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INVESTIGATION OF FLASHING AND INTENSITY CHARACTERISTICS FOR VEHICLE-MOUNTED WARNING BEACONS

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Abstract

Reducing the potential for crashes involving front line service workers and passing vehicles is important in increasing worker safety in work zones and similar locations. Flashing yellow warning beacons are often used to protect, delineate, and provide visual information to vehicles within and approaching work zones. Field studies of simulated workers (with and without reflective vests) present outside trucks were simulated to evaluate the effects of different warning beacon intensities and flash frequencies. Interactions between intensity and flash frequency were also analyzed. This study determined that intensities of 25/2.5 cd and 150/15 cd (peak/trough intensity) provided the longest detection distances of the simulated worker. Mean detection distances in response to a flash frequency of 1 Hz were not statistically different from those in response to 4 Hz flashing. Simulated workers wearing reflective vests were seen the furthest distances away from the trucks for all combinations of intensity and flash frequency.

Keywords

Warning beacons; Disability glare; Safety apparel; Flash frequency

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1. Introduction and Background

Vehicles in work zones and at other locations where service workers are present near the roadside use flashing yellow warning beacons. These lights are designed to attract the attention of drivers and, by extension, to the workers who may be adjacent to the lights (and who are at greater risk of work-related injury or fatality than other road workers [NIOSH, 2014]). While barricades and other physical elements are often present in work zones in part to help protect workers, many roadside incidents (e.g., utility repairs, fallen tree limbs, or traffic accidents) do not allow sufficient time to set up such barriers, leaving warning beacons as a primary line of defense against approaching vehicles.

For these reasons, it is important for warning beacons to serve multiple purposes: to attract the attention of oncoming drivers, convey information about the nature of the situation that a driver is about to encounter, and to communicate the appropriate course of action that drivers should take as they navigate through the location. While serving these purposes, warning beacons should not provide distraction or glare to oncoming drivers, which could detract from their ability to see workers and hazards, or to drive safely through the area without incident.

Existing standards for warning beacons (SAE, 2007, 2008) stipulate minimum characteristics such as the peak intensity and the optical power, presumably to ensure detection. These standards do not stipulate different intensity minima for daytime versus nighttime conditions, nor do they specify maximum values to ensure against glare or distraction. There is some reason to think that limiting intensity during the nighttime would be prudent. For example, Rea and Bullough (2016) measured response times to the onset of a simulated flashing warning light; under worst-case conditions (daytime ambient light, off-axis detection, and older observers) the peak intensity needed to be 750 cd in order to result in asymptotic response times. Under nighttime conditions, a peak intensity of 200 cd resulted in asymptotic response times, and higher-intensity lights were not detected more quickly. In comparison, Flannagan et al. (2008) reported that a peak intensity of 1000 to 2000 cd was necessary during daytime conditions when the warning beacon was located about 45^{o} from the line of sight. This peripheral angle was substantially larger than those studied by Rea and Bullough (2016), who used peripheral angles up to 5^{o} on the bases that the principal viewing angles for warning beacons were no larger than 5^{o} (Howard and Finch, 1960), and drivers' gaze locations were rarely more than 5^{o} from the road ahead (Mourant and Rockwell, 1970).

For a visual task in which observers judged the visibility of a low-contrast object adjacent to the warning beacon, ratings of visibility were not substantially affected during simulated nighttime viewing conditions until the peak intensity reached 2000 cd (Rea and Bullough, 2016). Ratings of visibility may not always be correlated with visual performance, however. Bullough and Rea (2016) conducted visual performance analyses of the visibility of workers or other hazards located adjacent to warning beacons; a peak intensity of 750 cd worsened visual performance relative to a peak intensity of only 150 cd. Further, in a field study of work zone flashing light intensity (Rea et al., in press), drivers approaching a flashing light with a peak intensity of 750 cd rated the light as substantially more uncomfortable than a light having a lower peak intensity.

