HHS Public Access
Author manuscript
Light Res Technol. Author manuscript; available in PMC 2019 June 01.

Published in final edited form as:
Light Res Technol. 2018 June 1; 50(4): 552–570. doi:10.1177/1477153516670935.

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Toward the Development of Standards for Yellow Flashing Lights Used in Work Zones

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Abstract

Flashing yellow warning lights are important for worker and driver safety in work zones. Current standards for these lights do not address whether and how they should be coordinated to provide course-way information to drivers navigating through work zones. A field study in which the intensities and flash patterns of warning lights along a simulated work zone were varied during daytime and nighttime, was conducted to assess drivers' responses to different configurations, leading to several conclusions. During the daytime, driver responses were relatively insensitive to warning light characteristics, although they preferred sequential and synchronized flash patterns over random, uncoordinated flashing. At nighttime, a temporal peak intensity of 25 cd with a sequential flash pattern was optimal for providing course-way information. A single initial warning light having a higher intensity may help drivers detect the work zone without creating unacceptable visual discomfort.

Keywords

warning lights; sequential flashing; discomfort glare; work zones

1. Introduction

Warning lights are commonly used in work zones. Photometric and colorimetric standards for flashing warning lights mounted on stationary infrastructure in work zones (e.g., traffic barrels) are promulgated by the Institute of Transportation Engineers (ITE ST-017B)[1] for nighttime operation (Type A) and for daytime or nighttime operation (Type B). Table 1 summarizes the ITE minimum intensity, flash frequency and color (chromaticity) requirements for warning lights that would be used in work zones.

ITE (2001) does not explicitly describe the safety benefits expected from warning lights, so it is not clear from these standards when and if flashing lights should be used, or how they should be deployed in a work zone. The ITE standard does, however, reflect the need to have different intensity requirements for nighttime and for daytime operation. The minimum intensity requirements for Type B warning lights are higher than they are for Type A warning lights, presumably to ensure adequate conspicuity of a warning light during bright

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ambient, daytime operations. The ITE standards are, however, limited to minimum intensity requirements for warning lights. *Maximum* intensity requirements are not provided by the ITE even though bright lights can limit detection of potential hazards in and around the work zone, particularly at night.[2–4] Moreover, the ITE standards are specific to the performance of individual warning lights, even though *multiple* warning lights are nearly always used in work zones. Analogous to airport approach lights,[5] coordinated warning lights could potentially guide drivers safely through the work zone. Thus, current requirements for work zone warning lights appear to be incomplete with regard to supporting driver and front-line worker safety. In support of this inference, warning lights have been implicated as a potential risk factor in about 20% of vehicle crashes involving front-line workers, who are consequently over-represented with respect to the general population for work-related injuries and fatalities.[6]

Given what appears to be incomplete guidance on the design and deployment of warning lights for work zone applications, we postulate that warning lights should serve three general functions in support of driver and front-line worker safety.

1.1. Attracting Attention to Potential Hazards

Flashing lights attract attention better than steady lights.[7] Indeed, flashing lights are used almost universally for emergency and warning lights. ITE (2001) makes provisions for flashing warning lights (Table 1), but as already noted, it is not clear when and if flashing warning lights should be used.

Recent research into the photometric characteristics of flashing warning lights indicates that, under clear atmospheric conditions, higher intensity shortens response times for detection, during both day and night. However, there is a diminishing return on reducing response times as intensity increases, up to about 750 cd, above which further increases do not produce significantly shorter response times.[2, 3, 8] Arguably then, warning light intensities above approximately 750 cd are not necessary for increasing attention.

Thus, flashing warning lights with a maximum intensity of 750 cd should probably be used to attract driver attention in work zones, particularly those located in complex visual environments where other bright and/or flashing lights are being used (e.g., in urban environments with commercial advertising).

1.2. Differentiate Work Zones from Emergency Situations

Light source color is commonly used to communicate warning light function. In fact, chromaticities standards are promulgated by many if not all regulatory bodies, including those pertaining to traffic signal lights for roadways,[1] emergency vehicles,[9, 10] road maintenance vehicles,[9, 10] nautical hazards and shipping,[11] aircraft and aviation infrastructure,[12] and, relevant to the present study, warning lights used in work zones (Table 1).[1]

Thus, current ITE chromaticity standards (Table 1) should be used to identify active work zones.

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1.3. Provide Course-Way Information

Uncoordinated flashing of warning lights can be detrimental to drivers' situational awareness in work zones. For example, in their study of the effectiveness of warning lights, Steele et al.[13] reported that focus group participants preferred sequential and synchronized flash patterns to random, asynchronous flashing, which was judged as confusing. Several evaluations of sequentially flashing lights have been conducted. Finley et al.[14] found that drivers shifted lanes sooner in response to sequential flashing lights mounted on traffic drums than when the drums were used without the sequential lights. Sun et al.[15] showed that driving speed variability was reduced in the presence of lane-change tapers with sequentially flashing lights compared to the same tapers without the lights. Sequentially flashing lights in the direction counter to the direction of traveling traffic is not recommended because it can result in confusion among drivers.[16] Bullough et al.[17] developed prototype barricade flashing warning lights in which the luminous indication could "sweep" from left to right or vice versa, and reported that drivers approaching lane-change tapers equipped with these warning lights changed lanes earlier than when conventional flashing lights were used to delineate the taper.

Thus, multiple, coordinated warning lights used in work zones should provide better course-way information to drivers than randomly flashing warning lights.

Several factors can compromise these three important functions.

1.4. Limiting Potential Hazard Detection from Glare

Warning lights can cause glare, both disability glare, where entoptic scattered light reduces the apparent contrast of potential hazards near the warning light, and discomfort glare, the annoying or painful sensation created by a bright warning light.[18] Quantitative formulae exist for predicting disability glare that might be caused by a warning light.[4, 19] The obfuscation of a potential hazard from disability glare depends upon the intensity of the warning light (thus, the illuminance at the cornea) as well as the contrast and the angular distance between the line of sight to the potential hazard and the warning light; higher warning light intensities and smaller angular distances result in greater disability glare.

Discomfort glare is much more complicated. Like disability glare, discomfort glare increases with warning light intensity and with reductions in the angular distance between the warning light and the line of sight. Unlike disability glare, however, the spectral composition (color) of the source also influences discomfort glare; sources with relative greater short-wavelength content are seen as producing more discomfort for equal (photopic) intensity. All other factors being constant, yellow warning lights produce less discomfort glare than, say, blue or even white warning lights.[20] The apparent size of the warning light itself also impacts discomfort glare. Again, all other factors being constant, visual elements larger than about 0.3 degrees of visual angle will produce more discomfort glare than smaller visual elements. For those warning lights larger than about 0.3 degrees of visual angle, the maximum luminance of the light source must be known to predict discomfort glare.[21, 22] Flashing lights, particularly ones that increase and decrease intensity very rapidly, will cause more discomfort glare than steady lights.[23, 24] This is caused by mechanisms in the retina that

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enhance the neural signal from a transient light pulse relative to the neural signal from a steady light.[25, 26] Finally, unlike disability glare, discomfort glare is influenced by psychological factors. For example, discomfort glare will be increased while someone is performing tasks requiring more concentration, such as driving through a work zone.[27, 28] Consequently, specifying the photometric, colorimetric and geometric quantities associated with a warning light will not be sufficient to predict discomfort glare accurately. Nevertheless, it is possible to address the photometric and geometric quantities such that discomfort glare can be mitigated.

1.5. Limiting Potential Hazard Detection by Atmospheric Scattered Light

Bullough and Rea[4] found that the spatial distribution of warning light intensity is important for the detection of workers or other hazards illuminated by headlights at night. Light that is not directed toward the viewer (i.e., the oncoming driver) will be scattered in perturbed atmospheric conditions such as fog and falling snow. This phenomenon is, of course, compounded by higher warning light intensities. Optical control and shielding of warning lights that limit scattered light in perturbed atmospheric conditions at night can be extremely important for driver safety.

1.6. Flash Frequency and Modulation Depth

Current standards for work zone warning lights[1] require a modulation frequency of approximately 1 Hz (Table 1). Flash frequencies for vehicle-mounted warning beacons[9, 10] are permitted to flash at frequencies up to 4 Hz. This range of frequencies is near the maximum temporal frequency sensitivity by humans[29] for both daytime and nighttime viewing conditions; and despite differences between the ITE[1] and SAE[9, 10] requirements, flash rate is never used to differentiate warning light function. Although unspecified in current standards, many flashing warning lights have a modulation depth of 100%. In other words, warning lights are usually operated as oscillating between “fully-on” and “fully-off.” Bullough and Rea[3, 8] reported, however, that drivers’ ability to judge the relative speed and motion of a flashing warning light was improved if the flashing warning lights never went “fully-off.” Empirically, they found that a modulation pattern from “fully-on” to “10%-on” provided drivers with better information about relative motion than the “fully-on/fully-off” pattern.

The published research on the visual effectiveness of warning lights[2–4] lead to several recommendations:

- Luminous intensities approaching 750 cd support reliable detection of warning lights during daytime conditions
- Luminous intensities of 750 cd can reduce drivers’ ability to detect workers and other hazards in a work zone at night during conditions of fog or snow
- Flash modulation pattern of “fully-on/10%-on” supports a drivers’ ability to accurately judge the closing speed and distance of flashing warning lights

The present study was designed to provide added insight into one of the three general functions of warning lights used in work zones, namely, *to provide course-way information*.

