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A Comparative Analysis of Electroluminescent and Retrorefelective Materials as Nighttime Pedestrian Conspicuity Aids

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A COMPARATIVE ANALYSIS OF ELECTROLUMINESCENT AND RETROREFELECTIVE MATERIALS AS NIGHTTIME PEDESTRIAN CONSPICUITY AIDS

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ABSTRACT

Recent literature suggests that retroreflective materials, when configured in a biological motion pattern, make vulnerable road users (such as pedestrians) more conspicuous to drivers at night. However, retroreflective elements in clothing can be effective only when a light source (e.g., automobile headlamps) illuminates the material in such a way as to allow the material to reflect sufficient light back to the eyes of the driver. Thus, retroreflective materials are not useful for pedestrians who are positioned outside the beam pattern of an approaching vehicle's headlamps. Electroluminescent materials, flexible light sources that can be attached to clothing, have the potential to enhance conspicuity in these conditions. This project investigated the conspicuity benefits of adding electroluminescent material to clothing that contains retroreflective elements. Using an open-road course at night, the current work compared the distances at which observers responded to pedestrians wearing one of two different kinds of high-visibility garments, who were at one of three different lateral positions relative to the vehicle's path. The results show that a garment containing both electroluminescent and retroreflective materials yields longer response distances than garments containing only retroreflective material, particularly when the test pedestrian is positioned farther outside of the area illuminated by an automobile's headlamps. These findings suggest electroluminescent materials can be especially useful to enhance the conspicuity of pedestrians who are outside a vehicle's headlamp beam.

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INTRODUCTION

Worldwide an estimated 1.2 million people die in traffic-related crashes per year, and vulnerable road users, such as pedestrians, cyclists and other non-motorists, account for nearly half of these fatalities (World Health Organization, 2009). Research has shown that pedestrians in particular are most vulnerable at night, with 70% of pedestrian fatalities in the United States occurring during nighttime hours (NHTSA, 2014). This suggests that pedestrians are more likely to die in nighttime traffic crashes than daytime crashes, despite fewer people using roadways at night compared to daytime hours. One reason for this finding is the lack of natural ambient illumination and reduced pedestrian conspicuity during nighttime hours (Sivak, Schoettle, & Tsimhoni, 2007). This is true even when factors such as alcohol consumption, driver fatigue, and time of day are held constant (Owens & Sivak, Differentiation of visibility and alcohol as contributors to twilight road fatalities., 1996; Sullivan & Flannagan, 2002). Rather unsurprisingly, darkness is detrimental to pedestrian safety in a roadway environment.

Finding ways to make pedestrians and other vulnerable road users more conspicuous to drivers at night has been a topic of interest as early as the 1940's (e.g., Ferguson, 1944), and since then transportation safety researchers have contributed a great deal to our understanding of this problem. Hazlett & Allen (1968) found that simulated pedestrians covered in white fabric were visible at farther distances than black- or gray-clad pedestrians, and pedestrians with reflective elements yielded recognition distances even farther than all three of these. Other early studies found that the distance at which a dark-clad pedestrian is visible to a driver is often less than the distance needed for a driver to avoid a collision with this pedestrian (Allen, Hazlett, Tacker, & Graham, 1970). More recent studies have shown that the use of high-visibility elements in clothing, e.g., retroreflective materials found in safety vests and road signs, have been beneficial in making pedestrians (e.g., Shinar, 1984; Luoma, Schumann, & Traube, 1996; Balk, et al., 2008), bicyclists (e.g., Wood, et al., 2012), and roadway workers (e.g., Sayer & Mefford, 2004a; Wood, et al., 2011) more conspicuous to drivers.

Retroreflective surfaces appear bright at night because the light that illuminates a retroreflective object is reflected back towards its source. Most objects in the roadway environment are diffuse reflectors; that is, illumination scatters off the object in many different directions. This means that when a source illuminates a diffuse object from one particular angle, the object appears about as bright as it would if it were illuminated from any other angle. As seen in Figure 1 below, the angle between the 'beam' of light from a source and the angle perpendicular to the object's surface is called the entrance angle. The observation angle, on the other hand, represents the angle between the light source and the observer's eye. In the driving environment, the observation angle is created by the vertical separation between the driver's eyes and their vehicle's headlamps. Observation angle increases as a driver approaches a retroreflective stimulus.

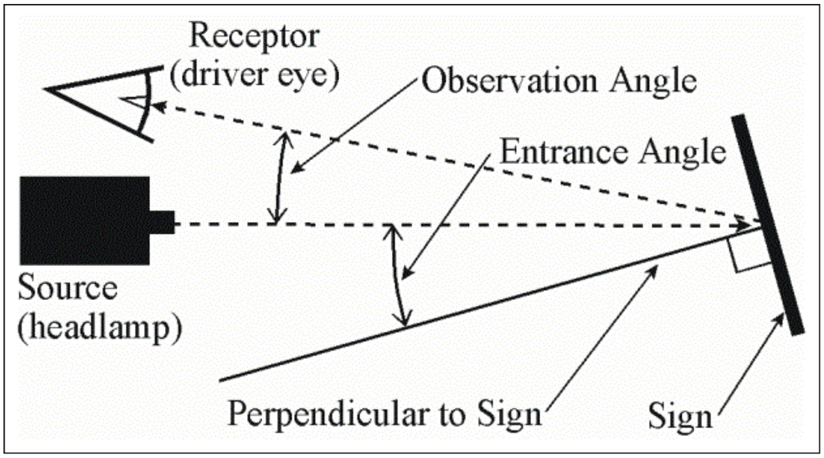


Figure 1: Entrance and observation angles in relation to a flat target surface. Image source: http://safety.fhwa.dot.gov

Retroreflective materials, unlike common diffuse reflectors, are carefully engineered to reflect light back toward its source. This means that, in a situation where a retroreflective object is being illuminated by a vehicle's headlights, this light is reflected back toward the vehicle. The two most prominent types of retroreflective materials found in roadway environments have surfaces that contain either tiny spherical glass beads or arrays of microscopic prisms ('corner-cubes') (see Figure 2). These types of materials are often used on highway signage, airport runways, or bicycle pedals because in low illumination conditions they enhance the luminance and contrast of objects relative to surrounding non-retroreflective surfaces (Olson & Farber, 2003). Although a similar effect on conspicuity could be achieved by simply adding more fixed lighting structures on roadways (Retting, Ferguson, & McCartt, 2003), the use of retroreflectors allows important objects in these environments to be more conspicuous at a lower cost to power and long-term maintenance.

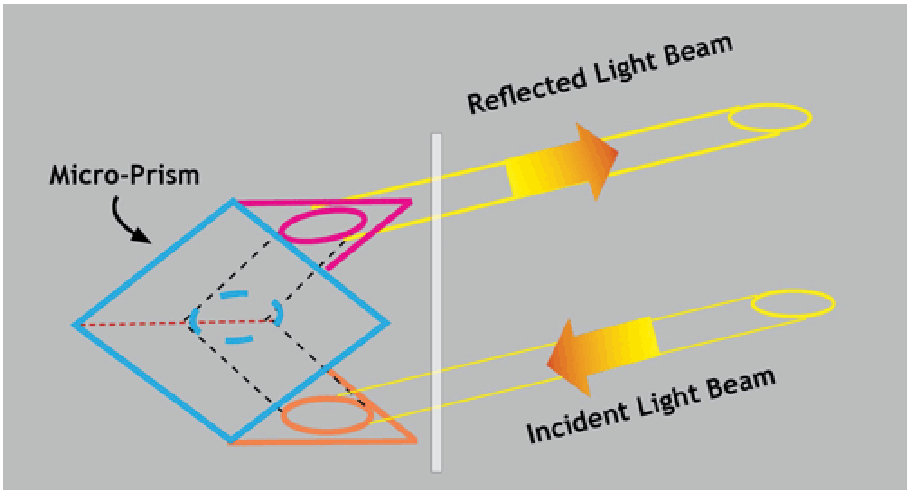


Figure 2: Microscopic detail of light entering and reflecting off the prisms in a retroreflective surface. Image source: http://www.safetysigns-mn.com

