agreement between those two ways of evaluating lamp effectiveness. Figure 27 shows this relationship, in terms of reaction time for the lamp search task in daytime and daytime subjective ratings of conspicuity. The correlation coefficient is $-.86$ for this relationship.

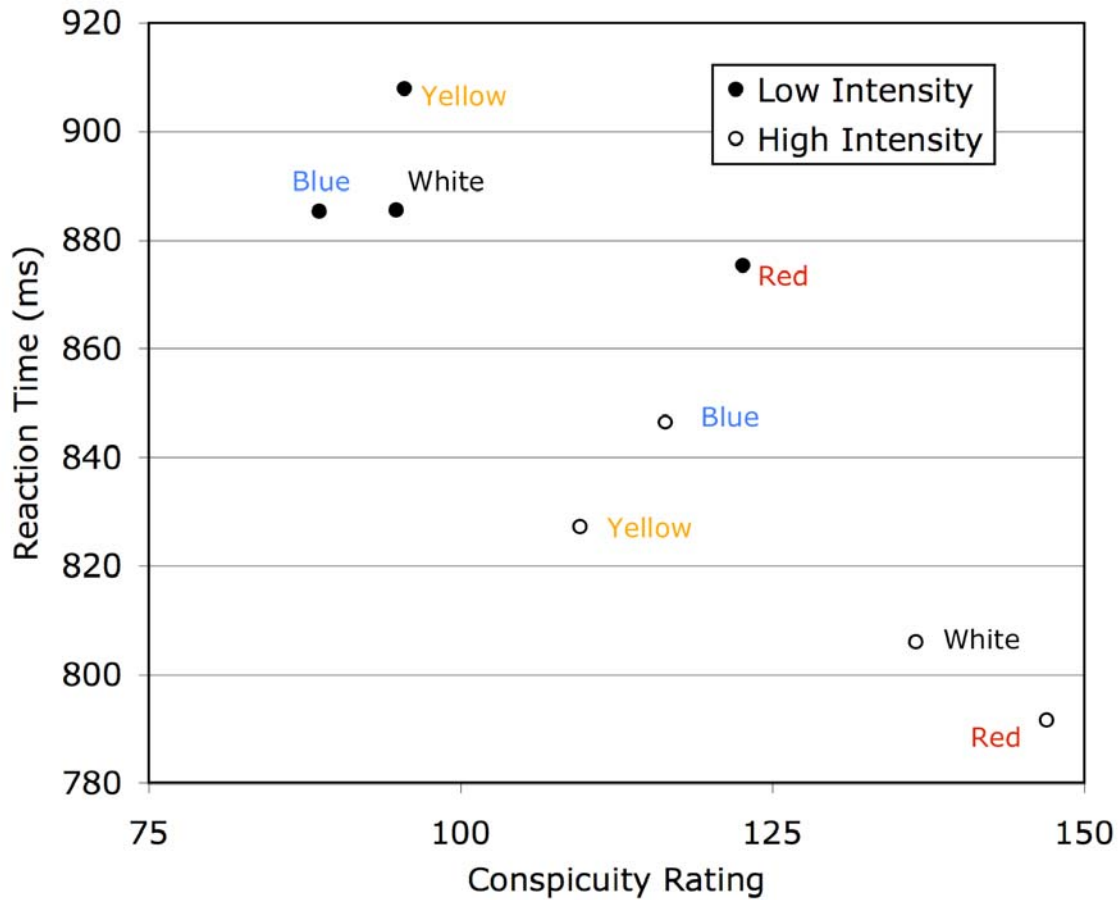


Figure 27. The relationship between objective search performance (reaction time for the lamp search task in daytime) and subjective conspicuity ratings for the eight combinations of lamp color and intensity used in this experiment.

DISCUSSION

Summary of findings

The strongest findings in the current data concern the differences between night and day in performance on the lamp and pedestrian responder search tasks. These effects were of course expected, and are consistent with the common experience that emergency warning lamps are far more visually impressive in the generally dark context of night than against the much brighter context encountered during the day. However, in order to make the best use of warning lamps under all conditions it is important to quantify these differences, and the current results at least

By far, the biggest differences are between day and night.

Within the range used here, greater intensities led to improved daytime visual performance.

begin that effort. For the range of intensities and the flash pattern used here, nighttime performance in locating the warning lamps was not affected by intensity. Although the older participants made a large number of errors, all participants appeared to be performing as well as possible, at least in the sense that greater stimulus intensities would not have helped. In the daytime, however, the higher intensity level of each of the four colors led to improved performance, indicating that even for the very high range of intensities used in this experiment visual performance in the search task can still improve. The large overall difference in performance between day and night on the lamp search task (853 versus 473 ms) is consistent with that finding, although the very high ambient light levels encountered in the daytime probably make it impossible for any practical warning lamp to achieve in daytime anything close to the conspicuity levels that most warning lamps have at night.