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Experimental focus was given to *limiting potential hazard detection from glare*. Specifically, subjective and behavioral responses from drivers and subjective responses from passengers were recorded while a vehicle was navigated through simulated work zones equipped with multiple flashing warning lights. Those lights were systematically varied in their intensity and their collective flash patterns. Sessions were conducted during both day and night in a within-subjects experimental design. It was expected that during the daytime, when substantially more visual information about the work zone would be available to observers than at night, factors such as intensity or the flash modulation pattern would have relatively little influence on responses to the warning lights. During the nighttime, when the warning lights would be the primary visual cue in the work zones, it was expected that intensity and flashing characteristics of the lights would be relatively more important. For example, sequential or synchronized flash patterns should be superior to random, uncoordinated flashing of multiple lights to support course-way navigation through a work zone.

In summary, each of 12 subjects drove through and was driven through a simulated work zone demarcated with flashing warning lights during a daytime session followed by a nighttime session. Three warning light flash patterns, random, synchronized and sequential, demarcated the course-way through the work zone, either with or without a lane change. The intensity of the initial flashing warning light for the work zone course-way was balanced to either be bright (750 cd) or off. Driving speeds through and while approaching the work zone were objectively measured together with subjective impressions of discomfort glare and of performance (speed, accuracy and difficulty).

2. Methods

The study was conducted on a straight (300 m long), flat section of a closed, unlighted, two-lane, dead-end road running northwest to southeast (Figure 1), with a posted speed limit of 30 mph (50 km/h). The road was closed in cooperation with the town and local police department during every experimental session. Near the center of the straight section, 12 traffic drums spaced 9 m apart were positioned in two tapers of six drums each to simulate a closure of the right lane when traveling toward the northwest, and a closure of the left lane when traveling toward the southeast. The first two drums in both tapers were positioned at the edge of the road; each subsequent drum was offset 0.9 m toward the center of the road. In the 9 m space between the tapers, a parked pick-up truck (P) was located with all of its interior and exterior lights switched off. The truck was parked perpendicular to the direction of vehicle traffic to allow the first experimenter inside the parked truck to control the lights on the drums and to have a view of the oncoming test vehicle during each trial.

The test vehicle was a 2003 Ford Taurus sedan equipped with a Race Technologies DL1 data-logger used in several previous studies.[17, 30–32] Global positioning system (GPS) location and speed were recorded. Two subjects, a driver and a passenger, rode in the front seat and the second experimenter rode in the backseat of the test vehicle on every trial.

Slight curves were located at both ends of the straight section. These right-turning curves were of sufficient radius to obscure views of the test apparatus by a driver and a passenger approaching the straight section.

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One warning light was affixed to the top of each traffic drum (Figure 2). The maximum (centerbeam) intensities of the six warning lights nearest an approaching driver were positioned to be parallel to the driver's direction of travel; the rear face of each warning light was covered in black, opaque foil. The distribution of the warning lights' intensity was such that the maximum intensity was produced in the direction normal to the face of the warning light. When viewed by an approaching driver from 30 m away, the intensity of the warning lights on the right edge of the road was 92% of maximum, and the intensity toward a driver approaching the lights on the left edge of the road was 74% of maximum (a difference of 20% between the driving directions). The warning lights were always flashed with a frequency of 1 Hz and the "fully-on/10%-on" modulation depth, as recommended by Bullough and Rea.[3]

The drum-mounted warning lights were grouped into two sets, a "right taper" and a "left taper" corresponding to the driver's direction of travel on a particular trial. All six lights in each set could be controlled by the first experimenter in the parked truck to flash in one of three patterns: *random*, in which the timing of the warning light flashes were uncoordinated, *synchronized*, in which all flashes occurred simultaneously, and *sequential*, in which each flash was timed to appear to travel along the taper in the same direction, forward and toward the center of the road, as the approaching driver. In the *sequential* pattern, successive lights flashed every seventh of a second for a duration of two-sevenths of a second; thus, at any given time, two lights would be "fully-on." The propagation speed of the sequence of flashes was 63 m/s.

For each trial the warning light nearest the oncoming test vehicle in both sets of lights was programmed to either be completely off (0 cd) or to flash as part of the *random*, *synchronized* or *sequential* pattern with a (temporal) peak intensity of 750 cd. The peak intensities of the subsequent warning lights in a set were programed to be of 7.5, 25, 75 or 250 cd during daytime trials, or 2.5, 7.5, 25 or 75 cd during nighttime trials.

Twelve (7 female) adult subjects (mean age 36 years, range 20 to 69, s.d. 17) with valid driver's licenses participated in the study.

Every subject completed 96 trials in a single day-and-night session, grouped into pairs of trials on each run; a run is defined as a loop starting and ending at the location southeast of the simulated work zone. Every subject acted as a driver and as a passenger for 12 runs each during the daytime, and again during that same night. When subjects were driving, they were instructed to drive along the road (while obeying the posted speed limit) and to maneuver through the work zone safely (without colliding with the traffic drums). After driving through the work zone, drivers and passengers were asked to answer questions as described below, before continuing to the next trial.

The daytime runs started in the mid-to-late afternoon when the sun was located southwest of the road, eliminating direct sun in the drivers' field of view and in their rearview mirrors. In the first trial of each run, the test vehicle was moving toward the right taper (and was required to execute a lane change maneuver), and in the second trial of each run it was

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moving toward the left taper (and was not required to change lanes). Every trial started at a position beyond the slight curve where the straight section was not visible.

Three sets of four runs, one set for each flash pattern (*random*, *synchronized* or *sequential*), were counterbalanced across subject pairs (driver and passenger). The intensities of the initial warning light (0 or 750 cd) and those of the subsequent warning lights (daytime: 7.5, 25, 75 or 250 cd; night: 2.5, 7.5, 25 or 75 cd) in each trial were also counterbalanced across subjects. Counterbalancing between the initial warning light intensities and the direction of travel (right or left taper) was incomplete so that the session length was less than four hours; however, every subject experienced every condition either as a driver or as a passenger.

Immediately after driving through the simulated work zone, the driver was asked by the second experimenter in the backseat of the test vehicle to estimate the level of discomfort glare with the following two questions:

- What was the level of discomfort glare experienced from the initial flashing light (either the initial light flashing with an intensity of 750 cd, or if this light was off, the first flashing light of the remaining five lights)?
- What was the level of discomfort glare experienced from the entire array of lights?

The passenger was also asked to answer the second glare-related question drivers were asked, which was to rate the level of discomfort glare from the entire array of lights. Both subjects were asked to provide responses using the De Boer discomfort rating scale[33] where numerical values between 1 and 9 are assigned to the reported discomfort glare sensation:

- 9: just noticeable glare
- 7: satisfactory
- 5: just permissible
- 3: disturbing
- 1: unbearable

Drivers were then asked the following three questions:

- How easy or difficult was it to drive through the work zone?
- How quickly or slowly could the driver navigate through the work zone?
- How accurately could the driver navigate through the work zone?

Responses from the driver to the easy/difficult, quickly/slowly, and accuracy questions were recorded in terms of a five-point integer scale:

- +2: very easy / very quickly / very accurately
- +1: somewhat easy / somewhat quickly / somewhat accurately
- 0: neither easy nor difficult / neither quickly nor slowly / neither accurately nor inaccurately

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- –1: somewhat difficult / somewhat slowly / somewhat inaccurately
- –2: very difficult / very slowly / very inaccurately

3. Results

Data were analyzed using within-subjects general linear model analyses of variance (ANOVAs). Separate analyses were run for the daytime and for the nighttime sessions. As mentioned previously, because counterbalancing was incomplete for trials requiring a lane change (left taper) or not (right taper) and for the presence of the initial 750-cd warning light (on) or not (off) among all of the subjects, the type of lane change maneuver was used as a covariate in each of the ANOVAs rather than as a within-subjects independent variable.

3.1. Daytime

3.1.1. Discomfort glare from the initial warning light.—The ANOVA revealed no statistically significant main effects nor interactions ($p>0.05$) of any of the independent variables on glare from the initial warning light.

3.1.2. Discomfort glare from the overall array of warning lights.—Mean ratings from subjects to the question about the discomfort from the entire array of lights were highly correlated ($r=0.95$, $p<0.001$) between subjects' responses as passengers and as drivers and differed in absolute value from each other by an average of 3%, so the responses of subjects from both seating positions were combined to increase statistical power. The ANOVA on these responses revealed no statistically significant main effects nor interactions ($p>0.05$) of any of the independent variables on discomfort glare ratings from the overall array of warning lights.

3.1.3. Driver judgments: Easy/difficult.—There were no statistically significant main effects nor interactions ($p>0.05$) among any of the independent variables on drivers' ratings of the ease/difficulty of navigating through the work zone.

3.1.4. Driver judgments: Quickly/slowly.—There were no statistically significant main effects nor interactions ($p>0.05$) of any of the independent variables on drivers' judgments of how quickly or slowly they were able to navigate through the work zone.