Retroreflective materials are especially useful when illuminated by a car's headlights at night because their reflective surface directs light back toward the driver, thereby creating contrast (Benz, Pike, Kuchangi, & Brackett, 2009; 3M Personal Safety Division, 2013). This effect is most prominent when a retroreflective surface is being illuminated directly; that is, the entrance angle of illumination is 0º. This is because an object's coefficient of reflectance (R_A, measured in cd/lux/m^2) depends on the ratio of reflected light reaching an observer's eye to the amount of illumination at the object's surface, per square meter (m^2) of surface area (Rennilson, 1982; Greene & Filko, 2010). Under ideal conditions, retroreflective surfaces can be detected by approaching drivers from long distances—up to 350 meters when used as roadway markings or 220 meters when worn by a pedestrian (e.g., Zwahlen & Schnell, 1999; Wood, Tyrrell, & Carberry, 2005). However, the R_A of a retroreflective object is sensitive to changes in the entrance and observation angles, even though the R_A of retroreflective materials varies by manufacturer and the application for which the material is designed. In general, as entrance angle increases (e.g., due to a retroreflective sign being poorly oriented and not facing approaching drivers) and as observation angle increases, the lower the luminance will be from the driver's eye position.

Retroreflective materials are particularly effective as pedestrian conspicuity aids when they are configured on the body in such a way that facilitates the perception of biological motion (e.g., Owens, Antonoff, & Francis, 1994; Luoma, Schumann, & Traube, 1996; Tyrrell, et al., 2009). Biological motion (or biomotion) describes a pattern of body movement that creates a visual stimulus uniquely identifiable as a biological organism in motion (Johansson, 1973). In other words, the complex pattern of body movement made by a locomoting human is unlike any other movement pattern found in nature, and the human visual system is exceptionally sensitive to these patterns of form and motion. This is still true even when an image of a locomoting human is broken down into its simplest visual components—single points of light representing the major appendages and joints of a body in motion (i.e., head, shoulders, elbows, wrists, waist, knees, and ankles). Research has shown that these locations of the body, when marked with retroreflective material, are the strongest indicators of both human figure and human motion to a distant observer.

Gunnar Johansson pioneered research on the perception of human biological motion in the 1970s (Mass, Johansson, Janson, & Runeson, 1971; Johansson, 1975). Research in this area has since broadened to explore situations where this perceptual phenomenon is most effective. Humans have been shown to be highly sensitive to perceiving and identifying various activities of a figure in a 'point-light' display, including walking, jogging, climbing, and dancing (Mass et al., 1971; Johansson, 1973). Surprisingly, even certain social characteristics of a figure are perceptible in point-light displays, such as the figure's identity as a friend or a stranger (Loula, Prasad, Harber, & Shiffrar, 2005), their sex (Kozlowski & Cutting, 1977; Barclay, Cutting & Kozlowski, 1978), their sexual orientation (Ambady, Hallahan & Conner, 1999), and even their intent to deceive (Sebanz & Shiffrar, 2009). It appears that the perception of biological motion is strongly aided by contextual information related to the movement of point-light figures, and it is this type of visual information that aids drivers in recognizing pedestrians in a nighttime environment.

Open- and closed-road experiments have confirmed that placing retroreflective markings only on the ankles and wrists (or only the ankles and elbows) can be sufficient to enhance conspicuity dramatically (e.g., Owens, Antonoff, & Francis, 1994; Luoma, et al., 1996; Balk, et al., 2008). Research has also indicated that in certain conditions a 'full' biological motion configuration (with retroreflective markings on all major joints of the body) offers no significant advantage over a 'simpler' biomotion clothing design (with retroreflective markers in fewer locations on the body), though a 'simple' configuration can still offer a conspicuity advantage over plain dark clothing or a standard fluorescent safety vest (Owens, Antonoff, & Francis, 1994; Balk, et al., 2007). With this in mind, research on biological motion has since helped guide the creation of high-visibility garments for vulnerable non-motorist roadway users mentioned previously (e.g., Blomberg, Hale, & Preusser, 1986; Sayer & Mefford, 2004b).

As discussed previously, a limitation of using retroreflective materials in pedestrian clothing is the fact that they require illumination from a light source that is positioned near the driver (i.e., headlamps). When these conditions are met, retroreflective materials are powerful conspicuity aids due to the artificially high level of contrast they provide. However, the further away a retroreflective object is from a light source (either in distance or entrance angle, or both), the less visible the object is to an observer.

The fact that visual acuity is not constant across the human retina contributes to the danger experienced by pedestrians at night. Many objects detected by a driver are initially imaged in their periphery, which is an area of markedly poor visual acuity relative to acuity levels for images on the fovea. The farther away objects are from the driver's fixation point, the less likely they are to be detected due to the retinal periphery's low resolution (Olson & Farber, 2003; Ikeda, Blake & Watanabe, 2005). To illustrate, imagine a nighttime situation in which a pedestrian is approaching a vehicle's path from the driver's left (e.g., approaching an intersection at angles perpendicular to each other). Here, the typical conspicuity problems associated with low contrast clothing are exacerbated by both the pedestrian's angular separation from the driver's likely fixation point and the pedestrian being positioned initially outside the cone of illumination provided by the driver's headlamps. These factors combine to produce a situation where the pedestrian's position relative to the vehicle is not conducive to being seen from a distance that would allow the driver to prevent a collision. Therefore, the consequences of a human's poor resolution for peripheral images combined with an approaching pedestrian's lateral distance from the vehicle's headlamp illumination can increase the risk of a collision. The application of electroluminescent panels to pedestrian clothing may be particularly useful in such a situation.

Electroluminescent (EL) panels are flexible, luminous sheets of film or wire, whose applications can include backlit instrument clusters, television screens, and other visual displays (Fischer, 1971; Rothberg & Lovinger, 1996). It is also possible to use EL as wearable technology in garment designs. Early EL garments had the practical disadvantage of requiring large, bulky battery packs that powered the panels and that were carried by the wearer. However, power sources have since become smaller and less cumbersome (Quinn, 2010), and EL materials can now be configured in more complex patterns in clothing. Thus, these wearable materials can now be arranged on a pedestrian's body to facilitate the perception of biological motion. Electroluminescence may be particularly beneficial for situations in which a person's distance from a light source is too large to make wearable retroreflective materials useful. As discussed previously, retroreflective materials exhibit varying levels of luminance depending on the entrance angle of illumination, the viewer's observation angle, and the distance from which the retroreflective material is observed. In contrast, EL materials have the advantage of a constant luminance output irrespective of viewing angles and distances. This could supplement the usefulness of retroreflective garments, potentially allowing the wearer to be visible even when not directly illuminated.

The purpose of the current study was to test the effectiveness of adding EL materials to retroreflective materials as pedestrian conspicuity aids. Both of these materials were positioned on a garment in a biological motion configuration designed to increase the distance at which drivers responded to pedestrians at night. This configuration was compared to one other garment design utilizing only retroreflective materials, configured in the same biological motion pattern. This was designed to test whether the distance that drivers respond to pedestrians increased in certain conditions with the addition of electroluminescent materials in the garment. It is important to note that this study was designed to investigate the potential benefits of EL materials when *supplementing* (instead of replacing) retroreflective garments as conspicuity aids. It was expected that drivers would respond from farther distances when the pedestrian wore a garment containing electroluminescent *and* retroreflective materials. This difference was also expected to be more prominent when the pedestrian was on the far left side of the road, where headlight illumination on the pedestrian is lower.