Similarly, reaction times and error rates for the pedestrian search task at night were substantially worse than during the day, even though the pedestrians in this experiment were always marked with strong retroreflective treatments.

begin that effort. For the range of intensities and the flash pattern used here, nighttime performance in locating the warning lamps was not affected by intensity. Although the older participants made a large number of errors, all participants appeared to be performing as well as possible, at least in the sense that greater

Relative conspicuity of the four colors was different for day versus night.

But blue was always the most conspicuous color at a given intensity, day or night.

However, the lighting situation was unfavorable to the retroreflective markings, both in terms of the amount of light on the markings and in terms of observation angles, and different situations

might result in near-daytime levels of performance for pedestrian responder search. For at least the older group of participants, there appeared to be a measurable negative effect of the flashing warning lamps on the pedestrian responder search task at night. During the day, performance on the pedestrian responder search task appeared to be unaffected by the warning lamps, as was expected given the relatively reduced effectiveness of the warning lamps in daylight.

There was no difference in performance for the black versus yellow turnout gear either in the day or night. This was expected at night, because under the night lighting conditions only the retroreflective markings were relevant, and the only difference between the black and yellow turnout gear was in the background material. In daytime, the yellow turnout gear had considerably higher luminance, although, at least for the conditions of this experiment, the difference did not affect visual search for the pedestrian responder.

As was expected, color had effects on both objective search performance and subjective rating of conspicuity. During the daytime, there were marked differences in lamp search performance for the different colors beyond the effects that could be attributed to intensity. We interpolated to determine intensity levels of each of the four colors that corresponded to a single value of reaction time (see Figure 19), and found that those levels were at least in rough correspondence to the photometric requirements currently specified in SAE J595 (SAE 2005, see Figure 2). The main exception was that red was less effective in the search task than would be expected based on the SAE requirements. The reaction time data suggested that blue was very effective in aiding the search task, even in daytime. This is consistent with the SAE requirements, but goes against some statements that have been made about the effectiveness of blue in the daytime. It has often been said that blue is very effective at night (consistent with the idea that the blue-sensitive rod photoreceptors are strong contributors to driver vision at night), but that blue lamps provide weak stimuli in daytime.

Subjective ratings of conspicuity were also affected by color, beyond the differences that could be accounted for by differences in intensity. We also modeled the effects of color on subjective ratings by determining the levels of intensity for each color that corresponded to a single response level (in this case, a certain value for conspicuity rating). The results of that modeling are shown in Figure 25 and Figure 26. The daytime results are consistent with the SAE J595 requirements, but are inconsistent with the results from the search task. The main discrepancy is that red is subjectively rated as more effective, relative to the other three colors,

than it appears to be in the search data. However, there is a reasonably high overall similarity between the effects of color on subjective ratings of conspicuity and the objective effects on reaction time in the lamp search task in daytime (see Figure 27). The nighttime subjective ratings in Figure 26 show a strong difference between red and blue, with red being rated less conspicuous than white, and far less conspicuous than blue. These results are qualitatively consistent with a shift from photopic toward scotopic vision between the daytime and nighttime conditions. They are inconsistent with the current SAE recommendations, as shown in Figure 2, which are meant to apply to both nighttime and daytime conditions. However, the new results are from a limited range of conditions, and it was not possible to quantify the effect of color on the objective search task at night.

Recommendations

In this section, we discuss our primary recommendations for how warning lamps should be used, based on the results of the present study as well as previous results. The recommendations are summarized in Table 2.

Table 2. Summary of recommendations for warning lamps

1	Consider different intensity levels for day and night
2	Make more overall use of blue, day and night
3	Consider signals to distinguish stopped-in-traffic-path (e.g., red only) from stopped-out-of-path (e.g., blue only)

Based on the results of this experiment, and considering past research as well as much practical experience, limiting warning lamps to a single level of intensity appears to require a compromise between having lamps that are intense enough for daytime conditions and lamps that are not too intense for night conditions. While it may be possible to fine-tune a single compromise level to produce the best overall effect, it appears that using at least two levels (one to be used under any daytime conditions, and one to be used under any nighttime conditions) would probably be considerably better than the best possible compromise. It might even be advantageous to use a greater number of levels, adapted to a finer set of conditions (e.g., higher levels in full sunlight than in daytime cloudy conditions), but determining how fine the distinctions should be would require more detailed analysis.