3.1.5. Driver judgments: Accuracy.—There were no statistically significant main effects nor interactions ($p>0.05$) of any of the independent variables on drivers' judgments of how accurately they were able to navigate through the work zone.

3.1.6. Driving speed.—The flash pattern had a statistically significant ($F_{2,22}=13.3$, $p<0.001$) main effect on the mean driving speed in the center of the work zone. As illustrated in Figure 3, speeds were higher for the *random* and *sequential* flash patterns, and lower for the *synchronized* pattern. No interactions among any of the independent variables were found on the mean driving speed.

In most trials, drivers increased their speed up to a maximum value and then slowed down when navigating through the work zone. These reductions in speed were calculated by

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subtracting the speed when the vehicle passed through the road constriction in the center of the work zone directly in front of the parked vehicle (denoted by “P” in Figure 1), from the maximum speed. For the relatively few cases (14%) when the speed in the center of the work zone was faster than any speed achieved while approaching this location, the reduction in speed was defined as zero. These reductions in speed were evaluated with ANOVAs, and the covariate of whether a lane change was required had a statistically significant ($F_{1,65}$=83.2, $p<0.001$) effect on the speed reduction; greater reductions (2.6 mph) were found when a lane change was required than when one was not (0.6 mph). There was also a statistically reliable ($F_{2,22}$=4.6, $p<0.05$) main effect of the flash pattern on the speed reduction (Figure 4); with the *synchronized* pattern eliciting the greatest reduction in speed, which is consistent with the mean driving speed results in Figure 3.

3.2. Nighttime

3.2.1. Discomfort glare from the initial warning light.—Figure 5 shows the mean discomfort glare rating values when the initial warning light was 750 cd and when the initial light was off (0 cd); this difference was statistically significant ($F_{1,11}$=24.6, $p<0.001$).

The initial warning light was judged as more or less glaring depending upon which flash pattern was being displayed during each trial, a statistically significant ($F_{2,22}$=3.8, $p<0.05$) main effect. As shown in Figure 6, the *random* pattern resulted in the greatest discomfort (lowest rating values: mean 6.2, s.e.m. 0.2) and the *sequential* pattern resulted in the least discomfort (highest rating values: mean 6.8, s.e.m. 0.2) from the initial light in that pattern. The *synchronized* pattern was associated with a mean discomfort glare rating value of 6.6 (s.e.m. 0.2).

There was also a statistically significant ($F_{3,33}$=3.1, $p<0.05$) two-way interaction between the intensity of the initial warning light (750 cd or 0 cd) and the intensity of the subsequent warning lights in the array on drivers’ judgments of discomfort glare to the initial flashing warning light (Figure 7). When the warning light with the 750-cd intensity was flashing, discomfort glare ratings were lower (more discomfort glare) and relatively constant for every subsequent warning light intensity (2.5 cd, 7.5 cd, 25 cd and 75 cd). When the initial flashing warning light was off, discomfort glare ratings of the initial flashing warning light increased slightly (less discomfort glare) from 2.5 cd to 7.5 cd and then decreased (more discomfort glare) as the intensity of the subsequent warning lights increased from 7.5 cd to 25 cd and from 25 cd to 75 cd.

The covariate of whether drivers had to execute a lane change maneuver (left or right taper; see Figure 1) during each trial also had a statistically significant ($F_{1,65}$=6.6, $p<0.05$) impact on their ratings of discomfort glare from the initial flashing warning light. The mean rating value of the initial flashing warning light when drivers had to change lanes (left taper) was 6.4, but increased (indicating reduced discomfort glare) when they did not have to change lanes (right taper) to 6.7. This increase in subjective ratings (less discomfort glare) was associated with the previously-mentioned 20% decrease in the intensities of the initial flashing warning light from the driver’s perspective when approaching the right taper versus the left taper of the simulated work zone.

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3.2.2. Discomfort glare from the overall array of warning lights.—As mentioned previously, the responses from subjects viewing the warning lights as both drivers and passengers were combined, since they were highly correlated ($r=0.95$, $p<0.001$) with, and similar in magnitude (average difference of 3%) to each other.

The ANOVA on the glare ratings from the overall array of warning lights revealed a statistically significant ($F_{1,11}=15.7$, $p<0.005$) main effect of the presence of the 750-cd initial warning light, with numerically higher rating values (indicating less discomfort) when this light was not present (mean value of 7.5) than when it was present (mean value of 6.8).

The covariate of whether drivers had to execute a lane change maneuver during each trial also had a statistically significant ($F_{1,353}=7.6$, $p<0.01$) impact on their ratings of discomfort glare from the overall array of warning lights. The mean rating value when drivers had to change lanes (left taper) was 7.1, but increased (indicating reduced discomfort glare) when they did not have to change lanes (right taper) to 7.3.

Of interest, all of the two-way interactions among the independent variables denoting the characteristics of the flashing warning lights were statistically significant. There were consistent differences in the overall discomfort glare ratings among the three flash patterns with the *random* pattern having the lowest numerical rating values (indicating greater discomfort) and the *sequential* pattern having the highest numerical rating values (indicating the least discomfort). These differences were larger without the 750-cd initial warning light and smaller when it was present (Figure 8), a statistically significant ($F_{2,22}=3.8$, $p<0.05$) interaction.

There was also a statistically significant ($F_{6,66}=4.4$, $p<0.005$) interaction between the intensity of the subsequent warning lights in the taper and the flash pattern on ratings of discomfort glare. Differences in the ratings of discomfort glare from the entire array of warning lights were larger among the three flash patterns when the intensity of the remaining lights was highest, and smallest for the lowest intensity (Figure 9).

Finally, a statistically significant ($F_{3,33}=5.0$, $p<0.01$) interaction was found between the intensity of the subsequent warning lights in the taper, and the presence of the initial 750-cd warning light, on discomfort glare ratings. Differences in the ratings of discomfort glare from the entire array of warning lights were larger when the initial 750-cd warning light was not present, and were smaller when it was present (Figure 10).

3.2.3. Driver judgments: Easy/difficult.—Drivers' ratings of the ease/difficulty of navigating through the work zone were statistically significantly ($F_{2,22}=6.0$, $p<0.01$) impacted by the flash pattern, as illustrated in Figure 11. The mean ratings were 0.68 (s.e.m. 0.13) for the *random* flash pattern, 1.08 (s.e.m. 0.09) for the *synchronized* pattern, and 1.42 (s.e.m. 0.08) for the *sequential* pattern.

There was also a statistically significant ($F_{6,66}=3.4$, $p<0.01$) two-way interaction between the flash pattern and the intensity of the warning lights in the array on drivers' judgments of the ease/difficulty of navigating through the work zone at night. Figure 12 shows how ratings changed as a function of warning light intensity for each flash pattern. Ratings were consistently low for the *random* flash pattern; for the *sequential* flash pattern, ratings were highest for a warning light intensity of 25 cd.

3.2.4. Driver judgments: Quickly/slowly.—Drivers' judgments of how quickly or slowly they drove through the simulated work zone were qualitatively very similar to their ratings of how easy or difficult it was to drive through, exhibiting the same trends. As with ease/difficulty, the flash pattern had a statistically significant ($F_{2,22}$=4.9, $p<0.05$) effect on drivers' ratings of how quickly or slowly they were able to navigate through the work zone. Drivers felt they were able to drive through most quickly through the *sequential* flash pattern (mean rating 1.32, s.e.m. 0.08), and most slowly through the *random* pattern (mean rating 0.74, s.e.m. 0.12). For the *synchronized* pattern the mean rating was 1.07 (s.e.m. 0.08).

The presence of a lane change maneuver also statistically significantly ($F_{1,65}$=14.1, $p<0.001$) influenced drivers' perception of how quickly they were able to navigate through the work zone. When a lane change was needed, the rating (mean value 0.94) was lower than when no lane change was needed (mean value 1.15).

Although not statistically significant ($p>0.05$), the interaction plot showing mean ratings of ease/difficulty for each flash pattern as a function of warning light intensity was qualitatively similar to Figure 12, with the highest rating of ease for the 25-cd intensity in the *sequential* flash pattern.

3.2.5. Driver judgments: Accuracy.—Again, ratings of how accurately drivers were able to navigate the simulated work zone mirrored the ratings of ease/difficulty; the flash pattern had a statistically significant ($F_{2,22}$=3.6, $p<0.05$) effect on drivers' ratings of how accurately they were able to navigate through the work zone. Drivers felt they were able to drive through most accurately when the *sequential* flash pattern was used (mean rating 1.45, s.e.m. 0.07), and least accurately with the *random* pattern (mean rating 0.97, s.e.m. 0.12). For the *synchronized* pattern the mean rating was 1.23 (s.e.m. 0.08).

As with judgments of how quickly or slowly drivers were able to navigate through the work zone, the presence of a lane change maneuver also statistically significantly ($p<0.005$) influenced drivers' perception of how accurately they were able to navigate through the work zone. When a lane change was needed, the rating (mean value 1.14) was lower than when no lane change was needed (mean value 1.30).

Although not statistically significant ($p>0.05$), the interaction plot showing mean ratings of accuracy for each flash pattern as a function of warning light intensity was also qualitatively similar to Figure 12, with the highest rating of accuracy for the 25-cd intensity in the *sequential* flash pattern.