METHOD

Participants

One-hundred and ninety six (196) undergraduate students received class credit for their participation in this study. Participants' vision was screened based on presenting 20/40 corrected binocular visual acuity or better on a Bailey-Lovie chart, with no self-reported visual pathologies. Additionally, all participants were required to present a log contrast sensitivity score (Pelli-Robson) of at least 1.65. Finally, participants were required to have a valid driver's license in order to take part in this study.

Design

The current study utilized a 3 (pedestrian location) by 2 (pedestrian clothing) between-subjects factorial design. Refer to Table 1 for the six experimental conditions created for this study. The location of the test pedestrian on the side of the road was manipulated between-subjects, such that each participant encountered a test pedestrian positioned in one of three possible locations on the side of the road. Pedestrian clothing was also manipulated between-subjects, such that each participant was exposed to only one clothing type during their experimental session. Thus, each participant experienced only one of six possible combinations of clothing and location during their experimental session. The dependent variable is response distance – the distance at which a participant (seated in a moving vehicle) responded to the presence of a test pedestrian.

Table 1. Summary of experimental manipulations

Pedestrian Clothing	**Pedestrian Location**		
	Far left	*Near left*	*Right*
Retro	Retro × Far left	Retro × Near left	Retro × Right
EL+retro	EL+retro × Far left	EL+retro × Near left	EL+retro × Right

A male member of the research team acted as the test pedestrian, and was positioned in one of three fixed locations on the shoulder of the road (See Figure 3 below). These locations were all at the same longitudinal position but varied in terms of their lateral position relative to the vehicle's lane. Specifically, the test pedestrian was either located on the left shoulder of the road far from the road's edge ("far left"), on the left shoulder of the road near the road's edge ("near left"), or on the right side of the road near the road's edge ("right"). The test pedestrian was positioned 13.8 m, 10.8 m, and 2.8 m away from the center of the vehicle when in the far left, near left, and right locations, respectively. The angular separation between the center of the approaching vehicle and each of the three pedestrian locations can be seen in Figure 4. Refer to Appendix A for a more detailed visual depiction of the layout used in the current study. In all three, the test pedestrian was facing the roadway (perpendicular to the flow of traffic) and walking in place.

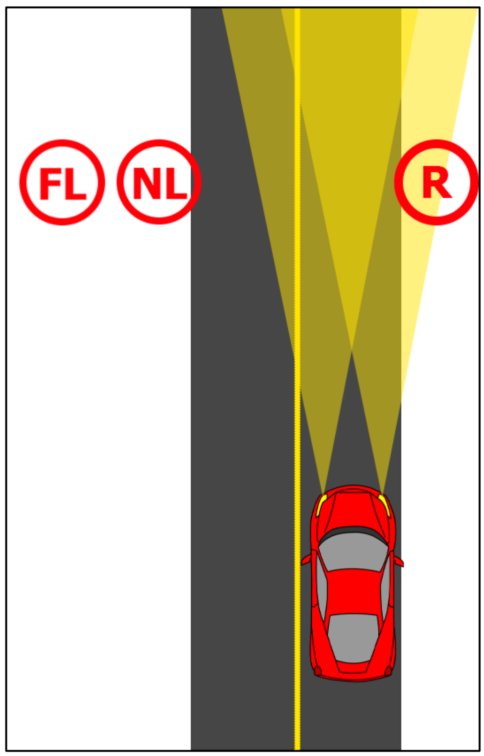


Figure 3: The three locations of the test pedestrian. “FL” = far left; “NL” = near left; “R” = right.

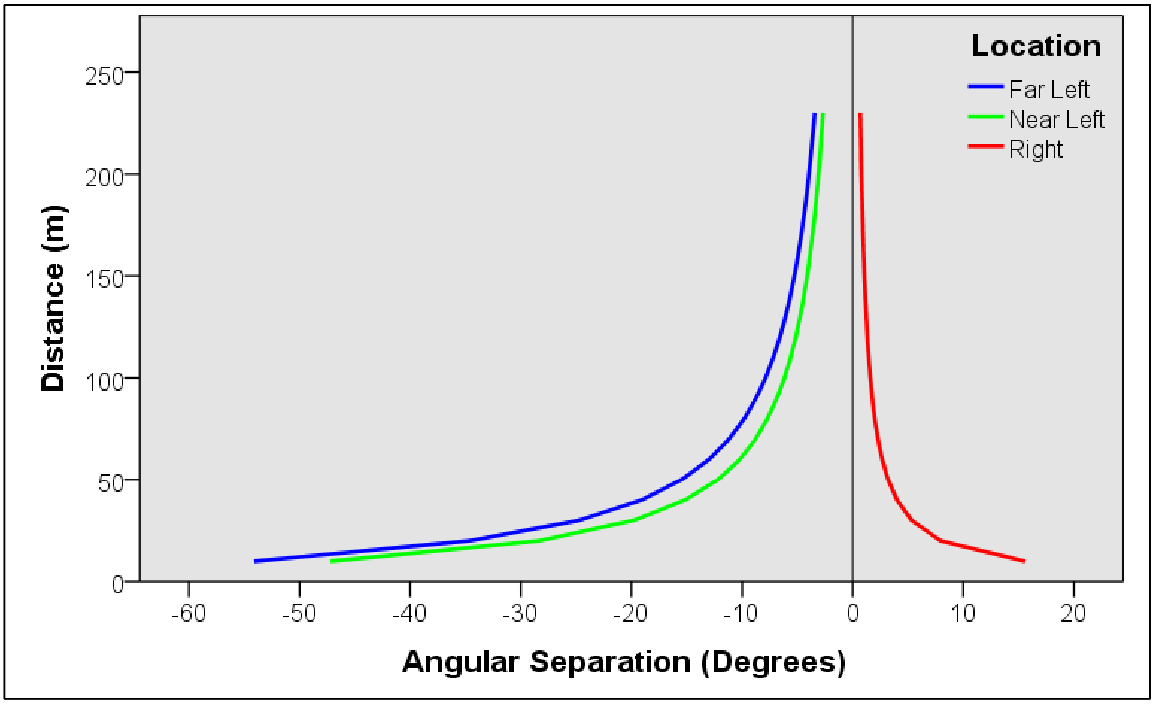


Figure 4: Angular separation between each of the three pedestrian locations and the center of the approaching test vehicle. Positive angles indicate rightward deviation from center.

The test pedestrian always wore black athletic pants and jackets. The “retro” condition included 2-inch wide strips of retroreflective tape placed around the wrists, knees, and ankles (See Figure 5a). The “EL+retro” garment had both 1-inch wide retroreflective tape and 1-inch wide electroluminescent lamps (placed parallel to each other), wrapped around the same body locations (See Figure 5b). This ensures the total surface area occupied by high-visibility materials was equal across the two garment configurations (203.2 cm^2 or 80 in^2).

