

EFFECTS OF MOUNTING HEIGHT, OFFSET DISTANCE, AND NUMBER OF LIGHT TOWERS ON DRIVERS' VISUAL PERFORMANCE AND DISCOMFORT GLARE IN WORK ZONES

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ABSTRACT

Portable light towers are a significant source of glare to motorists entering a work zone. Although existing research has evaluated the effect of light tower orientation on visibility and glare, the effects of factors like (mounting height, offset distance from the roadway, and number of light towers in the work zone) on visual performance and discomfort glare is not known. Understanding these relationships can help in developing illuminating guidelines for work zones that can reduce glare for drivers. The goal of this paper is to understand the effect of mounting height, offset distance to the roadway, and number of light towers in the work zone on drivers' visual performance and discomfort glare. Participants drove through a realistic work zone and evaluated portable light towers in varying mounting heights, offset distances, and number of light towers in the work zone. Results showed that the mounting height and offset distances play a critical role in affecting the driver's visual performance and discomfort glare rating. Portable light towers, irrespective of wattage and lumen output, at lower than a mounting height of 20 ft. and closer to the roadway result in decreasing driver visual performance and increasing their discomfort glare. Portable light towers should be mounted at a height of at least 20 ft. and balloon light towers with higher wattage (4,000 W and greater) and lumen output (400,000 lumens and greater) should be located at an offset distance of at least 10 ft. from the roadway.

INTRODUCTION

Portable light towers are commonly used in nighttime work zones to provide illumination to workers. However, they are a significant source of glare to motorists entering the work zone. Glare in the eyes of the drivers entering the work zone could reduce their visibility and potentially increase the risk of a crash. Great care should be taken when prescribing lighting for work zones so that workers have adequate light levels to effectively and safely complete their tasks without introducing glare for drivers entering the work zone.

Prior research in this area examined the effect of several commercially available portable light towers and their orientation on drivers' visual performance and their perceptions of visibility and glare (1). In the above mentioned study, three commercially available portable light towers (4000-W metal halide, LED and balloon type) in three orientations (angle to the drivers' line of sight: 45, 90 and 135 degrees) were used. Visual performance and perception of visibility and glare were evaluated in a realistic work zone designed to simulate a work zone on a limited access highway for the portable light tower types in all the three orientations. The results of this research showed that portable light towers aimed away from or perpendicular to drivers' line of sight (90 degrees or greater) resulted in increasing the driver's visual performance (longer detection distances) and lowering their perception of glare (lower glare ratings). However, the effect of mounting height and the location of the portable light towers with respect to the roadway on visual performance were not reported. Further, newer portable light sources like balloon light towers have been increasingly used in work zones. These newer light sources cannot be aimed and therefore care has to be taken to determine an ideal location for these light towers so that they decrease visibility for drivers entering the work zone. Previous studies (1, 2) have shown that improper aiming could limit the visibility of objects in the work zones. Thus, it is important to understand the effect of mounting height, location of the light towers with respect to the roadway (or offset distance) on visual performance, and discomfort glare of drivers. Understanding this relationship can help in recommending appropriate illumination guidelines for nighttime work zones, than can result in increased safety for motorists and workers.

This paper has two goals. The first is to evaluate objectively the effects of mounting heights, offset distances, and number of light towers on driver visual performance, especially on limited-access highways. The second is to understand the effects of the above-mentioned variables on the discomfort glare of drivers. Results from this study will add to the body of knowledge on work zone lighting, and glare. These results could also help in developing lighting specifications for work zones.

METHODS

Participants

Twenty-four participants were recruited to participate as drivers in this study. The participant sample was divided into two distinct age groups. The first group consisted of younger drivers whose ages ranged from 18 to 35 years ($M = 25.4$ years, $SD = 3.8$ years). The second group consisted of older drivers who were 60 years and older ($M = 63.5$ years, $SD = 2.7$ years). Both age groups comprised a participant sample with diverse visual capabilities and driving experiences. All the participants had a valid drivers' license and a minimum visual acuity of 20/40 (corrected).