The present study was conducted, in part, to validate the visual performance analyses from Bullough and Rea (2016) and to assess the impact of several additional factors on the ability of an approaching driver to detect workers in a roadside work zone and other work locations. These factors include warning beacon flash frequency and whether the worker is wearing high-visibility reflective safety clothing. Flash frequencies were investigated because previous research (Chan and Ng, 2009; Turner et al., 2014) indicated that higher flash frequencies are perceived as more urgent or dangerous. Present warning beacon standards permit frequencies between 1 and 4 Hz (SAE, 2007, 2008). The presence of reflective clothing was investigated because this factor increases the contrast of a worker, but workers do not always wear reflective clothing (Lultschik and Moore, 2016). The primary measure used in this study that is related to visual performance is the distance at which a person can determine that a target (simulating a worker) is present, while approaching a vehicle equipped with warning beacons.

2. Method

2.1. Location

The study was conducted at Penn State's Thomas D. Larson Pennsylvania Transportation Institute test track, shown in Figure 1. The test track is a one mile oval, consisting of two curves and two tangent sections. The experiment was performed only on the two tangent sections of the test track. The location of the trucks on the test track are indicated in Figure 1 with circles. No vehicles, other than the ones involved in the study, were on the test track during the time the experiment was conducted. The study occurred at night (no fixed lighting). No adverse weather conditions, such as rain, snow, or high wind velocities, were present during the experiment. The surrounding of the test track consisted of open fields, buildings associated with the test track, and trees.

2.2. Research Participants

Fourteen participants completed the study. All participants were required to have a valid United States (U.S.) driver's license, speak English, and be at least 18 years old; they were not tested for visual function. Half of the participants were female and the other half were male. An attempt was made to include over-representation of older drivers. Two participants were between 18 and 30 years old; two participants were 31 to 40 years old; three participants were 41 and 50 years old; two participants were 51 to 60 years old; five participants were older than 60.

2.3. Equipment

The vehicle driven by the research participants was a 2012 Chevrolet Malibu instrumented with a Race Technology DL1-Club data collection system, including a Global Positioning System (GPS) and a data recorder, which logged all data on a Secure Digital (SD) memory card. The data acquisition system collected acceleration, deceleration, distance, and speed information during the experiment at a frequency of 100 Hz. The data were then transferred to a laptop computer for analysis.

In addition to the test vehicle, two stationary trucks, one 2000 Ford F350 with a stake-body and one 2000 Ford F450 with a dump bed, positioned on opposite sides of the test track, were each instrumented with two programmable warning beacon lights. The lights were mounted on both trucks at the same height above the ground and the same width apart. The tail and marker lights on both trucks were masked off, since they were located in different places on each truck. To ensure that the trucks were readily seen when the warning beacons were extinguished, red and white reflective tape was applied to the rear of both trucks. The tape was applied to each such that the width and height above the ground was the same, resulting in a similar visual signature.

The warning beacon lights utilized in the study were custom made. They were designed so that the flash intensity levels and temporal profiles were remotely programmable through a computer interface, which was kept in the truck on which the lights were mounted. The lights consisted of several main components: the microcontroller, radio communication link, light source and driver, GPS receiver, and the housing.

The microcontroller used was a Texas Instruments MSP430 variant and served as the “brain” of the light unit. The microcontroller utilized the GPS receiver as a precise time reference to control the temporal profile of each flash pattern. The temporal profile was defined by setting the flash period, duration of the high-intensity portion of the flash, and the duration of the low-intensity portion of the flash (which is equal to the difference between the period and the high-intensity duration). All configurations in the study had equal high- and low-intensity durations resulting in a duty cycle of 50%. Additionally, a delay from the standard “zero time” when the flash pattern began could be specified if flash synchronization was not desired (e.g., for randomly flashing profiles or non-synchronous configurations). This optional parameter was not used in the present study. The microcontroller received all of these parameters from a remote computer interface through the radio communication link, a 900 MHz XBee radio set.

The light source consisted of a single high-power light emitting diode (LED) and a custom designed and fabricated driver. The LED utilized was a phosphor-converted amber LED, and was mounted to an aluminum support, which also provided heat sinking for the LED. The driver was custom designed to provide constant current power to the LED to avoid flickering. The drive current level was set by the microcontroller to satisfy the intensity levels received from the remote computer interface. A commercially available barricade light housing, with its amber lens, was used to contain the warning light system. Calibration data were stored on the microprocessor to ensure that the appropriate drive current was provided to the LED so that the entire light assembly would produce the desired intensity level. The rise and decay times of the LED source were nearly instantaneous.