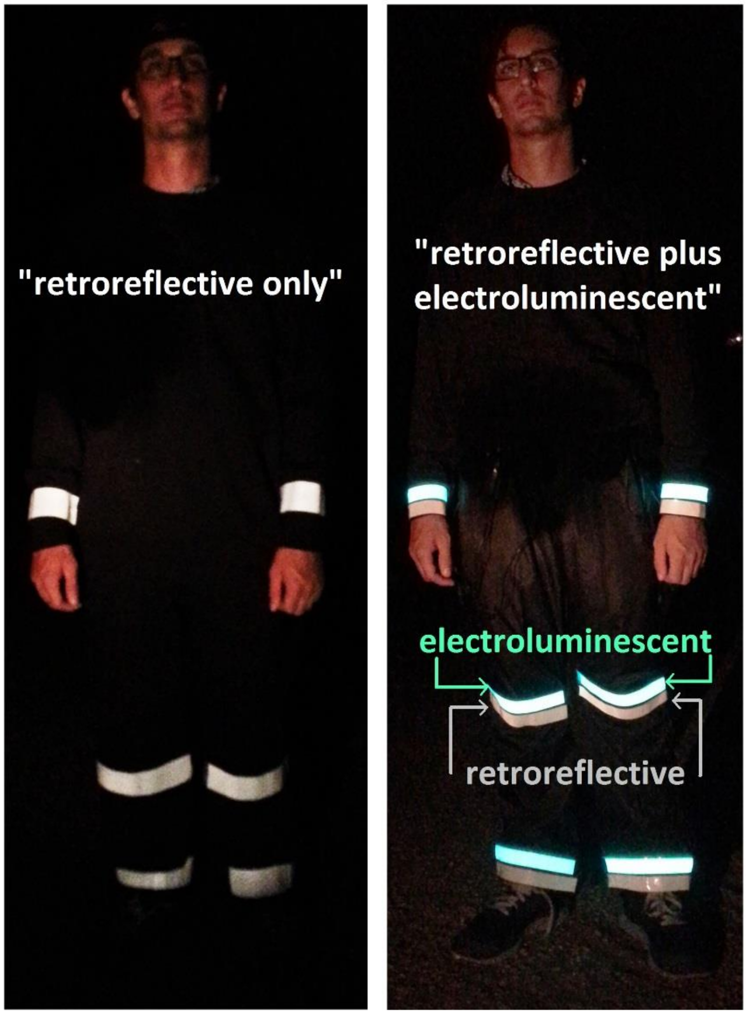
(a)  (b)

Figure 5: Pedestrian clothing designs. (a) “retro” (b) “EL+retro”. In actual experimental conditions, the test pedestrian also wore black cotton gloves on his hands and a black cotton beanie on his head.

Materials

The retroreflective materials used for this study were taken from rolls of silver 3M™ Scotchlite™ tape, produced by the 3M Company (St. Paul, MN). Oryon Technologies, Inc. (Addison, TX) provided the electroluminescent materials used for this research, also known as ELastoLite™. The electroluminescent materials from this manufacturer are available in five different colors (blue, blue-green, green, orange, and white). For the purposes of this study, the green electroluminescent bands were used because they are capable of emitting the highest luminance.

Pilot testing revealed that the luminance of electroluminescent materials used in the EL+retro garment decreases as their power source (AA batteries) drain. Therefore, to ensure that the electroluminescent materials emit a consistently high luminance, rechargeable AA batteries were fully charged before each night's series of experimental sessions. A graph showing the luminance output of a single electroluminescent lamp as a function of the charge in the batteries that power it (over time) can be seen in Figure 6 below. The correlation between the duration of constant lamp usage and the luminance output for disposable batteries (r = -0.861, $p < .01$) is somewhat stronger than that for the duration and rechargeable battery output (r = -0.414, p = .04). However, an independent-samples t-test showed no significant differences between the average luminance outputs of disposable and rechargeable batteries, $t(48) = 1.07$, p = .29. Due to the negligible differences between these two types of batteries, rechargeable AA batteries were used in the EL+retro garment.

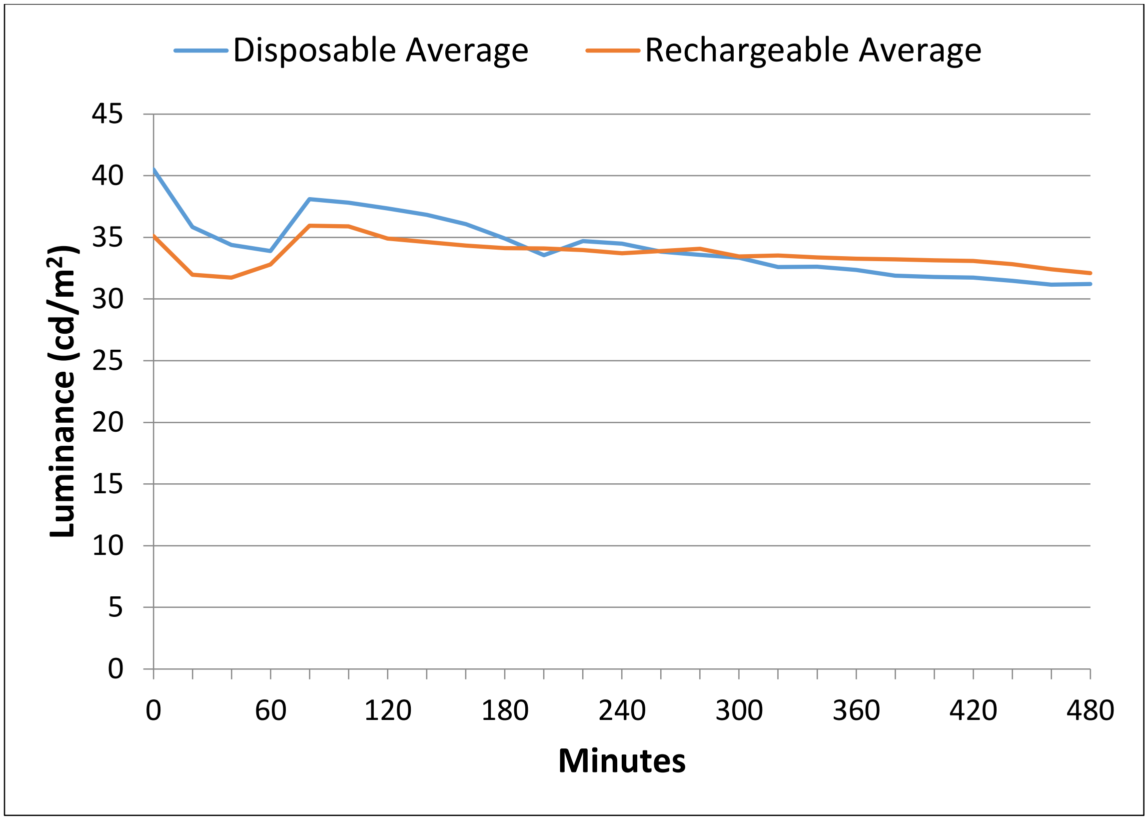


Figure 6: Average luminance output of an 8 inch × 1 inch ELastoLite lamp measured as a function of the duration of the lamp being continuously powered by either disposable or rechargeable AA batteries over an 8-hour period.

Figure 6 also shows how the EL lamps display a trend of relatively ‘high’ luminance when initially turned on, followed by an approximate 10 cd/m^2 drop in luminance over the first 60 minutes of usage, which is then subsequently followed by a recovery of approximately 10 cd/m^2 over the next 40 minutes. It is unclear why this fluctuation in luminance occurs. However, to mitigate this effect the researchers ensured that the EL lamps were turned on and running for at least 100 minutes before they were used for a night’s data collection trials. In effect, all AA batteries were used with at least

100 minutes worth of power drained from them prior to the start of data collection trials each night to achieve a stable luminance output.

Procedure

All data collection sessions began at least one hour after sunset and only on nights free of precipitation and fog. Before each experimental session, the vehicle's windshield and headlight casings were cleaned. First, vision testing was conducted and participants who did not meet the acuity and contrast sensitivity cut-offs were excused.