The idea of adapting the intensity of warning lamps to ambient lighting conditions has been discussed previously at some length. By quantifying differences in search performance between day and night, the present data add weight to the argument in favor of some form of adaptation. There are several drawbacks to the adaptation approach, including cost, reliability—and the possibility of misuse in which vehicle operators might choose to always use daytime levels, or even cover light sensors or otherwise override automatic controls, because they perceive the daytime levels to be more effective. However, recent technical developments may offer better options to address such drawbacks. LED sources, for example, can easily provide multiple light levels from the same lamps, and better automatic controls for day and night conditions—perhaps even involving sensing of time and position from Global Positioning System (GPS) satellites—may be possible and affordable.

In the lamp search task used in this study, blue was more effective in daytime, for a given level of intensity, than any of the three other colors tested (white, red, and yellow). While there has always been a reasonably strong agreement that there were advantages to blue at night, this new result provides additional evidence in favor of using blue under all ambient lighting conditions. The apparent advantage for blue in terms of conspicuity should be general to all emergency vehicle applications, and therefore it could be argued that blue warning lamps should be used more often on all types of emergency vehicles; including fire, law enforcement, and medical vehicles. This is already the case in much of Europe, suggesting that, in addition to the basic visual performance criteria that are the main subject of the current work, many practical considerations may also be at least compatible with broader use of blue lamps.

Interestingly, although blue lamps appear to offer the advantage of low masking effects in objective visual performance, this advantage is not reflected in subjective assessments of glare (Flannagan & Devonshire, 2007). This discrepancy does not appear to lessen the safety benefits of reduced masking, and, in fact, it could lead to a further advantage if drivers overestimate the extent to which their vision is impaired by blue lamps. They might then exercise more caution than they otherwise would while passing an emergency vehicle with blue lamps at night. This difference between actual and perceived visual impairment has also been noted by Wells (2004) who, while commenting on some peoples' reactions to blue lamps observed:

While complaints were lodged about the intensity at night, no one complained they could not see an object at the front of the vehicle. True night blindness

would prevent the seeing of these objects. People were actually reporting discomfort not night blindness. (p. 36)

Finally, we suggest a relatively innovative strategy that involves using color to make a clear visual distinction between parked emergency vehicles in two different states: those that are parked in the normal path of traffic, and those that may be near the normal path of traffic but are not actually obstructing it. While several authors have recently emphasized the value of establishing a signal that would distinguish between moving and parked vehicles (e.g., Wells, 2004), we believe it is worth considering this different, or further, distinction among parked vehicles. The distinction was made by Post (1978) in a comprehensive review of emergency vehicle signaling needs. As part of that work, he proposed a list of five key messages that should be conveyed by the warning lamps of emergency vehicles (see Table 3). For our current purposes, the messages of interest are “Hazard, vehicle on right-of-way” and “Vehicle present in hazardous location.” For a driver approaching an emergency scene, the critical difference in responding that is required by these messages is whether the driver must, (1) stop or deviate from the normal path of traffic to avoid a collision, or (2) proceed slowly and cautiously but maintain lane position.

Table 3. Messages to be conveyed by warning lamps, and corresponding recommended lamp characteristics (Post, 1978)

Message	Recommended lamp characteristics (partial)			
	Color	Intensity (cd)	Flash rate (Hz)	Flash pattern
Clear the right-of-way	Red	2 x 600 ¹	2.5	Synchronous
Hazard, vehicle on right-of-way	Red	2 x 600	1.5	Alternate
Caution, slow moving vehicle	Yellow	2 x 1,500 ¹	1.5	Synchronous
Vehicle present in hazardous location	Yellow	--	--	Synchronous
Stop immediately	Blue	--	--	Unique

¹ “effective” candlepower

As can be seen in Table 3, Post recommended that vehicles that were actually obstructing the normal path of traffic should signal that by displaying red lamps flashing alternately, while vehicles that were near the flow of traffic but that did not constitute actual obstructions should display yellow lamps flashing synchronously. We are not proposing flash patterns or intensities, but we believe this could be an especially good opportunity to use blue lamps. Specifically, we

propose that red warning lamps should be used for vehicles obstructing traffic, while blue should be used for vehicles that represent hazards by being parked near the flow of traffic but are not actually obstructing it. To make the color coding useful for conveying the proper messages to approaching drivers, the use of color would need to be exclusive: any red flashing lamps would mean that traffic was being stopped or somehow diverted, and a scene (or perhaps one side of a scene spanning a road) with only blue flashing lamps would mean that traffic could move through, albeit cautiously. (This proposal assumes that vehicles parked out of the flow of traffic would still display the usual red tail or stop lamps in addition to any flashing lamps, but they might be adequately distinguished by their steadily burning character.)