3.2.6. Driving speed.—Whether drivers had to execute a lane change maneuver in a given trial was the only factor that had a statistically significant ($F_{1,65}$=26.2, $p<0.001$) effect on driving speed in the work zone. The mean vehicle speed in the work zone when a lane change was required (left taper in Figure 1) was 29.0 mph, whereas it was 27.9 mph when no lane change was required (right taper in Figure 1). This finding appears to contradict the

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responses of drivers when they were asked to judge how quickly/slowly they were able to navigate through the work zone; they judged that they navigated the work zone more slowly when a lane change was needed. This contradiction might be explained by the fact that the work zone was positioned closer to the end of the road section where subjects began their trials in which no lane change was needed. Subjects drove longer on the straight section before approaching the lane change configuration than they did before approaching the no-lane-change configuration. This likely resulted in their driving faster when approaching the lane change scenarios.

Indeed, this seems to be consistent with the data for the mean reduction in speed drivers exhibited. When assessing the reduction in speed between the maximum approach speed to the simulated work zone and the mean speed when in the center of the work zone, the covariate of whether drivers had to execute a lane change or not had a statistically reliable ($F_{1,65}$=119, p<0.001) effect on driving speed; when a lane change was required, there was a greater reduction in speed (2.1 mph) than when no change was needed (0.3 mph).

Although only approaching statistical significance ($F_{1,11}$=4.5, p=0.06), nighttime driving speeds in the work zone were slightly lower in the presence of the 750-cd initial warning light (mean speed 28.2 mph) than when this light was not part of the configuration (mean speed 28.7 mph).

4. Discussion

The results of the present study suggest that within the range of variables tested, work zone warning lights can be operated at many intensities and at various flash patterns during the daytime without negatively affecting driver behavior or subjective responses. Indeed, with regard to determining the course-way through a work zone, flashing warning lights may not even be necessary in daylight; the barrels on which they are mounted may provide drivers with sufficient course-way information. It should be noted, however that flashing warning lights would likely still be important for attracting the attention of oncoming drivers to the work zone.[7,8]

The only factors that reliably impacted driving speed behavior were the warning light flash pattern and whether drivers had to execute a lane change or not; no significant effects were found in the daytime for any of the subjective judgments used in this study. Specifically, the *synchronized* flash pattern resulted in statistically slower driving speeds (and greater reductions in speed) through the work zone during the daytime than both the *random* and the *sequential* flash patterns, and the necessity of a lane change maneuver resulted in larger reductions in driving speed.

We infer from these results that the *synchronized* flash pattern was initially perceived by subjects as a warning for a potential barrier or impasse in the work zone course-way; thus, the drivers slowed down to assess the course-way ahead. As the experiment progressed, however, they learned that there was no barrier or impasse in the course-way. Two post hoc observations support that inference. First, as subjects became more and more familiar with the work zone as drivers, and as passengers, during the many trials, the differences between

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driving speeds for the three flash patterns dissipated. For example, the average difference in driving speed between the *random* and the *synchronized* pattern for the first four runs during the daytime was 1.8 mph, 0.8 mph for the next four runs, and 0.7 mph for the last four runs. Second, the difference among the three flash patterns was not statistically significant throughout the nighttime trials. For the present experimental design, all nighttime trials were performed after the daytime trials had been completed, giving subjects many trials during the daytime to learn there was no barrier or impasse in the course-way. Thus, it would appear that warning lights operated with *synchronized* flash patterns may be very useful for perceptually warning approaching drivers of a barrier or impasse in a course-way. Although this may be a reasonable extrapolation from the present study results, a specific experiment should be designed to test this hypothesis directly.

Many more variables associated with the warning lights were statistically significant at night, but only for subjective judgments. Only the covariate, lane change (right and left taper) variable was statistically significant when driving behavior was used as a dependent variable. It is worth noting that subjective impressions of lighting conditions when driving at night do not always have behavioral implications; for example, Theeuwes et al.[27] found large differences in ratings of discomfort glare in a nighttime driving study involving different levels of illumination from simulated oncoming headlights, but no reliable differences in driving speed were identified. Leibowitz and Owens[34] reported that some visual functions associated with driving a vehicle degraded rather quickly as light level decreased from daytime to nighttime levels, while others could be maintained even at low levels. Indeed, there are parallel neural channels in the visual system that likely influence these differences[35] and which can elicit themselves in the context of nighttime driving.[36]

As would be expected, discomfort glare ratings were strongly affected by the intensity of the initial flashing warning light at night. For the 750 cd condition the average discomfort glare rating was 5.5, slightly better than “just permissible,” compared to the 0 cd condition which was 7.5, slightly better than “satisfactory.” Also as would be expected, when the initial warning light was not energized (i.e., 0 cd), discomfort glare increased (lower rating values) as their collective intensity increased from 7.5 cd to 75 cd. The intensity of the subsequent warning lights had no effect on discomfort glare when the initial warning light was energized (i.e., 750 cd). Again, the discomfort glare ratings were never worse than “just permissible.” These findings are consistent with those from our previous study[8] investigating detection of flashing warning beacons at night. In that study, subjects did not find that the flashing warning beacon intensity affected visibility until its intensity was almost 2000 cd. Since detection of work zones from afar as well as facilitating course-way driving through the work zone are both important, the results of our two studies should be tested as a “complete solution.”

Interestingly, and in that context of a “complete solution” for work zone warning light deployment, the flash pattern of the subsequent warning lights affected the discomfort glare ratings of the initial warning light. The *random* pattern increased the perceived discomfort glare of the initial warning light more than the other two patterns and statistically more than the *sequential* pattern (Figure 5). This reinforces previous work[27, 28] showing that assessments of discomfort glare from warning lights cannot be properly performed from

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photometric and colorimetric measurements of a single warning light alone, as is currently the situation (e.g., ITE[1]). In fact, the present data show that the *sequential* pattern reduces perceptions of discomfort glare relative to the common practice of deploying randomly flashing warning lights. Whether the *sequential* pattern used here is ideal for limiting perceptions of discomfort glare, needs further systematic investigation.

It seems nevertheless true that the *sequential* pattern used in the present study, with or without energizing the initial warning light, is associated with significantly less discomfort glare than either of the other two patterns, especially the *random* pattern. This same generalization can be made based upon the subjective responses of the drivers with regard to how easy, how fast and how accurately they believed they performed while driving through the simulated work zone. It should be noted that there is some evidence to suggest that the *sequential* pattern may, counter-intuitively, contribute to faster speeds through work zones. There is evidence that better visual information provides greater confidence to drivers and thereby encourages drivers to drive faster.[37] If drivers become overconfident, however, front line workers may be at greater risk. This possibility is important to consider and test in a subsequent study.

5. Conclusions

The following conclusions can be drawn about the operation of warning lights as they might be deployed in and around work zones. Since warning lights are very important for the safety of front-line workers and for drivers, it is important that these conclusions be further validated experimentally.

5.1. Daytime

Within very wide limits, little can be done to compromise the effectiveness of warning lights during daytime operation. However, based upon previous research,[8] the initial warning light in a work zone should be operated with a “fully-on/10%-on” flash pattern, where “fully-on” is 750 cd. This flash pattern should be effective for attracting the attention of unsuspecting drivers approaching a work zone. For consistency with the nighttime recommendations (below), warning lights demarcating the course-way in a work zone should be operated in a *sequential*, near-to-far, pattern. There are many possible types of sequential patterns that could be used, but the ideal sequential pattern has not been systematically investigated.

5.2. Nighttime

Unlike daytime, there are narrower tolerances for effective operation of warning lights in work zones at night. Based upon the present study, a *sequential* pattern of warning lights demarcating the course-way in a work zone is best for ease of course-way driving and for minimizing discomfort glare. These warning lights should be operated with a “fully-on/10%-on” flash pattern, where “fully-on” is 25 cd. Although the present study showed that an initial warning light could be operated with a much brighter “fully-on/10%-on” flash pattern, where “fully-on” is 750 cd, without creating unacceptable discomfort glare, it also seems reasonable to suppose that the initial warning light could be operated at a lower level (e.g., 75 or 250 cd) without necessarily reducing its effectiveness for warning drivers approaching

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the work zone. The ideal “fully-on” intensity for the initial warning light in a work zone should be studied more systematically.

A “complete solution” for warning lights in work zones should be developed and experimentally tested. In principle, the work zone warning lights should serve two distinct purposes: (1) attract attention of unsuspecting drivers approaching a work zone and (2) facilitate ease of course-way navigation through a work zone; both purposes should be accomplished without creating unnecessary glare to drivers. In addition, a “complete solution” should make provisions to control scattered light when the warning lights are operated in perturbed atmospheric conditions, such as fog and falling snow.[4]

Acknowledgments

The authors gratefully acknowledge Timothy Plummer and Charles Jarboe from the Lighting Research Center (LRC) for assistance. Dennis Guyon from the LRC prepared the final graphics, and Rebekah Mullaney from the LRC edited the manuscript and assisted with the references. The Town of East Greenbush Supervisor and Police Chief are also gratefully acknowledged for permission to conduct the study on a closed town road.

Funding

This publication was supported by Grant no. R01OH010165 to Mark S. Rea and funded by the National Institute for Occupational Safety and Health (NIOSH) of the Centers for Disease Control and Prevention. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Centers for Disease Control and Prevention or the Department of Health and Human Services.