Participants were then led outside to the test vehicle (a 2012 Subaru WRX with halogen low beam headlamps). For most of the data collection sessions, two participants were tested at the same time. This meant that one participant sat in the front passenger seat of the test vehicle while the other participant sat in the middle seat of the second row in the test vehicle (viewing the road from between the two front seats). For sessions where only one participant was tested, this participant sat in the front passenger seat. Two researchers were also present in the vehicle during the course of every data collection session. One researcher drove the vehicle along an 8.14 km (5.0 mi) path (Figure 7) which passed through the Clemson University campus and surrounding roads within the city of Clemson. This route included a 235.9 m straight section, where data collection took place. The vehicle did not exceed posted speed limits for the roads on this route and used low beams throughout the route.

Figure 7: Route driven by experimenter ("S" represents the starting point of the route and "P" represents the pedestrian's location during the experiment). Map used from Google Maps (maps.google.com).

A second researcher was positioned in the back seat with a laptop computer. This laptop computer had two external numeric keypads extending to the participants seated in the vehicle. Participants were instructed to press a button on the keypad whenever they saw a pedestrian on or near the road. Pressing this button initiated a stopwatch timer on the laptop computer, and the experimenter in the back seat of the car terminated the stopwatch as soon as the vehicle passed the test pedestrian. During this time, the driver maintained a constant vehicle speed throughout the approach to the test pedestrian (56.33 km/h / 35 mph). Measurements of the time elapsed between the participants' response to the test pedestrian and the point at which the vehicle passed the pedestrian were be used to calculate and record the participants' recognition distances (Distance = Speed × Time). This technique was verified for accuracy (see Figure 8) and used in a similar on-road study to estimate response distance (Whetsel, 2011).

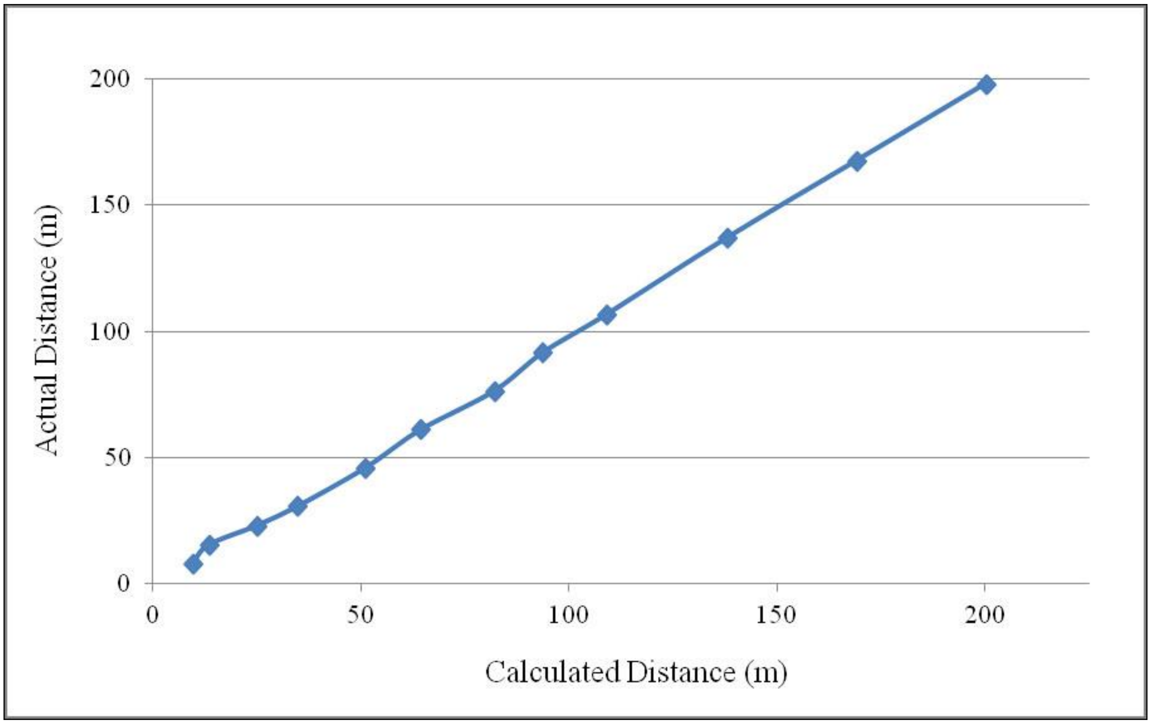


Figure 8: Linear regression model of the relationship between the calculated distance and actual distance, showing the accuracy of the method for distance calculation. Calibration data are sourced from Whetsel, 2011.

The instructions to the participants also included clarification on what “counted” as a pedestrian. Participants were told to refrain from responding when they saw someone on a bicycle, skateboard, or on roller-blades, effectively limiting their responses to those who were on foot. Participants were also told that there would be no negative consequences for responding incorrectly (e.g., pressing the response button for something that was not a person at all). Therefore, they were told that they could respond even if they were not 100% certain that what they were seeing was actually a pedestrian, as long as they were able to respond to ‘all’ of the pedestrians on the route without missing any of them (i.e., reducing the participants’ Type II error rate in responses). The decision to include this in the set of participants' instructions is justified by the fact that pilot participants sometimes mistook the EL+retro garment as some object that was not being worn by human, due to its novelty and unfamiliarity. This point will be discussed further in the Results and Discussion sections.

The location of the test pedestrian was in an area with minimal ambient illumination (e.g., less than 0.10 lux at all three locations). Appendix B shows the amount of headlight illumination reaching a vertical surface positioned at 22 cm above the ground surface (i.e., the height of the knee of a 50^{th} percentile male) at each of the three locations. After passing the test pedestrian, participants were informed that the experimental session was completed and that they did not need to continue searching for pedestrians. The experimenter then drove the participants back to the starting point of the test route where the participants were debriefed and released.

Participant responses to pedestrians who were not part of the study were ignored and excluded from analysis. Values were removed and replaced if any other vehicles were present near the test pedestrian as the test vehicle approached his position. Instances in which participants failed to respond to the test pedestrian before passing him were recorded as a 0 m response distance.

RESULTS

Data from 76 participants were excluded from the analysis. Data from 50 participants were excluded due to the presence of other vehicles during the test vehicle's approach to the test pedestrian. Data from seven participants were excluded because the test pedestrian missed the radio signal to begin walking in place as the test vehicle approached. Data from seven participants were excluded because of a malfunction of the test pedestrian's clothing. Data from four participants were excluded because these participants informed researchers that they did not press the response button when they saw the test pedestrian because they believed the test pedestrian was an animated Halloween decoration (data collection took place during October and November). Data from three participants were excluded due to precipitation, fog, or other unfavorable weather conditions during the trial. Three participants' data were excluded from the data set because their responses were influenced by having prior knowledge of the study. Data from two participants were excluded because of a technical malfunction with the test vehicle's recording equipment.

After these exclusions, the final data set includes data from 120 participants, with the participants distributed across conditions as follows: N=21 in "EL+retro × right," N=20 in "retro × right," "retro × near left," "retro × far left," and "EL+retro × far left" conditions, and N=19 in the "EL+retro × near left" condition.

Prior to analyzing these data, a violation of the homogeneity of variance assumption was detected in the sample using a Levene's Test for Equality of Variances, $F(5,114) = 6.054$, $p < .001$. To address this heteroscedasticity, a Weighted Least Squares (WLS) regression model was used (Rosopa, Shaffer, & Shroeder, 2013). This method allows greater weight to be applied to those cells with smaller variance, thereby counteracting the changing variances across the six conditions. A follow-up analysis of the variance across conditions after WLS corrections revealed no such violation of the homogeneity of variance assumption, $F(5,114) = 0.345$, $p > .05$. For the purposes of this report, descriptive statistics of the study conditions are given without WLS adjustments.