Experimental Design

A repeated measures experimental design was used to evaluate the effects of mounting height, offset distance, and number of light towers on visual performance and discomfort glare. Visual performance was assessed by measuring detection and recognition distances of a worker as the participants drove through a simulated work zone on the Virginia Smart Road. Discomfort glare was assessed by means of a rating scale. The simulated work zone was set up in such a way that the lane closure was on the right lane when the participants were traveling in one direction and in the left lane when the participants were traveling in the opposite direction. Having the participants travel in both directions saved time and required fewer runs to collect the required data.

The independent variables and their levels are summarized in Table 1. In each experimental session, participants encountered all conditions. The presentation of the mounting heights, offset distances, and the number of light towers were counterbalanced to minimize order effects. Presentation of the simulated worker was also randomized with blanks (no work presentation) to actively discourage participants from guessing.

Independent Variables

Types of Portable Light Towers

Three types of commercially available portable light towers were used (Figure 1). The first was a conventional metal halide portable light tower with four 1,000-W (440,000 lumens) metal halide luminaires. The second was a balloon light tower (Manufacturer: 812 Illumination, model 4000-W HID) with four 1,000-W metal halide luminaires (440,000 lumens) enclosed within a balloon, which diffused the light. The third was also a smaller balloon light tower with an 800-W LED luminaire (Manufacturer: 812 Illumination; 84,000 lumens). In order to account of the different wattages and lumen output of the portable light tower types, the vertical illuminance on the simulated worker was matched at 50 lux across all the light tower types, mounting height, and offset distances.

Each portable light tower in the study was used only in certain orientations. The 4000-W balloon light tower was evaluated in three mounting heights and three offset distances. The 4000-W metal halide light tower was evaluated in only in three mounting heights, as changing the offset distance changed the beam angle to the vertical of the luminaires. The beam angle to the vertical was maintained at 60 degrees and the angle between the beam axis and line of sight of the driver was maintained at 90 degrees, as recommended by existing guidelines (3). The 800-W LED light towers were used at a fixed mounting height of 15 ft. as this was the highest setting provided by the manufacturer. These light towers are often mounted on paving or milling machines, either one or two towers at a time (4). Thus, the 800-W LED light tower was used in two configurations, one light tower at a time and two light towers at time, to simulate their use in real work zones.

In order to facilitate the comparison across different light tower conditions, several characteristics, such as light tower type, their respective mounting heights, offset distances, and number of light towers, were merged to form 15 discrete categorical levels of a single variable called "light tower orientation" (see Table 2). For example, the three mounting heights and three offset distances of the 4000-W balloon light tower were merged to give nine levels. The three mounting heights of the 4000-W metal halide contributed three levels. The two conditions of the number of luminaires for the 800-W balloon LED light tower contributed two levels. Finally, a

control condition with no light tower (only simulated worker under no lighting) was also used, which provided one level. Overall, the “light tower orientation” variable had 15 levels.

Mounting Height

Three different mounting heights were used. They were 15, 20, and 25 ft. from the surface of the roadway. Higher mounting heights could result in lower disability and discomfort glare for the drivers.

Offset Distance

Offset distance is the location of the portable light tower on the roadway. This distance was calculated from the center of the closed lane in which the simulated work zone was established. Three offset distances were used. They were 0 ft. (light tower in the lane), 10 ft. (light tower in the shoulder), and 20 ft. (light tower off the shoulder).

Dependent Variables

Visual performance was assessed by detection and recognition distances. These two variables are defined in the following subsections. Detection distance and recognition distance can be used to evaluate how well a lighting source can help the driver in hazard identification in a work zone.

Detection Distance

Detection distance was defined as the distance at which the participant was able to detect the presence of the simulated worker in the work zone. Detection distance has been used a measure of visual performance in nighttime roadway visibility research (1, 5-8).

Recognition Distance

The simulated worker oriented in the work zone always stood facing right or left. Recognition distance is the distance at which the participant was able to recognize the direction the simulated worker was facing. Similar to detection distance, recognition distances have been previously used in nighttime roadway visibility studies as measures of visual performance (9, 10).