The remote computer interface consisted of a laptop computer running National Instruments LabView software. A custom-written LabView program was used to program the warning beacons with the appropriate flash configuration and displayed the simulated worker configuration instruction for the experimenter. The configurations were programmed according to predefined randomized order files.

To simulate workers present outside the trucks, four cardboard, life-sized cutouts of workers, shown in Figure 2, were used. The “workers” were spray painted with matte gray paint to simulate dark clothing worn by many pedestrians (Bhise et al., 1977). Additionally, two of the “workers” wore reflective vests, while the other two did not. The vests resembled in-service vests that were in new condition.

2.4. Variables

The independent variables used in the study were warning beacon flash frequency (1 Hz and 4 Hz), peak/trough intensity (0 cd [off], 25/2.5 cd, 150/15 cd, and 700/70 cd), presence of worker (none present, present with a vest, and present without a vest), and track side (denoted A and B). The two flash frequencies studied correspond to the minimum and maximum values allowed by present standards (SAE, 2007, 2008); frequencies higher than 4 Hz might present issues related to photosensitive epilepsy (Harding and Jeavons, 1994). For the intensity variable, the first and last values describe the highest (peak) and lowest (trough) values, respectively, as the intensities do not completely turn off. The two track sides had different flashing configurations according to one of two predetermined randomized orders (participants did not view the same flashing configuration consecutively). The two beacons in each configuration flashed simultaneously. The dependent variable was detection distance (i.e., the distance from the truck that either a worker was detected or, in some cases, the participant recognized that no worker was present). Although the simulated workers in this study were stationary, the detection of moving targets has been found to exhibit the same relative trends as predictions based on stationary targets (Akashi et al., 2007). This resulted in 21 configurations (see Table 1). Every participant saw each configuration two times on opposite sides on the test track.

2.5. Procedure

The experimental set-up included mounting two warning beacons on the back of each of the two trucks, shown in Figure 3 and Figure 4, and starting the two computers that controlled the various warning beacon lighting conditions. Once the trucks were equipped with the instruments, they were driven by two study team members to opposite sides of the track on the tangent sections.

The research participants were met by a study team member in the test track parking lot and escorted to a conference room. The participant was then given a consent form approved by the Institutional Review Board (IRB) of Penn State and of Rensselaer Polytechnic Institute, instructed to read it, and ask any questions, if applicable. The experimental procedure was then reviewed, which included instructions for the research participant. For this experiment, participants were told that they would be driving around the test track at 30 mph with their low-beam headlights switched on, and that during each lap they would pass two stationary trucks. The participants were instructed that there might or might not be a cardboard cutout of a “construction worker” present next to the truck, and that sometimes the worker would have a reflective vest on, sometimes the worker will not, and sometimes there would not be any worker at all. (Figure 3 shows the cardboard cutout of the worker not wearing a vest next to the truck, while Figure 4 shows the cardboard cutout of the worker wearing a vest next to the truck.) The workers were positioned in the same location by the driver doors of the trucks, which was approximately in line with the warning lights.

The participants were then instructed to look for a worker as they drove toward the truck and, if they were certain that they identified the worker, to verbally let the team member know and proceed to pass the truck safely. Research participants were also instructed to verbally announce if they were certain a worker was not present. Finally, the participants were also told that this would be repeated for 21 laps around the test track and that there would be one practice lap before starting the experiment, in order to become familiar with driving the vehicle and familiar with the appearance of the trucks and workers. The participant drove the vehicle in order to simulate realistic conditions where a driver of a vehicle would encounter such a situation and be required to maneuver through the location.

The participant was then escorted to the test vehicle and instructed to make any necessary seat or mirror adjustments. Because of the brightness of the warning beacons and of the headlight illumination on the track surface ahead of the test vehicle, no special dark adaptation period was used. The vehicle data collection system was started, and the research participant sat in the driver’s seat with a team member in the passenger’s seat. The participant proceeded to drive around the test track for a total of 22 laps (1 test lap and 21 experimental laps). When the participant identified whether or not a worker was present, the study team member in the vehicle would press and hold a button that was attached to the data recorder, and the button was released when the vehicle was in line with the truck. This procedure measured the distance from the truck that was required to detect the presence of absence of the worker. The same study team member pushed the button each time in an effort to control for potential errors in reaction time that could arise from different study team members pushing the button. After the vehicle passed each truck, the study team member in the truck would set up the next lighting and worker condition.