A 3 × 2 (location: right, near left, and far left × clothing: retro and EL+retro) between-subjects Analysis of Covariance (ANCOVA) was then conducted to examine the separate and combined influences of pedestrian clothing and pedestrian location on response distances. This model incorporated three variables as covariates: test pedestrian (one of three), in-vehicle experimenter (one of two), and participant seating position (front vs. back). Response distances were not significantly affected by which experimenter was acting as the test pedestrian, by which experimenter was in the vehicle, or by the participants' seating position (all $p > .05$).

This model produced a significant main effect of location on response distances when averaged across clothing conditions, $F(2,111) = 4.095$, $p < .05$, $\eta^2 = .069$ (see Figure 9). Post-hoc pairwise comparisons (Least Significant Difference) between the location conditions revealed that response distances were significantly shorter when the test pedestrian was positioned in the far left location ($M = 102.9$ m, $SD = 68.9$ m) compared to the near left ($M = 129.8$ m, $SD = 58.9$ m) and right locations ($M = 140.8$ m, $SD = 59.8$ m), $p < .05$. The differences in response distance between the right location and near left location were not significant, $p > .05$.

There was also a significant main effect of clothing on response distances when averaged across location conditions, $F(1,111) = 24.084$, $p < .001$, $\eta^2 = .178$ (see Figure 10). Post-hoc pairwise comparisons confirmed that the response distances yielded from the EL+retro garment (*M* = 151.6 m, *SD* = 67.8 m) were greater than that of the retro garment (*M* = 98.1 m, *SD* = 47.8 m).

It was hypothesized that a significant interaction would exist between pedestrian clothing and location with respect to response distances, and this relationship should be viewed as the central focus for this experiment. Mean response distances for each of the six conditions in the model can be seen in Figure 11. There was a significant interaction between location and clothing condition, $F(2,111) = 3.587$, $p < .05$, $\eta^2 = .061$.

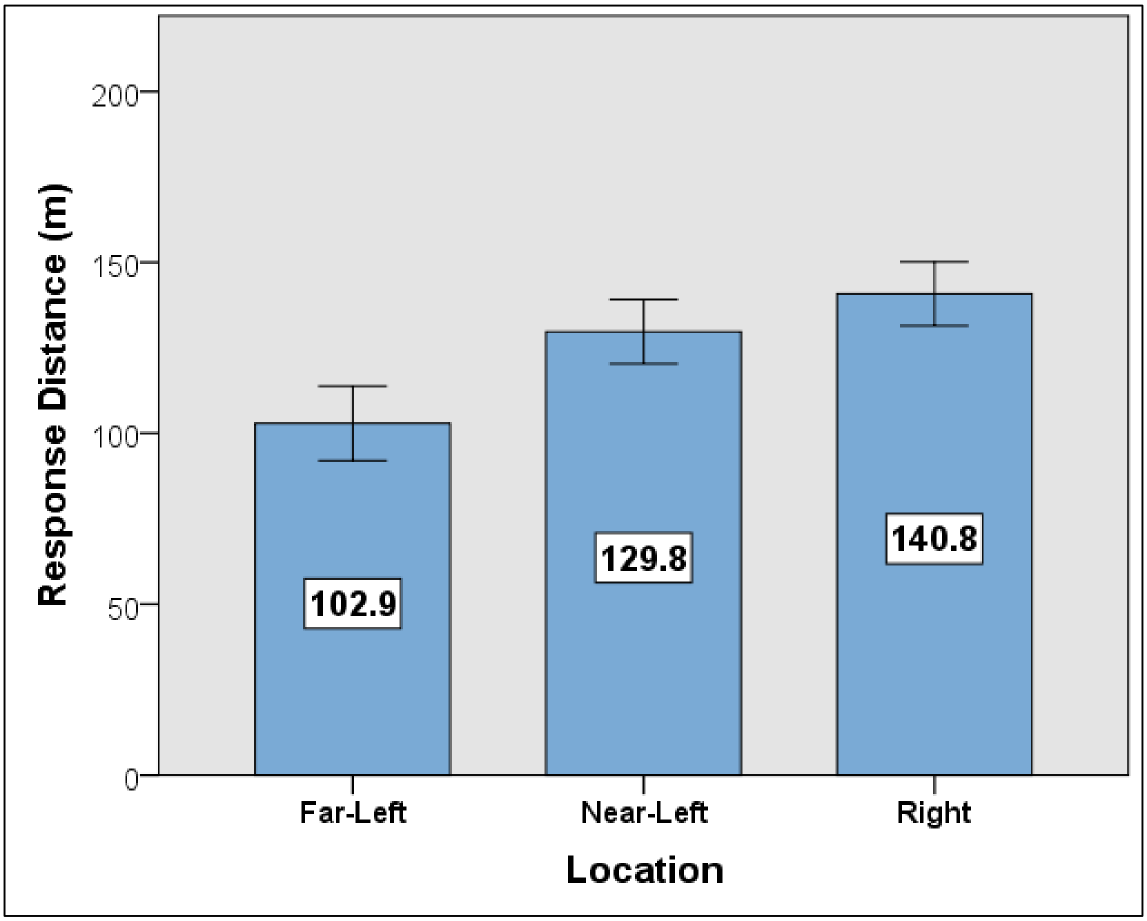


Figure 9: Mean response distance for each of the three pedestrian locations, averaged across the two clothing conditions. Error bars represent ± 1 standard error of the mean.

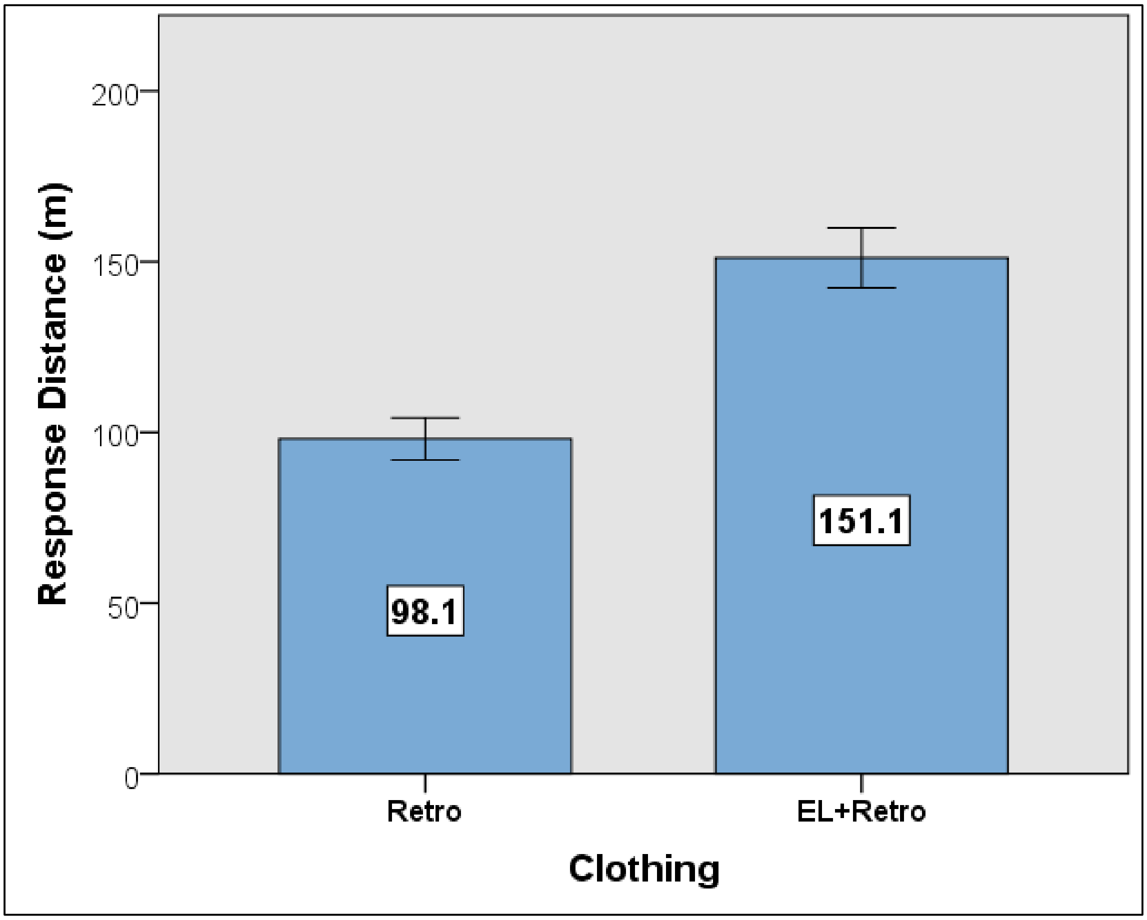


Figure 10: Mean response distance for the two pedestrian clothing conditions, averaged across the three pedestrian locations. Error bars represent ± 1 standard error of the mean.