Discomfort Glare

Discomfort glare was measured using a rating scale as shown in Table 3. This scale has been reported to produce reliable data, with smaller numbers meaning lower discomfort glare and higher numbers meaning higher discomfort glare (11, 12). The scale also has a “zero” anchor for no discomfort glare. An established discomfort glare rating scale such as, the deBoer rating scale, was not used, as research has shown that they are not good predictors of driving performance (13). Moreover, pilot tests showed that the 9 point deBoer rating scale was difficult for the participants to refer to or memorize while indicating their glare ratings, given the speed (55 mi/h) that was used in the current study. Participants had no issues with the selected discomfort glare rating scale for this study.

Procedure

Two participants were scheduled for each experimental session. Upon arrival, participants reviewed and signed the informed consent form. Participants’ driver’s licenses were checked for validity by the experimenters. Participants then performed a basic Snellen visual acuity test. Participants were required to have at least 20/40 vision (with or without corrective lenses) to

participate in the study. Participants who did not have 20/40 vision were not used for data collection.

Once participants had completed the paperwork, the experimenter read a brief overview of the driving portion of the study and answered participants' questions. Participants were then escorted to the test vehicle and orientated to the experimental vehicle. 1999 and 2000 model years Ford Explorers served as experimental vehicles for this study and were instrumented with a data acquisition system (DAS). The DAS collected kinematic data from the vehicle's Controller Area Network (CAN) system, including vehicle speed, differential Global Positioning System (GPS) coordinates, four video images (driver's face, forward roadway, left side of roadway, and right side of roadway), audio from the driver, manual button presses, and other input from the in-vehicle experimenter. Low-beam headlamps were used during the study. The headlamps were Hella 90 mm Bi-Xenon projector lamps with a single 1-F capacitor-stabilized headlamp input voltage on each vehicle. These headlamps were retrofitted along with a voltage stabilizer so that the headlamps' intensities were not affected by speed of vehicles. These retrofitted headlamps also allowed the headlamps to be at the same height from the ground across both the experimental vehicles. Before every experimental session, vehicle headlamps were aimed and the windshields were wiped clean.

Participants drove for six laps in both uphill and downhill directions on the VA Smart Road. Each lap involved driving through two simulated work zones at the assigned speed limit for the study (55 mi/h). Participants drove in the left lane when going downhill and in the right lane when going uphill. Portable light towers were located at two stations on the Smart Road. At the first station, the 800 W LED and the 4000-W metal halide light towers were located. The 4000-W balloon light tower was located at the second station. When travelling downhill, participants first encountered the light tower at first station and then the light tower at the second station. When traveling uphill, participants encountered the stations in the reverse order. All light towers were encountered in both directions. As the participants drove through the test area, they were asked to actively scan for a simulated worker located in the work area, who was dressed in retroreflective clothing along with a hard hat (see Figure 1) as recommended by the *Virginia Work Area Protection Manual (14)*. The vertical illuminance on the simulated worker was matched across all the light tower types, heights, offset distances, and number of light towers and was set at 50 lux. In order to match the vertical illuminance (light incident on a vertical plane) across each light tower and orientation, the worker's location within the work area was changed but it was always within the simulated work area.

Participants indicated when they could first see the simulated worker by saying "worker" aloud. The in-vehicle experimenter then flagged the data stream with a button press. Once participants recognized the direction the simulated worker was facing, they indicated the worker's orientation by saying "right" or "left" aloud. The in-vehicle experimenter then flagged the data stream with another button press. The GPS coordinates of the worker's locations were predetermined. The GPS coordinates at detection and recognition were cleaned up at a later point. The detections were adjusted to the point in time at which the participants said "worker" and stated the orientation, thereby eliminating the time delay due to experimenter input. A high precision GPS unit was used in the experimental vehicle and was also used to collect the GPS locations of the worker. The GPS system had an accuracy of about 0.1 m (0.33 ft.).