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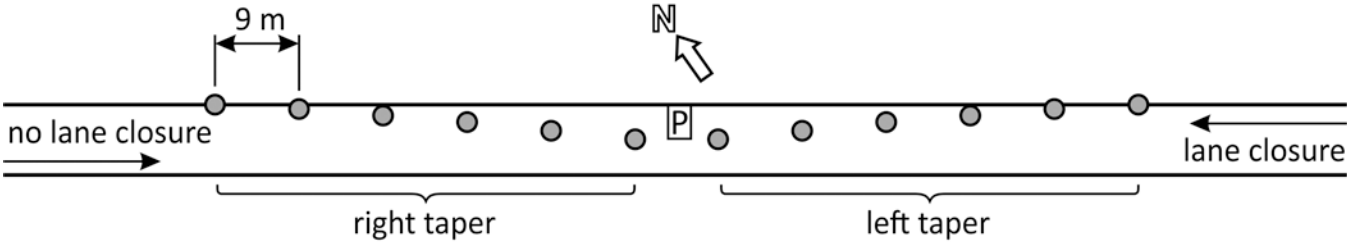

Figure 1.

Plan view layout of traffic drums. Arrows indicate the direction of travel for vehicles approaching from each side (see text); “P” indicates the location of the parked vehicle at the center of the work zone.

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Figure 2.
Warning light mounted on a traffic drum.

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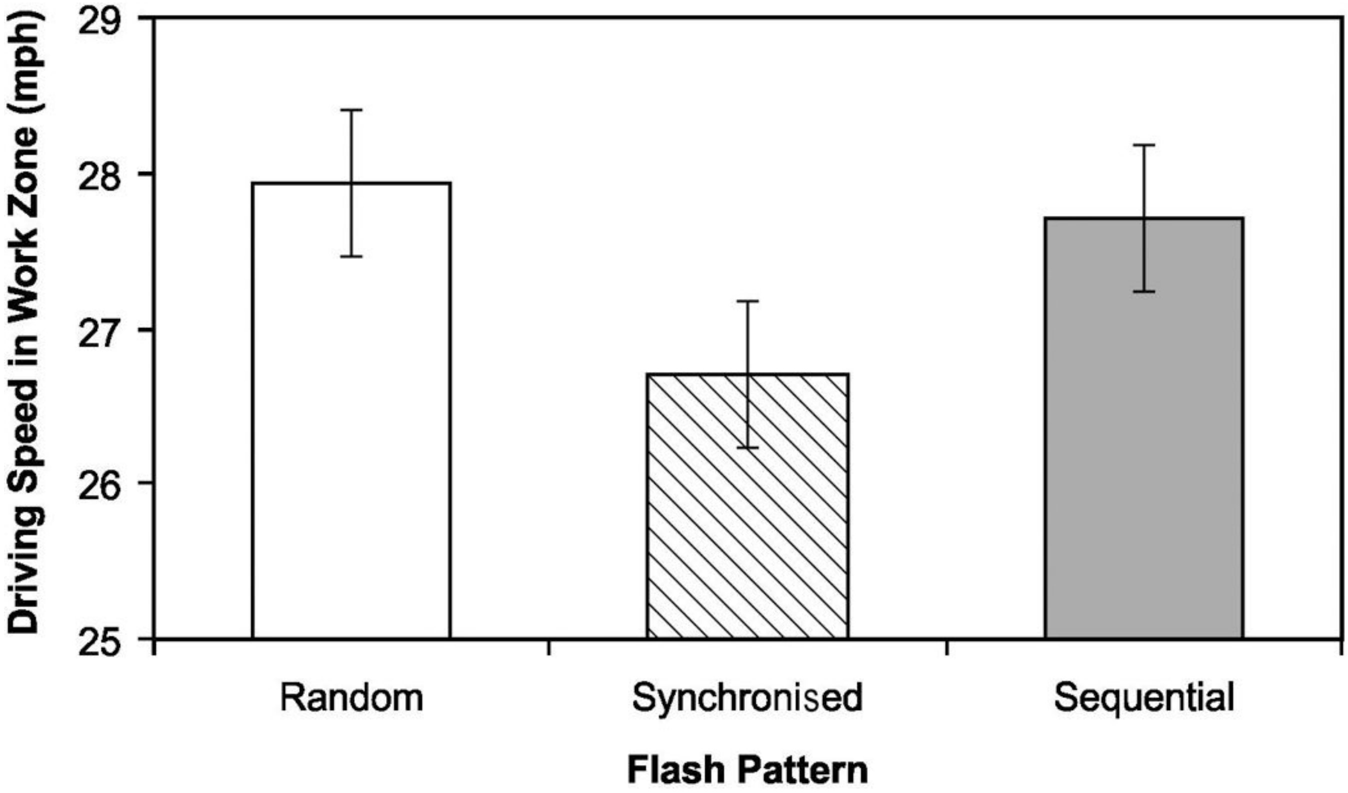

Figure 3.

Daytime driving speeds in the work zone for each warning light flash pattern.

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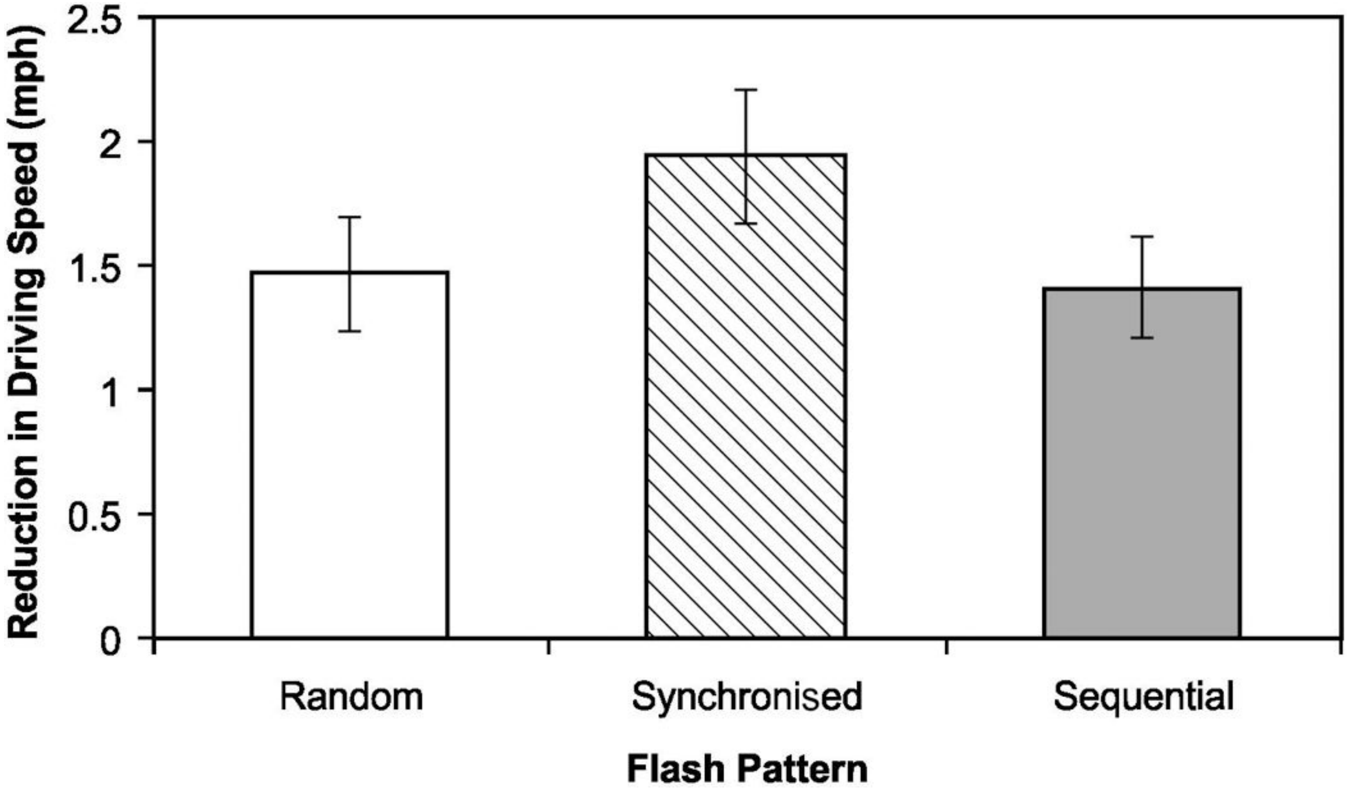

Figure 4.

Daytime reductions in driving speed for each warning light flash.