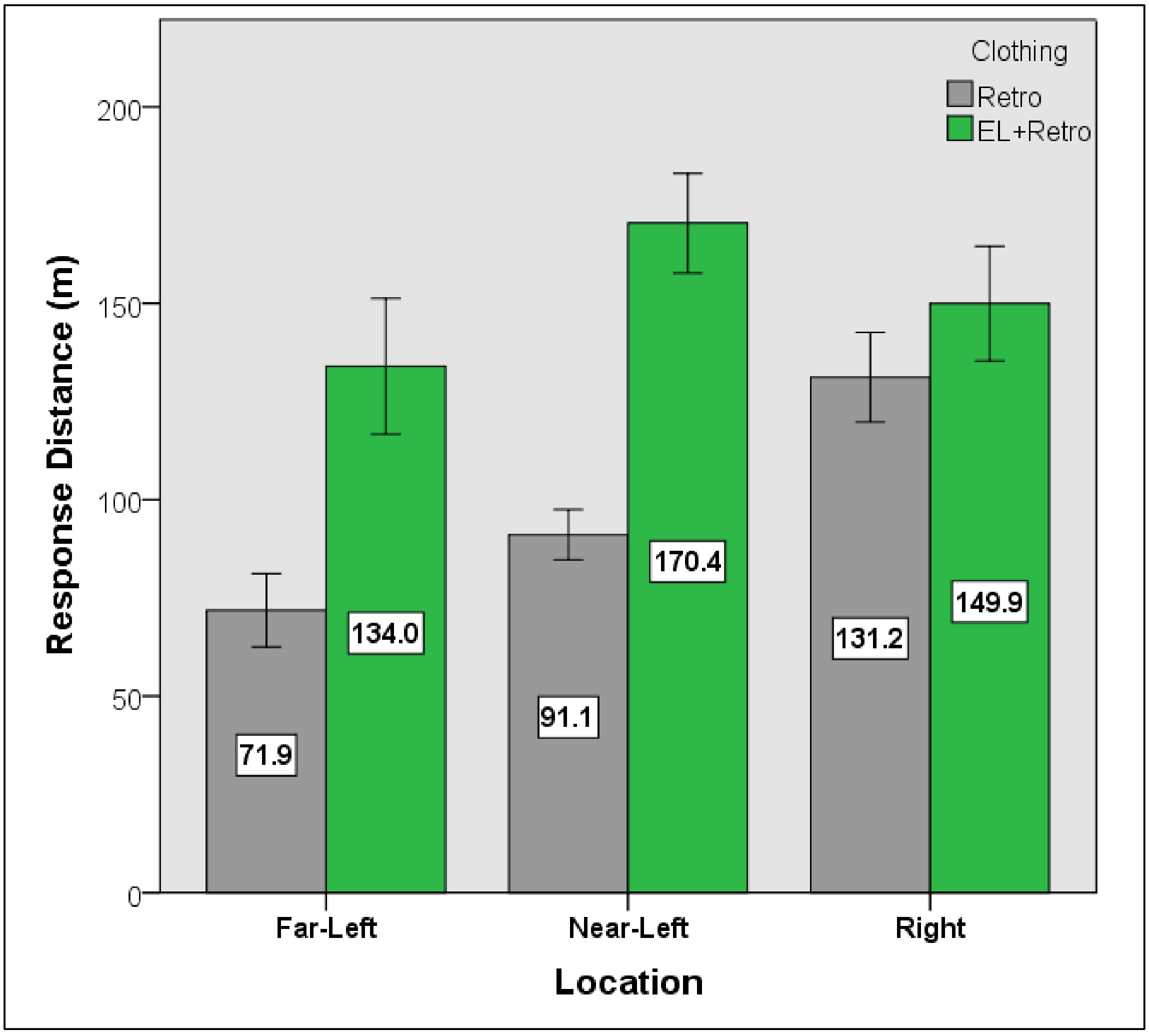


Figure 11: Mean response distances (m) as a function of location and clothing. Error bars represent ± 1 standard error of the mean.

This interaction was explored by testing the simple effects of location within each clothing condition. The effect of location within the retro condition was significant ($F(2,54) = 8.766$, $p < .001$, $\eta^2 = .245$), while the effect of location in the EL+retro condition was not ($F(2,54) = 2.071$, $p > .05$, $\eta^2 = .071$). Specifically within the retro condition, the mean response distance of the right location (*M* = 131.2 m, *SD* = 11.4 m) was greater than that of the near left location (*M* = 91.1 m, *SD* = 6.4 m), which in turn was greater than the far left location's response distances (*M* = 71.9 m, *SD* = 9.3 m). In other words: the retro clothing condition's response distances were more sensitive to changes in location. This was characterized by a trend of decreased response distance as the pedestrian was positioned farther from the test vehicle's headlamp beam pattern. In contrast, the response distances associated with the EL+retro garment were more robust to changes in location.

DISCUSSION

The current study examined the hypothesis that a pedestrian wearing a garment containing both electroluminescent and retroreflective materials that are configured in a biological motion pattern would be more conspicuous to drivers at night than a pedestrian wearing a comparable outfit containing only retroreflective material. This conspicuity benefit was predicted to be influenced by the decreased illumination reaching the retroreflective-only garment as the wearer is positioned outside the approaching vehicle's headlamp beam. This study defined pedestrian conspicuity as the distance at which participants responded to seeing the roadside pedestrian from a moving vehicle.

As hypothesized, participants responded to the garment containing both electroluminescent and retroreflective materials ('EL+retro') at longer distances than those who saw the retroreflective-only garment ('retro'). Response distances for the EL+retro garment were 35% farther than that of the retro garment, on average. The results also lend support to the hypothesis that drivers' pedestrian recognition distances are influenced by the pedestrian's location on the side of the road. The 8% increase in response distance between a pedestrian walking in place on the far shoulder of the road (i.e., near left) and the near shoulder of the road (i.e., right) is non-significant. However, pedestrians positioned farther away from the road (i.e., far left) were recognized significantly later than when they were at the shoulder of the road. There was a 26% increase in response distances between the far left location and the right location, and a 15% increase between the far left and near left locations on average. This result is presumably a result of the location-related decrease in headlamp illumination falling on the pedestrian in the far left position (see Appendix B) causing a decrease in luminance of the retroreflective material but not the EL material.

There was a significant interaction between pedestrian clothing and pedestrian location. The distance at which participants responded to the retro garment became progressively shorter as the pedestrian was positioned farther away from the vehicle's headlights. However, this location-related change in response distance was absent with the EL+retro garment due to its lower dependence on external light sources.