Once the first participant vehicle was clear of the test area, the in-vehicle experimenter notified the second participant vehicle via radio that they were clear to proceed and asked the participant to provide a discomfort glare rating for the condition that they had just observed. A

copy of the scale was provided for the participant for reference. After encountering the two simulated work zones in the downhill direction, the first vehicle was then parked in a turnaround and waited for the second vehicle. Once the second vehicle arrived at the turnaround, the process was repeated driving in the uphill direction. The two vehicles continued in this fashion until all light tower conditions had been observed.

Analyses

Three separate linear mixed model (LMM) analyses were used to assess the effect of light tower orientation on detection distance, orientation recognition distance, and discomfort glare rating. Age was included as a blocking factor. The level of significance was $p < 0.05$ for all statistical tests. Where relevant, post hoc analyses (pairwise comparisons) were performed using Tukey's honest significant difference (HSD) for main effects and simple effects testing for interaction effects.

RESULTS

Detection Distance Analysis

The main effect of light tower orientation was significant, $F(14, 342) = 16.06, p < 0.0001$. The effect of light tower orientation on detection distance is shown in Figure 2.

The longest detection distances were attained under 4000-W balloon light tower at an offset of 20 ft. and a mounting height of 25 ft. ($M = 549.3$ m, $SD = 205.7$ m). The shortest detection distances were attained under the two-800-W balloon LED light tower orientation ($M = 253.4$ m, $SD = 75.7$ m). For the 4000-W balloon light tower, the detection distances were significantly longer for the offset distances between 0 and 20 ft. at mounting heights of 20 and 25 ft. only. The detection distances between the 800-W balloon LED light tower and the 4000-W balloon light tower were significantly longer at every offset distance and mounting height except at the offset distance of 0 ft. and a mounting height of 15 ft. The differences in the detection distance between the 4000-W metal halide light tower and the 4000-W balloon light tower were only significant at mounting heights of 20 and 25 ft. for the offset distance of 0 ft. and at all mounting heights at an offset distance of 20 ft. The detection distance in the control condition was significantly lower than all light tower conditions except those of the 800-W balloon LED and the 4000-W metal halide at a height of 15 ft.

Recognition Distance Analysis

The main effect of light tower orientation on orientation recognition distance was significant, $F(14, 333) = 3.45, p < 0.0001$. The effect of light tower orientation on recognition distance is shown in Figure 3. None of the recognition distances between the light tower orientations was significant. Only the recognition distances for the control condition were significantly different from the 4000-W balloon light tower at all mounting height and offset distances except at the offset distance of 0 ft. and a mounting height of 15 ft.

Discomfort Glare Rating Analysis

The main effect of light tower orientation was significant, $F(14, 342) = 25.83, p < 0.0001$. The two-way interaction between age and light tower orientation was also significant, $F(14, 342) = 4.16, p < 0.0001$. The effect of light tower orientation on discomfort glare rating is shown in Figure 4. The two-800-W balloon light tower configuration had the highest discomfort glare rating ($M = 3.3, SD = 1.7$). This light tower orientation also had significantly higher glare ratings

than the 4000-W metal halide light tower at a mounting height of 20 and 25 ft. respectively. The control condition had the lowest glare rating, which was significantly lower than the glare ratings in all the light tower orientations for both the age groups. The only significant age difference was for the 4000-W metal halide light tower at a mounting height of 20 ft., where the older participants ($M = 0.8$, $SD = 0.8$) had a lower glare rating than younger participants ($M = 3.2$, $SD = 1.6$).

DISCUSSION

The goals of this paper were to evaluate the effects of mounting height, offset distance, and number of light towers in the work zone, of several commercially available portable light towers, on visual performance and discomfort glare ratings. Two major findings were evident based on the results of this study. First, an increase in the offset distance and mounting height resulted in an increase in the detection distance. Second, an increase in offset distances and mounting heights resulted in lower discomfort glare ratings.

Visual performance increased as mounting height and offset distance from the roadway increased, as evidenced by higher mean detection distances for the 4000-W balloon light tower at mounting heights of 20 ft. and 25 ft. for an offset distance of 20 ft. An increase in the offset distance from the roadway and the mounting height could result in lowering the veiling luminance, thereby reducing disability glare, resulting in increased visual performance. The result of higher mounting height in increasing visual performance is also supported by current recommendations on nighttime construction safety (15, 16). The results from this research also show that increasing the offset distance from the roadway or locating the portable light towers off the shoulder of the roadway could also increase visual performance (by increasing detection distances), especially for the higher wattage portable light towers like the 4000-W balloon light tower, which cannot be aimed (angle of the luminaire on the light tower cannot be altered).