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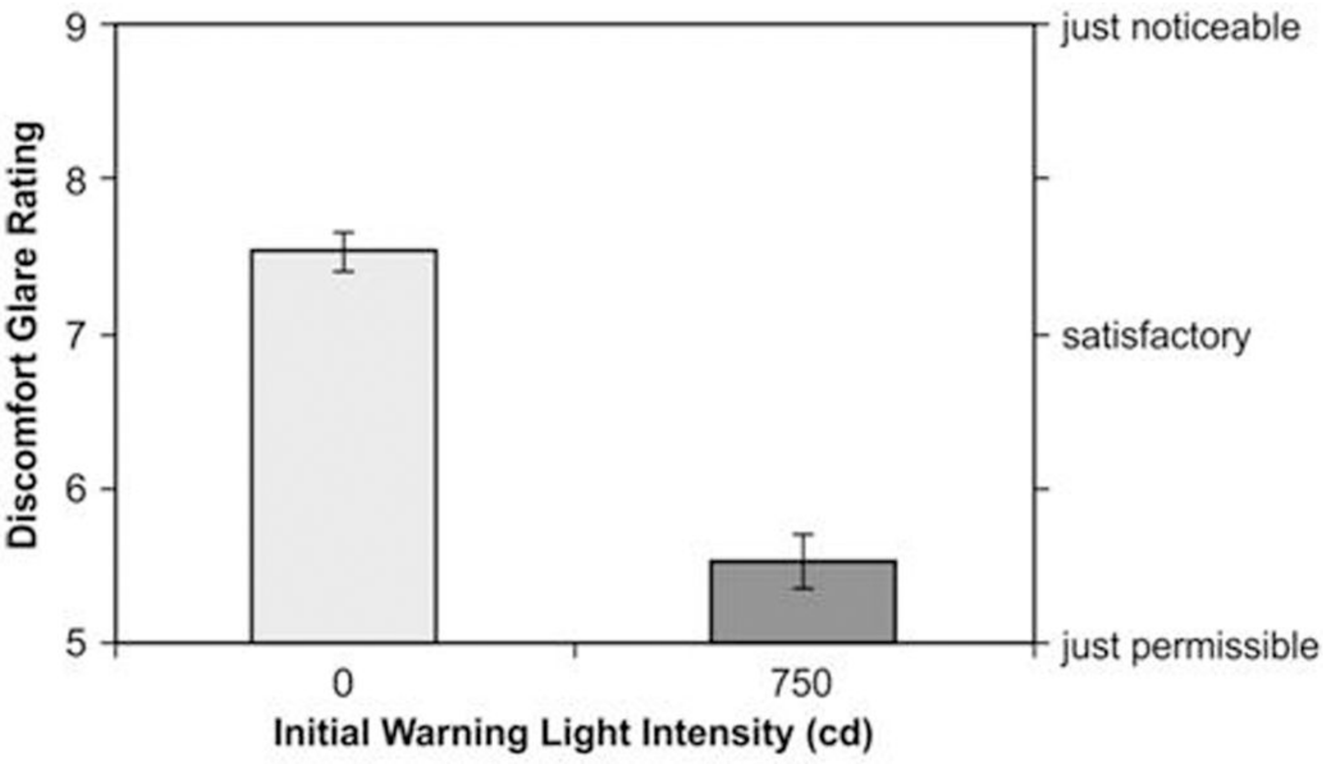

Figure 5.

Effect of initial warning light intensity on nighttime driver ratings of discomfort glare from the initial flashing light.

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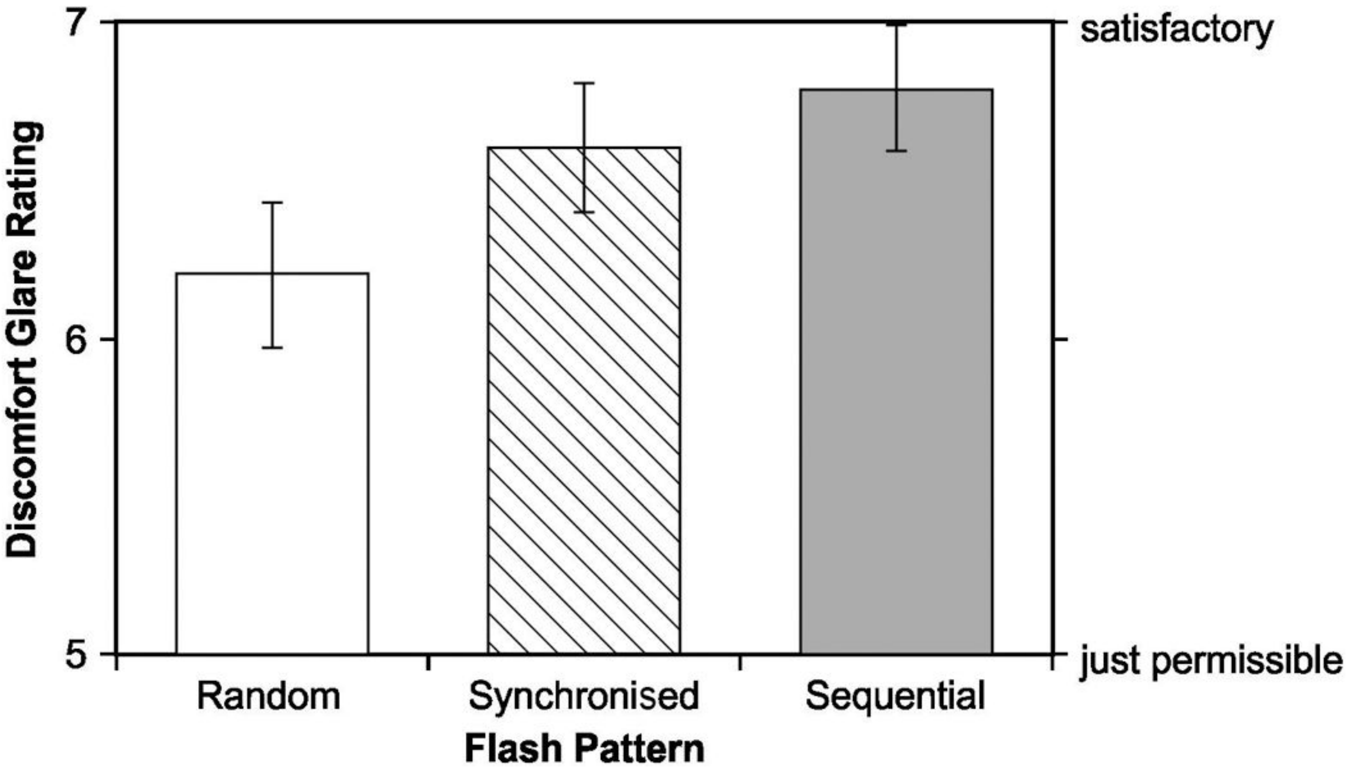

Figure 6.

Effect of flash pattern on nighttime driver ratings of discomfort glare from the initial flashing warning light at night.

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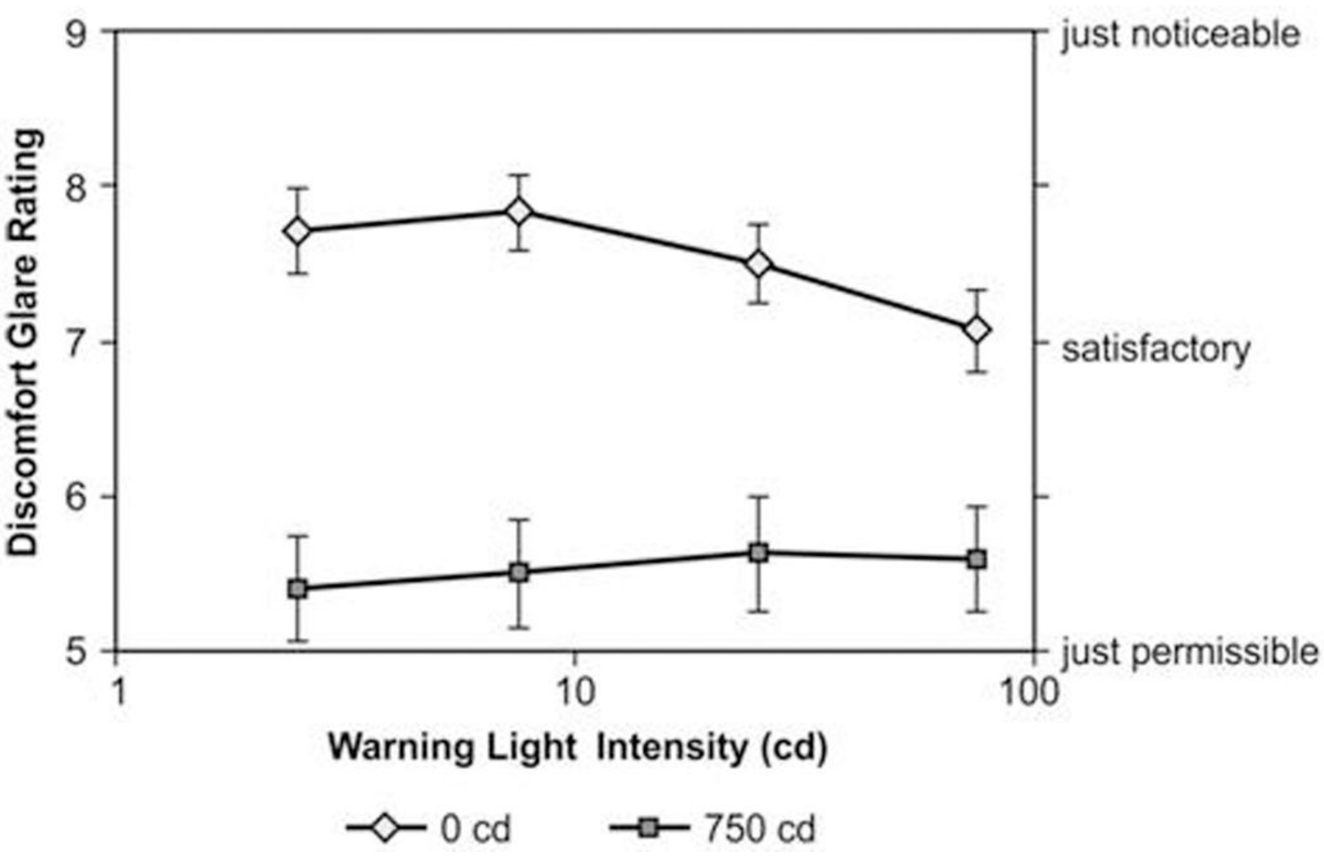

Figure 7.