Each participant saw 42 test conditions (21 configurations were seen twice), and the experiment was then concluded. The entire experimental procedure took approximately one hour to complete. The participants were paid $50.00 for their time.

3. Analysis and Results

The data for each participant were collected via an SD memory card and transferred to the study’s laptop after each participant completed the experiment. The data were compatible with the software Race Technology v8.5. All data were manually extracted from the software and compiled in a Microsoft Excel document. Minitab 17.3 was used to perform all statistical analyses shown in this section of the paper. In order to assess whether there might be any learning or fatigue effects over the duration of the experiment, the mean detection distances for each of the 21 laps completed by all subjects were determined and the slope of the best-fitting linear function was not statistically significant ($p < 0.05$). This indicates that there was little overall change in detection distances as the experimental sessions progressed.

3.1. Configuration Effect

3.1.1. Descriptive Statistics—The means for the distance (in feet) at which each configuration was identified are listed in Table 1 and illustrated in Figure 5. There were no misses or false positives in performing the study--all configurations were correctly identified by the participants. The 95 percent confidence interval was computed for each configuration by multiplying the standard error of each condition by 1.96, and the error bars with the calculated 95 percent confidence interval are shown in Figure 5 around the mean detection distance for each configuration. In Figure 5, means for conditions in which the error bars overlap are not expected to be reliably different from each other. Because all 21 configurations were observed twice (once on each side of the track), a statistical test to confirm that there were not any differential effects resulting from the side of the test track in which the configurations were displayed was completed. The results of this test indicated that the side of the track was not statistically significant ($F = 0.55$, $p = 0.458$) – the mean detection distance across all configurations was 407 ft when observing all 21 configurations the first time (referred to as side 1 of the test track) and 427 ft when observing the same, but randomized set of 21 configurations a second time (referred to as side 2 of the test track).

3.1.2. Inferential Statistics—A multi-factor analysis of variance (ANOVA) was conducted including the main effects of silhouette, intensity, and flash frequency and the interaction effects of silhouette and intensity to identify the statistical significance of the three factors and the interaction term. The multi-factor ANOVA revealed that the intensity ($F = 8.03$, $p < 0.001$) and silhouette ($F = 1760.68$, $p < 0.001$) had statistically significant effects on the detection distance. The interaction between silhouette and intensity ($F = 2.91$, $p = 0.008$) also had a statistically significant effect on detection distance. The flash frequency ($F = 2.78$, $p = 0.096$) did not have a statistically significant effect on the detection distance in the present study based on setting the probability of type I error at 0.05. Additionally, the adjusted coefficient of determination for the model was 86.9 percent, indicating that the model with the main effects and interaction term fit the data well.

The mean values for the intensities, silhouette types, and flash frequencies were used to draw inferences about differences in treatment levels for these main effects. An intensity of 25/2.5 cd had the longest detection distance (mean of 442 ft) among the intensities included in the present study; however, an intensity of 25/2.5 cd was not significantly different from an intensity of 150/15 cd (mean of 422 ft). The highest intensity condition, 700/70 cd (mean of 380 ft), was significantly worse ($t = -4.34$, $p < 0.001$) than the other three intensities (a mean difference between the best and worst condition being 62 ft). When evaluating the mean detection distances for the silhouette types, the worker wearing a vest had significantly longer ($t = 57.71$, $p < 0.001$) detection distances (mean of 834 ft) than the other two conditions, worker without a vest (mean of 291 ft) and no worker (mean of 124 ft). All research participants correctly identified instances when no worker was present and, as expected, this detection distance (mean of 124 ft) was statistically significantly shorter ($t = -40.81$, $p < 0.001$) than the other two target conditions. Additionally, while a flash frequency of 1 Hz produced the longest detection distance (mean of 425 ft), this flash frequency did not differ statistically from a flash frequency of 4 Hz (mean of 408 ft) when setting the probability of type I error equal to 0.05.

A plot for the interaction effects of intensity and silhouette type is shown in Figure 6. The silhouette type includes a silhouette with and without a vest and the no silhouette condition. The error bars with the 95 percent confidence interval for the detection distance for all intensities were calculated and included in Figure 6 around the mean detection distances.