For light towers that could be aimed like the 4000-W metal halide light tower, an increase in the height of the light tower, while keeping the angle between the beam axis and vertical constant, could also result in increasing the visual performance (as longer but not statistically significant detection distances were observed with increase in the height of the light tower). Overall, detection distances for the 4000-W balloon light tower at highest offset and mounting height, and were significantly longer than those at the highest mounting height for the 4000-W metal halide light tower. This result indicates that when located at the right distance from the roadway and mounting height, a balloon light tower with a similar wattage and lumen output to a metal halide light tower could result in higher visual performance. The results of this study also showed that light towers located closest to the roadway and at the lowest mounting height of 15 ft. had the lowest visual performance (lower detection distances) irrespective of the wattage and lumen output of the luminaires, as evidenced the lower mean detection distances of 800-W LED balloon light towers and both the 4000-W balloon and metal halide light towers at a mounting height of 15 ft. and an offset distance of 0 ft.

The discomfort glare rating analyses also showed that increasing the mounting height also resulted in lowering the discomfort glare ratings. This is evidenced by the significantly lower discomfort glare ratings of the 4000-W metal halide light tower at mounting heights of 20 and 25 ft. compared to the 800-W LED balloon light tower mounted at a height of 15 ft. The result of decreasing glare rating along with increasing mounting height and increasing offset distance was also observed in the 4000-W balloon light tower but these ratings were not statistically significant. The results from the discomfort glare ratings analysis reinforced the

results of the detection distance analysis for the portable light towers located closest to the roadway at the mounting height of 15 ft. as these orientations had the highest glare ratings and shortest detection distance.

The number of the light towers (800-W LED) did not affect the visual performance or the discomfort glare ratings as shown by the lack of significant post hoc pairwise comparisons between the one vs. two light tower configurations. Although, the discomfort glare ratings for the two-tower configuration were higher, it was not statistically significant. These results indicate the up to two light 800-W light towers could be mounted on work zone equipment without significantly affecting the drivers' visual performance or discomfort glare ratings.

Interestingly, there were no differences in recognition distances across the several light tower orientations. This result could be because the recognition of orientation of the worker in the currently study was dependent on visual acuity of the driver. Recognizing the orientation is dependent of detection of finer details like the direction of face, hands or shoes which is different from detecting the presence of a worker. Since all the participants for the study had a visual acuity of at least 20/40, statistical significant differences between recognition drivers could not be detected. However, more research is required to confirm this finding.

Age of the drivers' also did not significantly affect the drivers' visual performance, as evidenced by the lack of significant main. Age affected the discomfort glare ratings only for 4000-W metal halide light tower at a mounting height of 20ft, where younger drivers had a lower glare rating than older drivers.

The visual performance analyses also showed that in all the portable light tower conditions, detections and recognitions happened at distances beyond the range of the headlamps (greater than 100 m). However, the recognition distances in the of the control (no lighting) condition happened almost at the end of the range of the headlamps. The lack of lighting in the control condition could have resulted in the participants requiring the supplemental illumination provided by the headlamps.

The results of this study have several practical implications for nighttime work zones on limited access highways. The differences in the visual performance and discomfort glare ratings show that light tower orientation plays an important role in affecting a drivers' visibility in work zones. Light towers located closest to the roadway and at a mounting height of 15 ft. had the lowest detection distances and highest discomfort glare ratings, irrespective of the wattage and lumen output. Thus, efforts should be made to locate the light towers away from the roadway and mount them higher than 15 ft. The results from the study also show that mounting heights of at least 20 ft. can result in higher visual performance and lower discomfort glare. In addition to increasing the mounting height, increasing the offset distance of the portable light tower from the roadway, especially like the higher wattage (4000-W or greater) balloon light towers, can result in higher visual performance and lower discomfort glare ratings. Finally, the results also show that balloon light towers could offer better visual performance than conventional metal halide light towers of similar wattage and light output, only if they are mounted at a specified mounting height and offset distance from the roadway.