Drivers’ judgments of discomfort glare at night from the initial warning light with and without the 750-cd warning light on, and as a function of the intensity of the subsequent lights in the array.

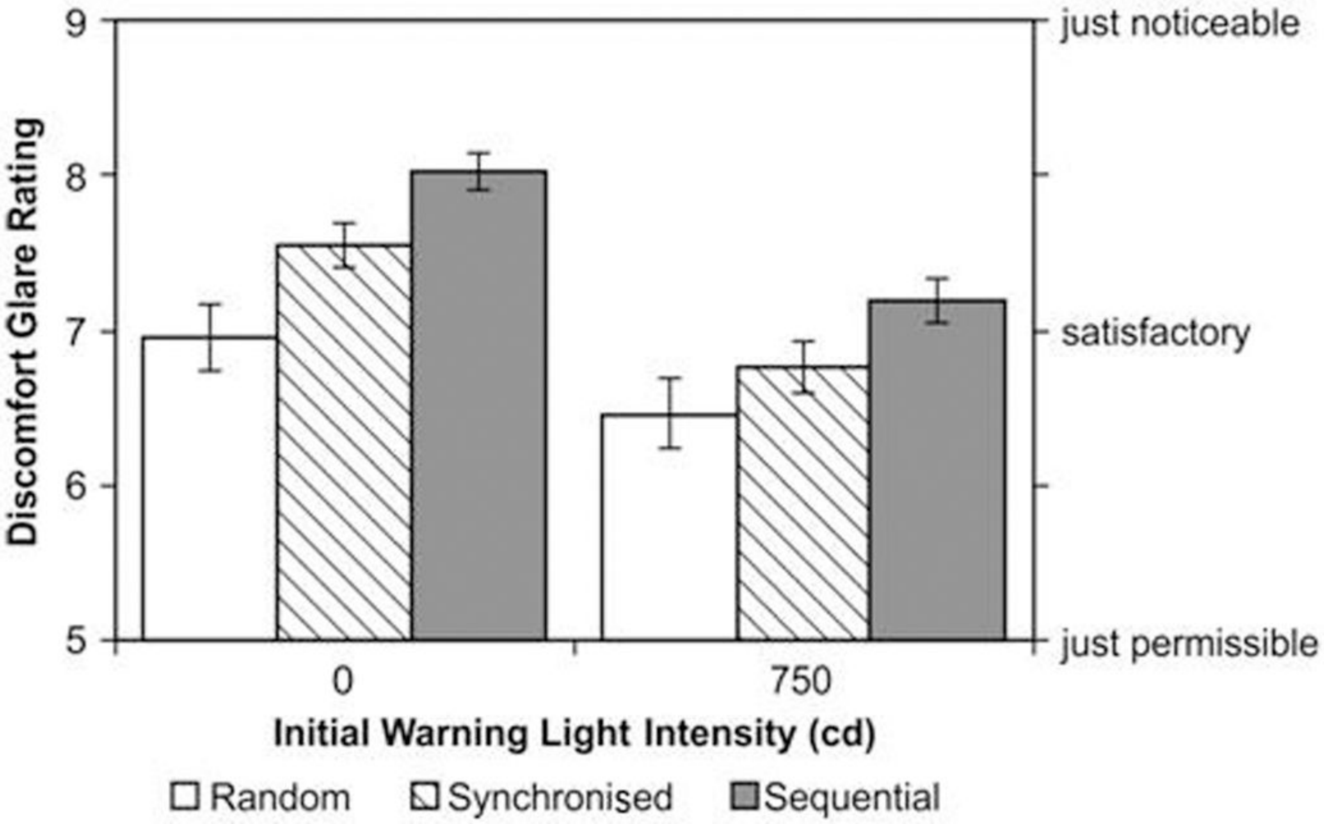

Figure 8.

Two-way interaction between the intensity of the initial warning light and the flash pattern on ratings of discomfort glare from the overall array of warning lights.

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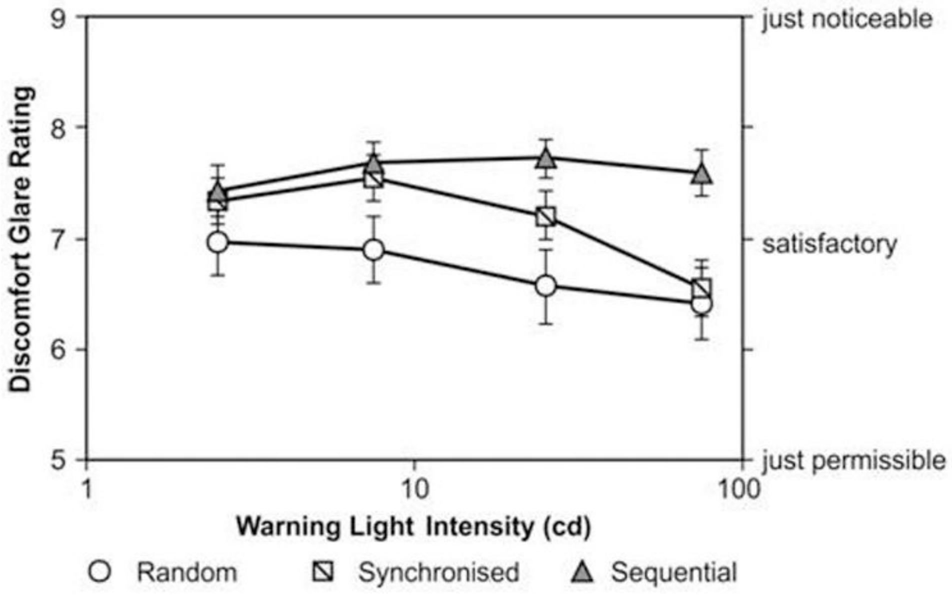

Figure 9.

Two-way interaction between the intensity of the warning lights in the array and the flash pattern on ratings of discomfort glare from the overall array of warning lights.

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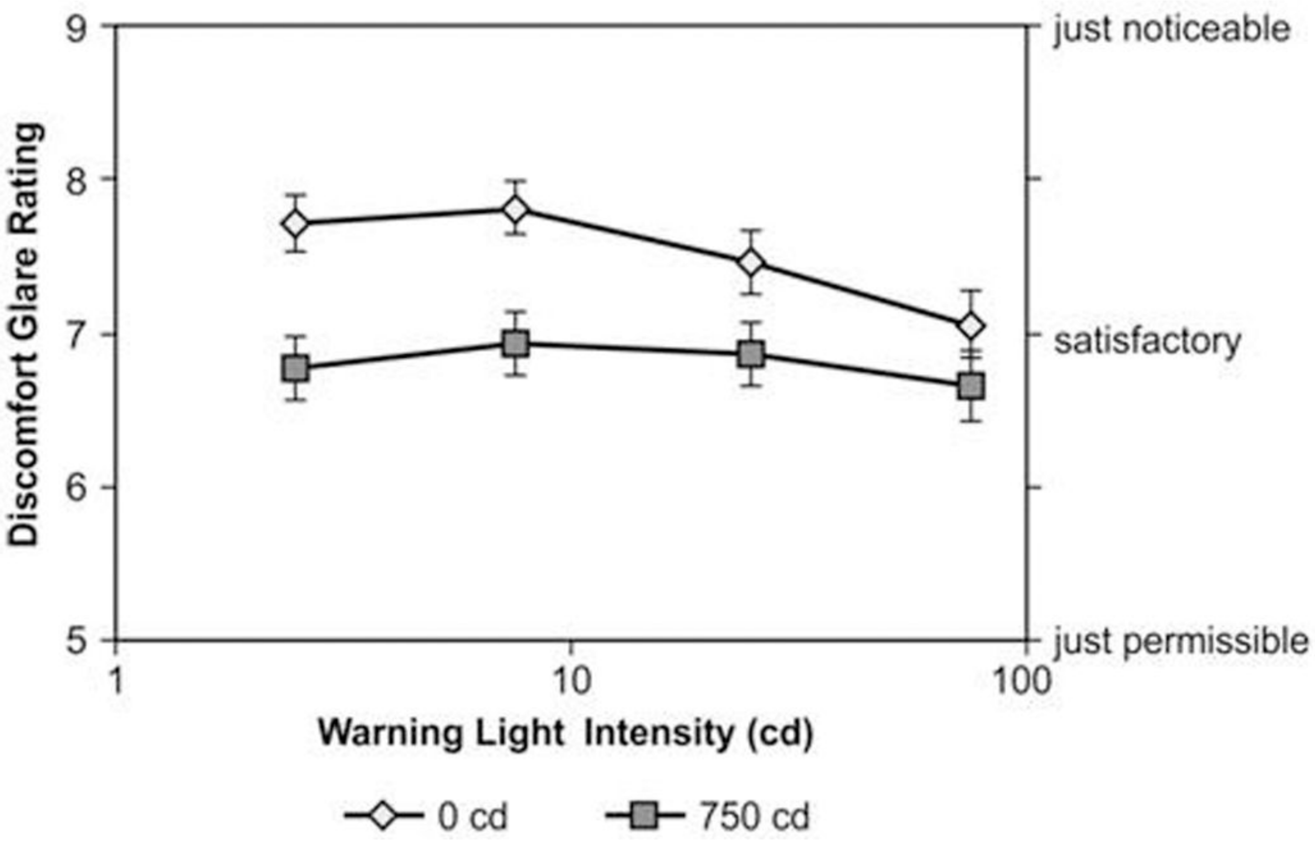

Figure 10.