The interaction plot in Figure 6 shows there are significant differences in detection distance between a silhouette with a vest and a silhouette without a vest. An intensity of 700/70 cd provided the shortest detection distance for both a silhouette with and without a vest, although the difference in detection distance was significant only for the silhouette without a vest; with the vest present, the intensity of the warning lights did not significantly affect the detection distance. Overall, the detection distance depended upon the peak intensity much more strongly without the reflective vest, and was less sensitive to the peak intensity when the vest was present.

Regarding the conditions without a reflective vest, there were not statistically significant differences in the mean detection distance between the 0 cd conditions and the 25/2.5 cd and 150/15 cd conditions, but the 700/70 cd condition was statistically significantly shorter ($t = 5.0247$, $p < 0.001$) than the 0 cd condition. This suggests that intensities as high as 150/15 cd will not strongly decrease detection distances of workers not wearing reflective clothing, but increasing to 700/70 cd can negatively impact drivers' ability to see these workers.

4. Discussion and Conclusion

The primary objective of this research was to assess the impacts of intensity and flash frequency of truck-mounted warning beacons that allow drivers to identify front line service workers present outside of vehicles sooner. In doing so, the goal was to provide information that would increase safety and reduce the number of crashes involving front line service workers and passing vehicles. This study allowed workers present outside trucks to be simulated and to identify the ideal combinations of intensity and flash frequency of warning beacons. This optimum combination among those in this study was determined based on the distance the workers were seen by the participants. Based on the results, intensities up to 150/15 cd would not be expected to have substantial impacts on the detection of workers at night compared to no warning beacons, either with or without reflective vests. Of course, workers are required to wear reflective apparel in work zones, and in one survey of workers, about 98% reported doing so (Ferreira-Diaz et al., 2009). However, a review of crashes occurring in work zones (Arditi et al., 2005) revealed that in 21% of those cases, either the lack of reflective apparel or poor performance of the apparel was a contributing factor in the crash. This suggests that workers who do not wear reflective apparel or whose apparel is not functioning properly can be at higher risk than others in work zones.

It is important to recognize that the optimum combination of intensity and flash frequency in this study would only be applicable to nighttime conditions. During the daytime, higher intensities would not be expected to have the same impact on detection distances of workers either with or without vests because of the higher ambient light levels.

Based on this nighttime study, workers wearing reflective vests were seen the furthest distance away from the trucks for all combinations of intensity and flash frequency, and other studies have yielded similar findings for both daytime and nighttime conditions (Sayer and Mefford, 2004; Sayer and Buonarosa, 2008). Intensities of 25/2.5 cd and 150/15 cd were determined to provide longer detection distances than 700/70 cd. While a flash frequency of 1 Hz resulted in the longest detection distance, this was not statistically different from a flash frequency of 4 Hz. The combination of a reflective vest, intensities of 25/2.5 or 150/15 cd, and flash frequencies of 1 Hz or 4 Hz all permitted research participants to detect workers from distances further away than other combinations tested in the experiment. Using truck-mounted warning beacon lights with these combinations could allow front line service workers to be detected sooner by passing vehicles than the other combinations investigated, thus potentially increasing their safety and reducing their risk of being involved in crashes.

Although the conditions where no flashing beacons were present resulted in similar detection distances to those of combinations with the highest intensity and flash frequency, it should be noted that flashing warning beacons are used for the purpose of being detected by approaching drivers. Reflections and the vehicle headlights make the worker visible to the participant. Additionally, the study was conducted with minimal visual clutter, which could be representative of emergency situations and small work zones. However, in large work zones or urban areas where lighting (including additional warning beacons as well as other sources of light) is more prevalent, detection distances might differ, and this could be an area for future study.

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Highlights

- Simulated workers wearing reflective vests were seen at the furthest distances for all combinations of intensity and flash frequency.
- Warning beacon intensities of 25/2.5 cd and 150/15 cd resulted in the longest worker detection distances.
- A flash frequency of 1 Hz resulted in similar detection distances to simulated workers as 4 Hz.

Figure 1.
Penn State's Thomas D. Larson Pennsylvania Transportation Institute Test Track.

Figure 2.
Cardboard Cut-outs Used to Simulate Workers.