Although this proposal is based on a distinction made in 1978 (if not earlier) it appears to us relatively novel, and we therefore recognize that it would need to be discussed from a number of perspectives before being seriously considered. The main perspective that we are applying here is visual performance, and specifically the possible benefits of color. Although we do not intend the present discussion to be definitive, there several arguments for and against the proposal that are worth mentioning. In favor of the proposal, it seems to achieve the distinction that Post was trying to make, although with a different set of colors. Furthermore, it would in itself achieve at least part of the advantages of the related distinction between parked and moving vehicles, because blue lamps would unambiguously signal stopped vehicles. The use of blue for vehicles not actually obstructing traffic could make good use of the relatively low visual masking effects that we discussed earlier. For example, most police traffic stops would use blue lamps, thus causing less impairment of the ability of approaching drivers to see a police officer standing on the side of the road beyond the warning lamps. Finally, the use of blue lamps might help in addressing any tendency that may exist for drivers to leave the normal path of traffic because they misperceive red lamps on vehicles stopped off the road as guides to follow traffic (the “moth effect”). It might still happen that drivers would drive toward the red lamps of vehicles stopped on the road, misperceiving those as being on moving vehicles. But there would be a benefit in cases in which drivers actually leave the road and collide with parked vehicles, because flashing blue lamps would be as visually distinct as is reasonably possible from steadily burning red lamps.

On the negative side, it can be argued that the distinction between vehicles that are actually blocking traffic, and those that are near the flow of traffic but not blocking it, is not a

clean distinction in the real world of emergency vehicle operations. There may be too many cases in which a vehicle is only slightly blocking the path of traffic. Or it could be argued that, in the complexity of many emergency operations, the distinction would not be made reliably, and without extremely consistent use of blue versus red lamps their meaning to approaching drivers would become ambiguous or even misleading. However, some technologies may be able to address the reliability problem, at least in the near future. Differential GPS alone might do reasonably well in automatically determining whether an emergency vehicle was blocking a lane, and various forms of optical lane sensing might do considerably better.

Possibilities for future research

The safety issues involved in emergency vehicle operations are in many ways more difficult to analyze and more difficult to remedy than those involved in most traffic operations. Nevertheless, the fact that emergency vehicle operations are a relatively small part of traffic operations in general has led to a situation in which the emergency vehicle safety issues have received less research effort than the issues involved in more typical operations. Several areas of future research on the specific topic of warning lamps appear technically promising and likely to yield practical benefits.

Flashing signals have traditionally been the main form of marking for emergency vehicles, and this is likely to be the best approach for the foreseeable future. Because of that, the concept of “effective” intensity (e.g., Howett, 1978) is of central importance for understanding the effects of warning lamps, and how they should be designed and measured. Effective intensity is intended to be a way to relate the overall visual effectiveness (primarily, conspicuity) of flashing lamps to the photometric measurements that are designed for stimuli with fixed levels. For example, if a lamp is flashing at 1.5 Hz with a 50% duty cycle and a certain peak intensity, what would be the intensity of a steadily burning lamp that was equally effective in evoking a visual response? In the present research, we largely bypassed this issue by using a single flash pattern and a single flash rate for all stimuli. But even so, it is not clear that some of the important variables that we did manipulate—such as color or ambient light—do not have different effects with different flash characteristics. Because of the importance of flashing signals, it would be beneficial if some of the future research on emergency vehicle warning lamps was devoted to better understanding the concept of effective intensity and how it should be measured. The use of objective performance measures, such as the search tasks used here,

may be especially useful in such work as a way of extending earlier work on effective intensity (which was primarily in the area of threshold detection) to above-threshold conditions, which are most important for emergency warning lamps.

In many areas of human performance, there are important discrepancies between people's subjective impressions and certain objective effects. The present results involved some examples of this, in particular with regard to the relative effectiveness of red and blue under day versus night conditions. A future goal of research on emergency vehicle warning lamps should be to further quantify, and possibly resolve, such discrepancies with regard to color, and possible other characteristics of warning lamps, such as flash patterns.