Two-way interaction between the intensity of the warning lights in the array and the intensity of the initial warning light (0 or 750 cd) on ratings of discomfort glare from the overall array of warning lights.

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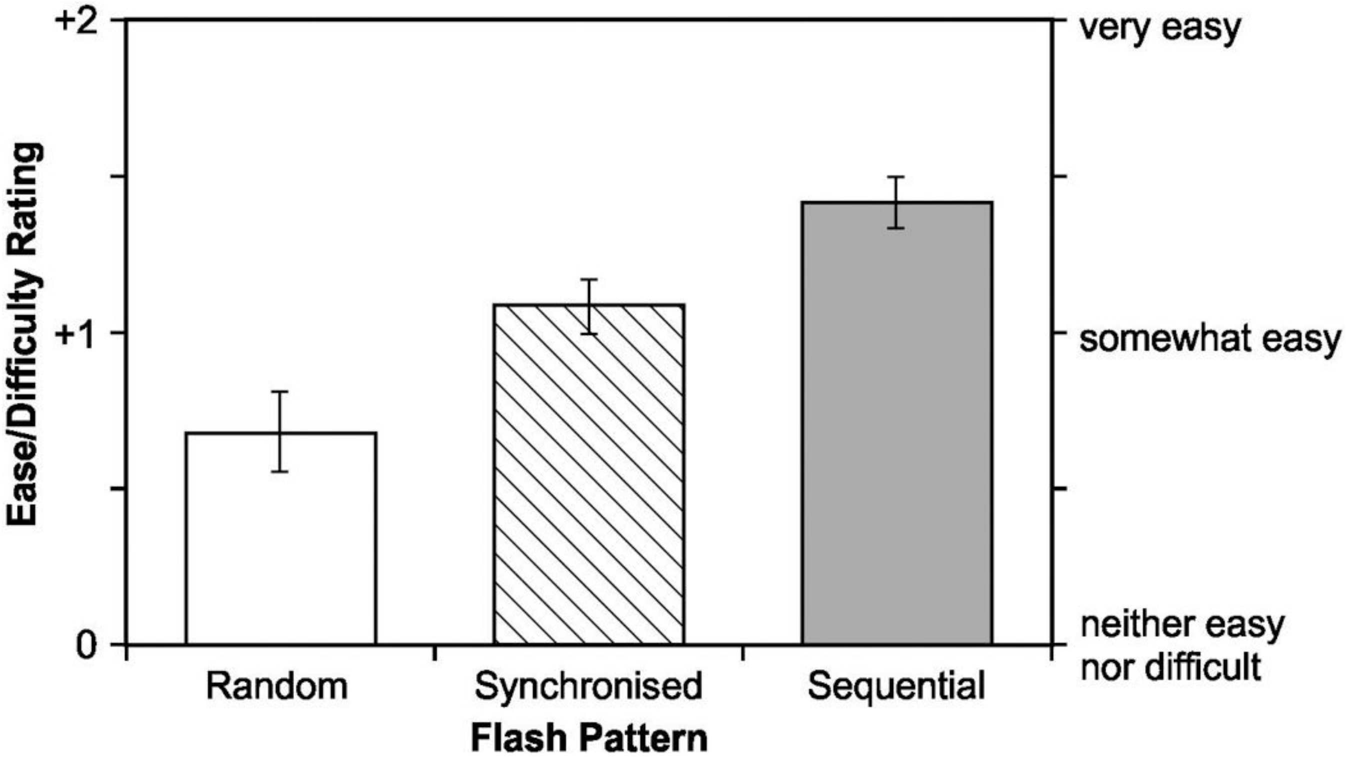

Figure 11.

Influence of flash pattern on drivers' mean (±s.e.m.) nighttime judgments of ease/difficulty of navigating through the work zone.

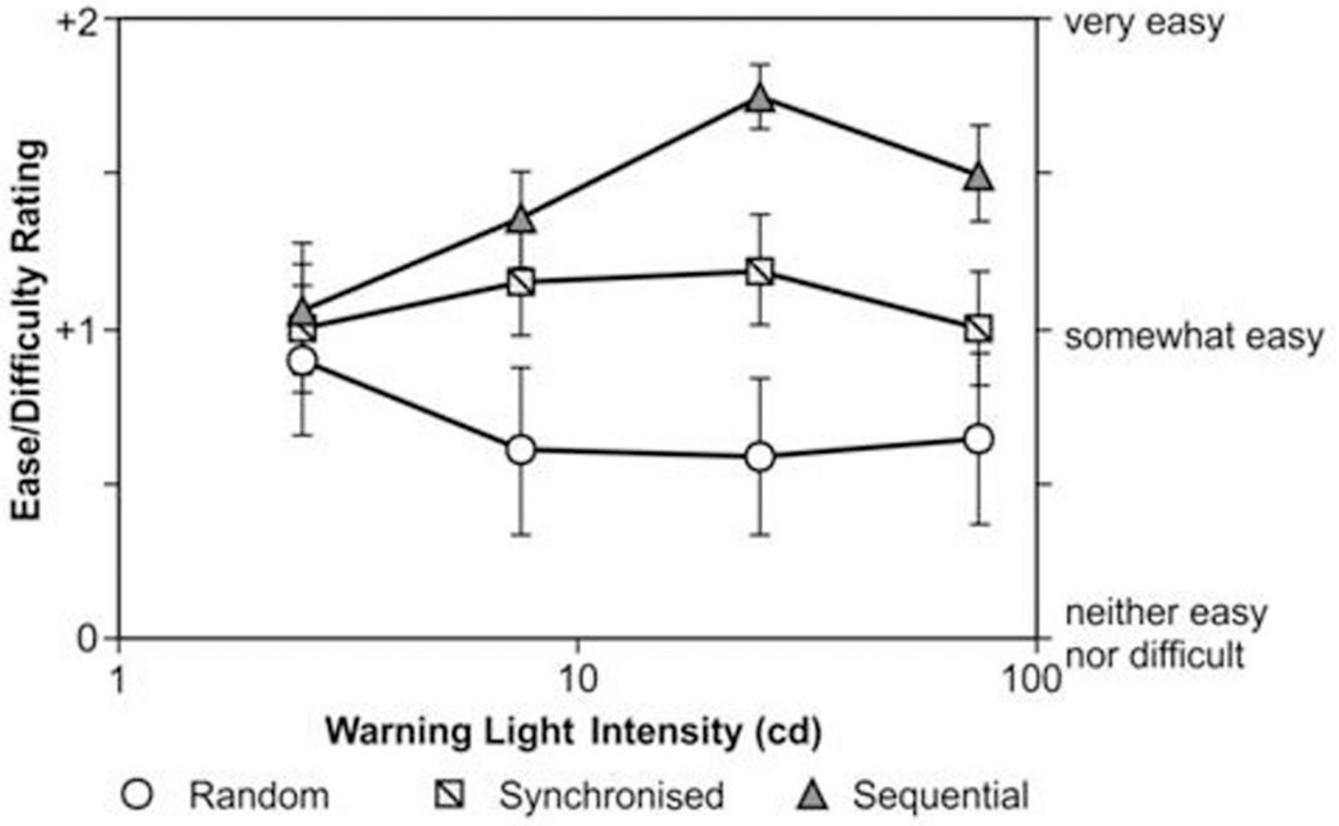

Figure 12.

Influence of flash pattern and warning light intensity on drivers' ratings of how easy/difficult it was to navigate through the work zone at night.

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Table 1.

Summary of ITE (2001) Performance Requirements for Work Zone Flashing Lights

Performance Aspect	**Requirement**
Intensity	Type A: 4 cd effective intensity [*] Type B: 35 cd effective intensity [†]
Flash Frequency	0.9–1.25 Hz
Color (yellow)	Chromaticity (x,y) Coordinates: $0.411 \leq x \leq 0.452$; $y \geq 0.995 - x$

[*] Corresponds to a luminous intensity of 6 cd when fully on and flashed with a duty cycle of 50%, and to a luminous intensity of 12 cd when fully on and flashed with a duty cycle of 10%.

[†] Corresponds to a luminous intensity of 49 cd when fully on and flashed with a duty cycle of 50%, and to a luminous intensity of 105 cd when fully on and flashed with a duty cycle of 10%. May be reduced by 50% during nighttime