Figure 3.
Worker without Vest Next to Truck.

Figure 4.
Worker with Vest Next to Truck.

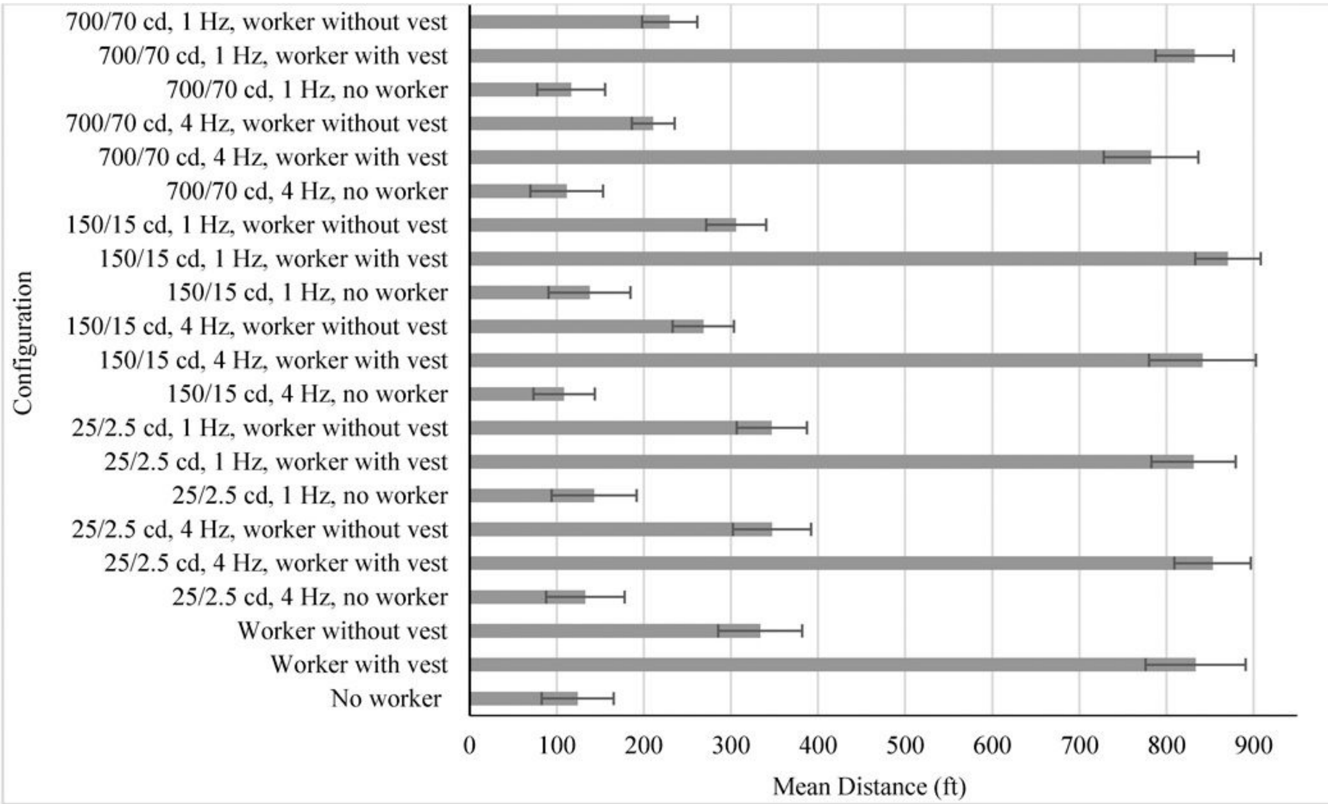

Figure 5.
Lighting and Worker Conditions Means and Error Bars (95% confidence interval).