This work has a few limitations. First, there was only one worker in the work zone and no other equipment with flashing beacons was present. Second, there was no other traffic in the test area other than the experimental vehicles. These simplifications were made in the experimental design to eliminate the confounding effects that could arise due to the presence of more workers, vehicles, and traffic. Adding more workers and vehicles could potentially reduce the detection and recognition distances as drivers have to scan the work zone to perform the detection task.

These results represent drivers' visual performance and glare ratings under optimal conditions and performance decrements should be expected in real road conditions. Finally, these results are only applicable to work zones on limited access highways where there are no other sources of roadway lighting other than the portable light towers. Presence of roadway lighting could further increase the detection and recognition distances and also reduce the perceptions of glare (as a result of increase in the adaptation level of the drivers'). To address the above-mentioned limitations, future work should evaluate the effects of work zone equipment, traffic density, presence of roadway lighting, and other more complex scenarios to better understand driver visual performance and their perceptions of glare in work zones.

CONCLUSION

In conclusion, the orientation of portable light towers, more specifically, the mounting height and offset distance, play a critical role in affecting driver visual performance and discomfort glare. Portable light towers, irrespective of wattage and lumen output, at less than 20 ft. mounting height and closer to the roadway result in decreasing driver visual performance and increasing their discomfort glare. Based on the results of the study, portable light towers that cannot be aimed like the balloon light towers should be mounted at higher than 20 ft. and at distances greater than 10 ft. from the roadway. In order to increase visual performance, portable light towers, like the conventional metal halide light towers that can be aimed, should be mounted at a height of at least 20 ft. where their angle between the beam axis and driver line of sight is greater than or equal to 90 degrees and the angle between the beam axis and vertical is less than or equal to 60 degrees.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Rajaram Bhagavathula, Ronald B. Gibbons; data collection: Rajaram Bhagavathula; analysis and interpretation of results: Rajaram Bhagavathula, Ronald B. Gibbons; draft manuscript preparation: Rajaram Bhagavathula.

All authors reviewed the results and approved the final version of the manuscript.

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TABLE 1 List of Independent Variables and their Categorical Values

Independent Variables	Levels
Age	Older (60+ years) Younger (18–35 years)
Light tower type	4000-W metal halide (MH) 4000-W balloon 800-W balloon LED
Mounting height (only 4000-W MH and 4000-W balloon)	15 ft. 20 ft. 30 ft.
Offset distance (only 4000-W balloon)	0 ft. (in the lane) 10 ft. (in the shoulder) 20 ft. (off the shoulder)
Number of luminaires (only 800-W balloon LED)	1 2

TABLE 2 Merging of Light Tower Characteristics into a Single Categorical Variable

Light Tower Type	Offset Distance (ft.)	Mounting Height (ft.)	Angle to the Vertical (deg.)	Number of Luminaires	Light Tower Orientation
4000-W balloon	0	15	60		Ball_0_15
	10				Ball_10_15
	20				Ball_20_15
	0	20			Ball_0_20
	10				Ball_10_20
	20				Ball_20_20
	0	25			Ball_0_25
	10				Ball_10_25
	20				Ball_20_25
4000-W metal halide		15	60		MH_30_15
		20			MH_30_20
		25			MH_30_25
800-W balloon LED	0	15		1	Ball_LED_1
				2	Ball_LED_2
Control condition					NoLight

TABLE 3 Scale Used to Measure Discomfort Glare Rating

Description	Rating
No discomfort glare	0
Glare between non-existent and noticeable	1
Glare noticeable	2
Glare between noticeable and disagreeable	3
Glare disagreeable	4
Glare between disagreeable and intolerable	5
Glare intolerable	6



FIGURE 1 Portable light towers used in study.