The present work was intended to further develop methods for objective assessment of warning lamps using search tasks. This was based primarily on the face validity of the approach, and many important encounters with emergency vehicles in actual traffic do appear to involve important components of visual search. However, if the approach is to be of long-term benefit it will be necessary to validate it in other ways. Most importantly, it would be valuable if the findings from search-based methods could be validated against the ultimate criterion for safety, crash data. This is difficult, especially because the details of drivers' visual behavior (e.g., eye movements) just prior to a crash are not usually known. However, detailed analysis of the circumstances of crashes, such as ambient light level, may provide better understanding of at least broad characteristics of how warning lamps affect crash risk (Flannagan & Blower, 2005). More detailed analyses of crash data would also be useful to help evaluate ideas about the overall mechanisms of emergency-vehicle crashes, including whether and how the "moth effect" occurs (e.g., Wells, 2004).

The present research provided some information about how the effects of color are different between day and night, particularly with regard to changes in ratings of subjective conspicuity. However, the range of intensities and other variables was not sufficient to provide a comprehensive picture of color in terms of the objective measures. The generally high range of lamp intensities that was used provided opportunities to measure positive effects on conspicuity during the day and negative effects on distraction or masking at night, but did not allow detailed comparisons of any single effect across day and night. It would be useful if the ranges of variables were increased in future work. This would be particularly important for guiding the development of different intensity levels for warning lamps in day and night conditions.

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APPENDIX

The following instructions were read to each participant, for both the daytime and the nighttime sessions:

Thank you for agreeing to participate in this study.

In this experiment, we would like you to sit in the driver's seat of a stationary car parked just outside this building. At some distance in front of that car, you will see two other cars parked a little to the right and left. Each of those cars will have a set of emergency warning lights mounted on the roof. The lights can flash in any of four colors: white, yellow, blue, or red. What we would like you to do is to push one of two buttons, marked "left" and "right," when the lights on one of the two cars starts flashing. We would like you to do this as quickly as you can, because what we are interested in is how effective the lights might be in quickly getting the attention of a driver in actual traffic. In a second part of the study, there will also be someone dressed as a firefighter in the scene, and then we would like you to indicate whether that person is on the right or left side of the scene, again by pushing one of the two buttons as quickly as you can.

Right now, I will give you a few more details about the first task—responding to the lamps. This part will take about 20 minutes, and then I will give you the details about the second task—the firefighter task. That part will also take about 20 minutes.

Here are the details for the first part: There will be a series of trials, all of which will work the same except that the lamps will be different from trial to trial. On each trial, we would like you to start out looking down in you lap, so that you can't easily see the scene in front of the car. You will hear a beep from a computer in the back seat. At that point, please look up, identify whether the right or left car is flashing, and as quickly as you can push either the right or the left button. On some of the trials, neither car will be flashing. For those trials, simply do not push either button. After each trial, please look back down in your lap, and after a brief pause I will start the next trial.

Do you have any questions?

[Experimenters present the lamp trials.]

The next set of trials will be similar to the first set: We would like you to start each trial looking down in your lap, and when you hear a beep from the computer please look up and respond as quickly as you can by pushing either the left or right button. The big difference is that this time there will be a person dressed as a firefighter in the scene. We would like you to ignore the lamps completely and respond "left" or "right" to indicate whether the firefighter is standing near the left car or the right car. The firefighter may be on either side of either car, so please remember that the answer "left" or "right" should be for which car the firefighter is standing by, not which side of the car the firefighter is on. You could also think of this as "Which side of the overall scene is the firefighter on?"

The lamps will sometimes be flashing on the same car that the firefighter is next to, and sometimes on the opposite car, and sometimes no lamps will be flashing. There will be no consistent relationship between the flashing lamps and the firefighter, so the best strategy will always be to try to completely ignore the lamps and look for the firefighter. Finally, there will be some trials on which the firefighter is not present. For those trials, simply do not push either button.

Do you have any questions?

[Experimenters present the pedestrian trials.]

The final part of the session will take only about 5 minutes. What I would like you to do now is to use numbers to rate the conspicuity of each of a set of lamps. By “conspicuity” we mean how effective you think a lamp would be in getting your attention if you should encounter it in a normal driving scene. There are no right or wrong answers to this question; we would like you to simply make your best judgment based on how the lamps look to you. I will present a series of lamps, with different colors and brightness, and I would like you to simply say a number that represents to you how conspicuous you think it is. In choosing these numbers, please consider the following lamp to correspond to 100.

[The experimenters present the low-intensity white lamp as the “100” example.]

If another lamp looks more conspicuous, please choose a number higher than 100; if another lamp looks less conspicuous, please choose a number lower than 100. In all cases, please try to choose the numbers to be proportional to your judgment of the lamps’ conspicuity. For example, if a lamp looks twice as conspicuous as the example, say 200. If a lamp looks half as conspicuous, say 50, and so on. For each trial, you can choose any number greater than zero. Do you have any questions?

[The experimenters present the conspicuity trials.]