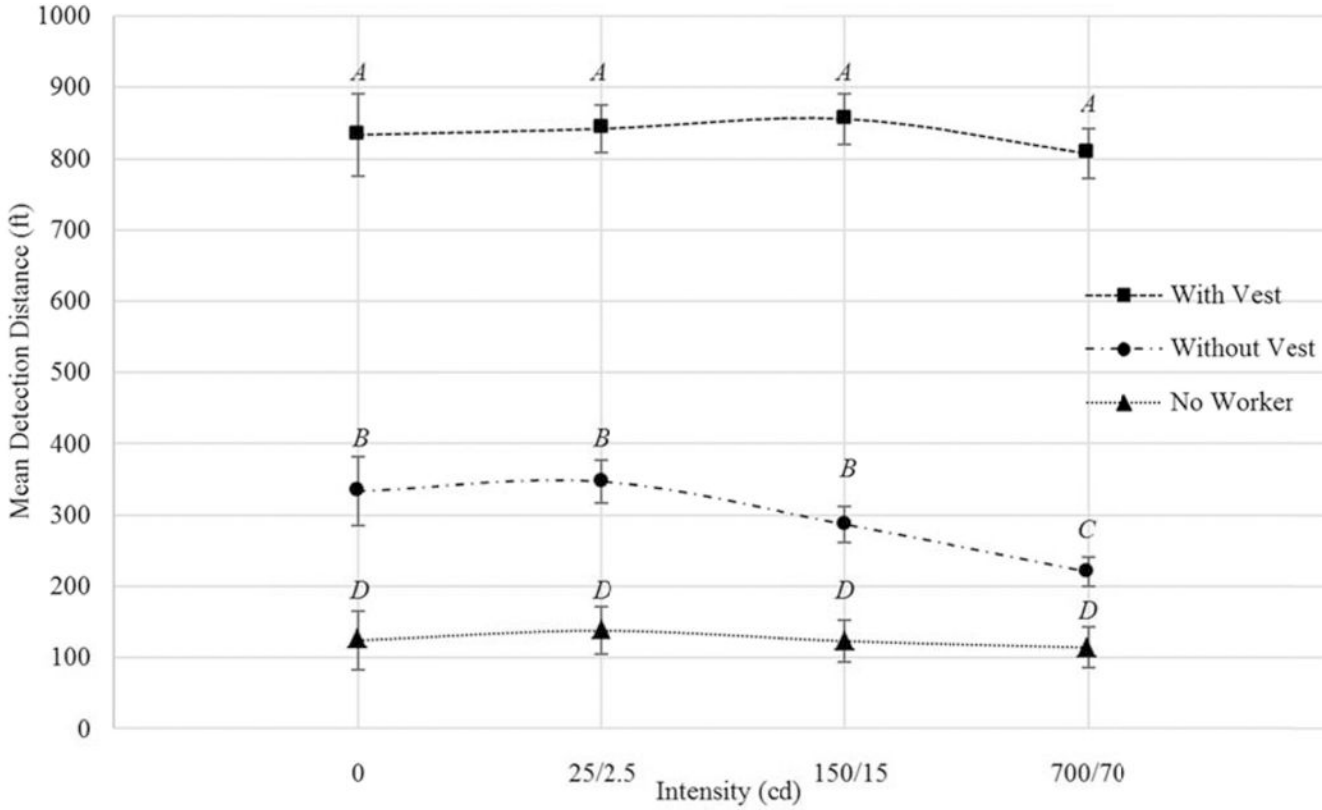

Figure 6.

Interaction Plot Between Silhouette and Intensity on Detection Distance. Different Letters Over Data Points Indicate Statistically Significant Differences Between Mean Values.

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Table 1.

Lighting and Worker Conditions. Table Entries Correspond to the Mean Detection Distance (and 95% Confidence Interval) for Each Condition.

Silhouette Condition	No Lights (*0 cd*)	Flash Frequency					
		1 Hz			*4 Hz*		
		Intensity			Intensity		
		25/2.5 cd	*150/15 cd*	*700/70 cd*	*25/2.5 cd*	*150/15 cd*	*700/70 cd*
No silhouette	124 ft. (83–166)	143 ft. (94–192)	138 ft. (91–185)	117 ft. (78–156)	133 ft. (88–178)	108 ft. (73–144)	112 ft. (70–153)
Silhouette with vest	834 ft. (776–891)	831 ft. (783–880)	871 ft. (833–908)	832 ft. (787–877)	853 ft. (776–891)	841 ft. (780–903)	782 ft. (728–836)
Silhouette without vest	334 ft. (286–382)	347 ft. (307–387)	306 ft. (272–340)	230 ft. (198–262)	347 ft. (302–392)	268 ft. (233–304)	211 ft. (186–235)