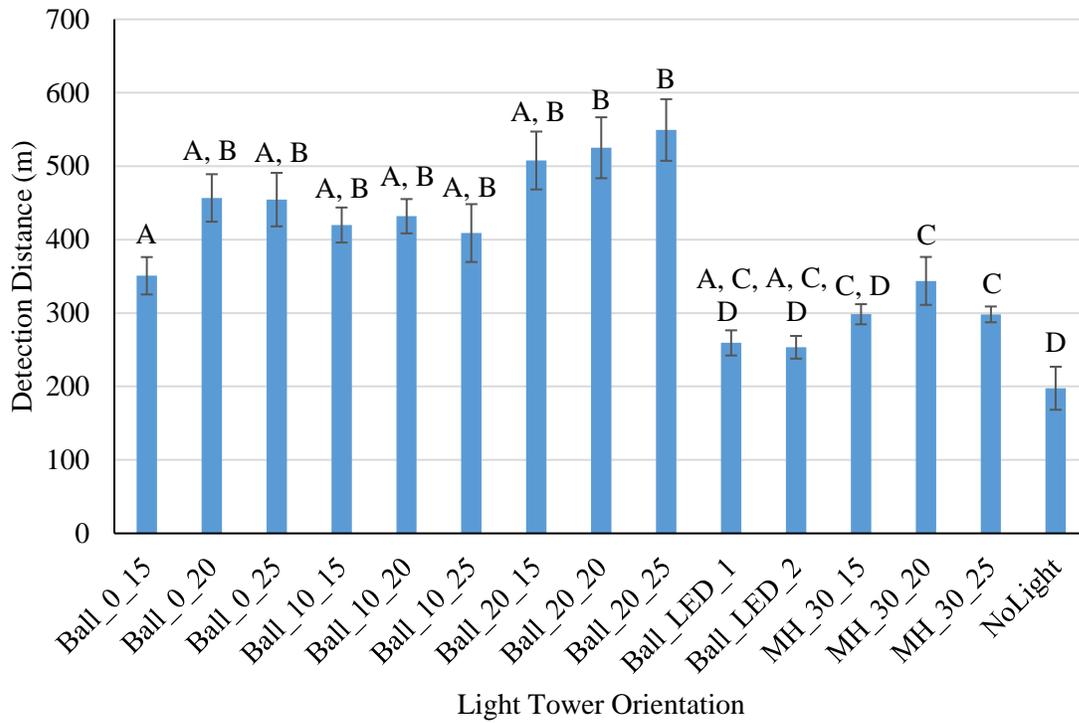


FIGURE 2 Effect of light tower orientation on detection distance. Values are means of detection distances and error bars reflect standard errors. Uppercase letters indicate significant ($p < 0.05$) post hoc groupings (from pairwise comparisons).

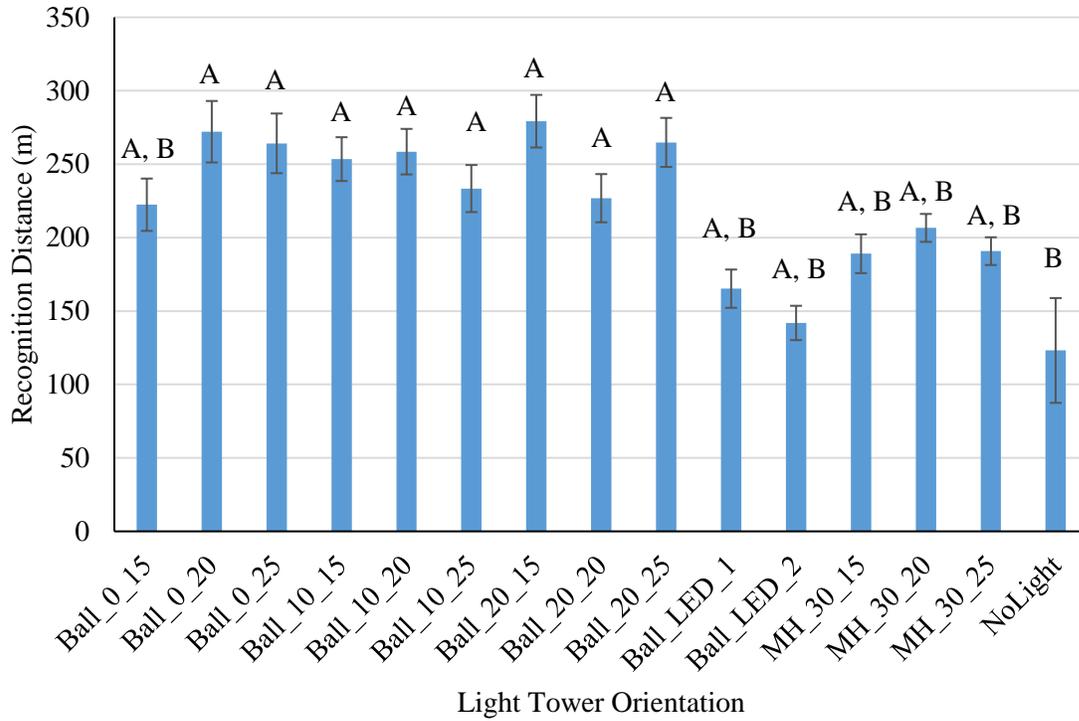


FIGURE 3 Effect of light tower orientation on recognition distance. Values are means of recognition distances and error bars reflect standard errors. Uppercase letters indicate significant ($p < 0.05$) post hoc groupings (from pairwise comparisons).

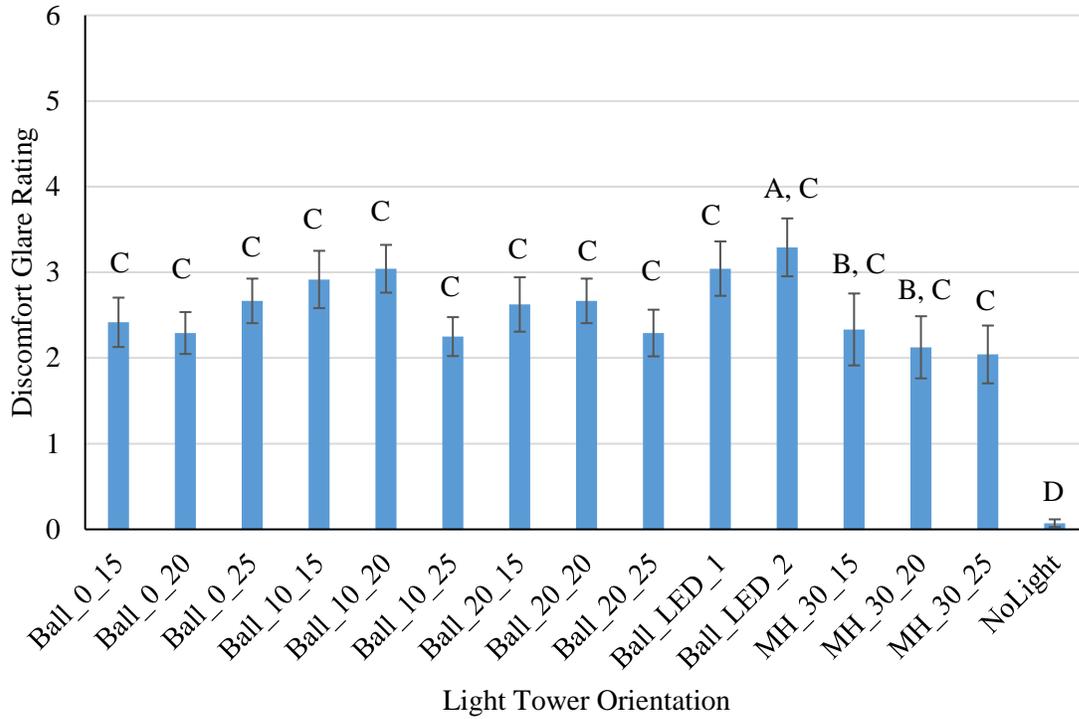


FIGURE 4 Effect of light tower orientation on discomfort glare rating. Values are means of discomfort glare ratings and error bars reflect standard errors. Uppercase letters indicate significant ($p < 0.05$) post hoc groupings (from pairwise comparisons).