One way to examine this interaction is to consider the differences in the three pedestrian locations for each garment separately. When the pedestrian wore the retro garment there was an effect of location such that all three locations significantly differed from one another. Participants responded to retro-clad pedestrians in the right location from a distance 31% farther than that of the near left location. Additionally, participant responses to the retro-clad pedestrians in the right location were 45% greater than in the far left location. Further, participant responses to the retro-clad pedestrian in the near left location were 21% farther away than the far left location. On the other hand, the participants responded to the pedestrian wearing the EL+retro garment at distances that were only 12% greater for the near left location than the right location, and 21% greater for the near left location than the far left location. There was also an 11% increase in response distances from the far left to the right location. As previously mentioned these differences in location were non-significant for the EL+retro garment, indicating that the conspicuity of this clothing is relatively stable across the roadside locations chosen for this study. This interaction can also be explained by comparing the two garments at each of the three pedestrian locations. The difference in average response distances between the retro and EL+retro garments was significant at the near left (with the mean for retro being 53% of the mean for EL+retro) and far left (54%) locations, but not when the pedestrian was in the right location (the mean for retro was 88% of the EL+retro mean).

It is also worth noting that the distance at which participants responded to the EL+retro clad pedestrian positioned in the far left location were on par with that of the retro garment in the right location (see Figure 11). In other words, the EL+retro garment in the 'worst' location was similar to the performance of the retro garment positioned in the 'best' location. The significant clothing × location interaction suggests that the EL+retro garment, by incorporating multiple materials in its design, can be a robust nighttime conspicuity aid in a wide range of locations within a driver's field of view.

The interaction between clothing and location has considerable practical importance. To revisit the illustrative example (described earlier) in which a pedestrian is about to cross an intersection from left to right, the path of the approaching vehicle is perpendicular to the path of the pedestrian (see Figure 12). The existing literature confirms that retroreflective clothing can increase the distance at which the driver can recognize the pedestrian so that collision-avoiding action can be taken sooner. However, the current study demonstrates that the effectiveness of retroreflective elements in pedestrian clothing declines when the pedestrian is positioned outside of the approaching vehicle's headlight beam. Because of changes in illumination from the approaching headlamps, retroreflectors can be effective when the pedestrian is just about to cross (i.e., when it may be too late for the driver to avoid a collision) but their effectiveness is more limited when the pedestrian is approaching a road crossing. The data from the present study show that garments containing both EL panels and retroreflectors have the potential to increase pedestrian conspicuity before the pedestrian reaches the shoulder of the road that he intends to cross. This is because EL's luminance is less dependent upon external light sources (i.e., headlamps).

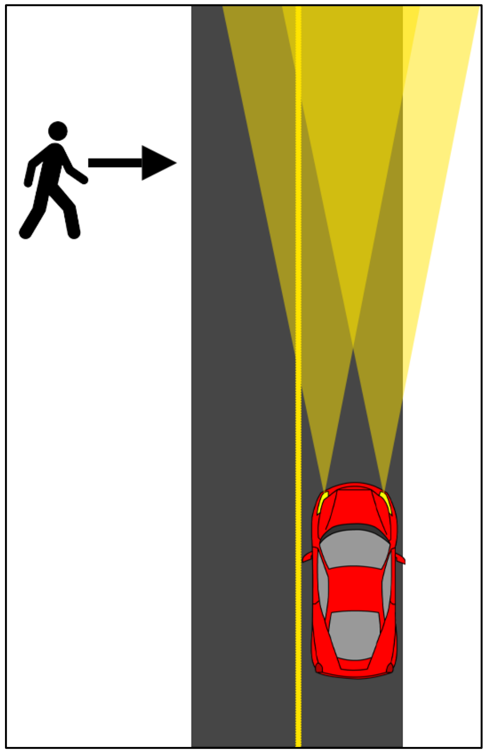


Figure 12. A pedestrian crossing a roadway from left to right. A driver approaches the pedestrian from a perpendicular path of travel.

A number of studies have examined the distance at which participants respond to nighttime pedestrians who are wearing a garment similar to the retro clothing condition in the current study (Wood, Tyrrell, & Carberry, 2005; Tyrrell, et al., 2009; Luoma & Penttinen, 1998). These studies shared the current work's focus on the use of biological motion to enhance pedestrian conspicuity. There are many methodological differences between these studies and the present one, and these differences prevent a meaningful and direct comparison of response distances. However, it is interesting that these studies reported average response distances that were more than 2 times greater than the present study's response distances in similar conditions.

One possible explanation for the apparent discrepancies between the current study and the findings from these three similar studies (aside from methodological approaches) is the influence of the test pedestrian's orientation relative to the roadway and the vehicle. In the three studies mentioned above, the test pedestrian was positioned on the shoulder of the road and facing the oncoming test vehicle. In the current study, the pedestrian was facing the roadway (perpendicular to the vehicle's path of travel). It has been suggested that the conspicuity advantages afforded by biological motion are more effective when the pedestrian is facing the vehicle instead of facing the roadway (Balk, et al., 2007). If this is the case, then the orientation of the pedestrian may offer one explanation for these differences in response distance.

It is unclear how the present results would have been affected if the test pedestrian had been rotated to face the approaching vehicle. However, it is important to understand that one goal of the current study was to simulate a pedestrian approaching a roadway that he intended to cross. When viewed from this perspective, there would be no appreciable benefit in positioning a pedestrian far off to the side of a road or intersection (e.g., the far left location in the current study) if this pedestrian were facing the oncoming vehicle. If someone's walking path is perpendicular to the road they are about to cross, this person would be facing the roadway and not an oncoming vehicle. Regardless, this is one research question that could be addressed in future work with the garments used in the current study.

As mentioned earlier, there are two main disadvantages of using retroreflectors as nighttime pedestrian conspicuity aids. First, the luminance of a retroreflective surface is illumination-dependent, and there are geometric limitations (entrance and observation angles). Second, it is difficult for the layperson to understand the conspicuity benefits of retroreflectors unless they are observed in specific conditions. Fortunately, electroluminescence does not share these limitations. Although there have been numerous studies conducted with pedestrian garments similar to the retro clothing condition used here, no peer-reviewed publications chronicling the conspicuity benefits of electroluminescence in pedestrian clothing (let alone the combined influence of electroluminescence and retroreflectivity) are known to exist at this time. There are a few reasons why this might be the case.

First, electroluminescence is a developing technology, which has yet to see widespread commercial use as a clothing material, and its applications to roadway safety are not yet documented. Second, the practicality of a pedestrian garment containing electroluminescent materials is currently an open question. On one hand, the EL+retro garment used for the present study is considered to be an early prototype and it suffered from several serious usability issues. Twenty AA batteries (10 separate packs each containing two batteries) powered the garment; the battery packs were carried in a custom harness around the test pedestrian’s waistline. Consequently, this garment contained numerous long wires, which had to be sewn into the outfit to avoid tangling. Finally, the EL lamps used in this garment experienced occasional technical malfunctions resulting in sections of the lamp turning off when they were bent or flexed. These factors limit the practicality of wearable electroluminescence. On the other hand, the incorporation of both EL and retroreflectors into a single suit can also be seen as a safeguard: in a situation where some or all of the electroluminescent material experiences a technical failure, the simple-yet-effective retroreflective material is still present and can enhance the wearer's conspicuity (albeit with the limitations described previously) even in the event of EL lamp failure. From this perspective, an outfit that both reflects and produces light is promising. As wearable electroluminescence develops to suit the different domains in which it is appropriate, so to should the benefits of this promising technology become more apparent to those concerned with pedestrian safety.

The green ELastoLite lamps chosen for this experiment were one of five color options produced by the manufacturer. Green EL lamps were selected because they emit the highest average luminance. However, the manufacturers also offered a white EL lamp option that was similar in appearance to the silver retroreflective tape used in this study. The choice to use the green lamps over the white lamps, therefore, could be interpreted as confounding the EL+retro garment's conspicuity with the color of the EL material. However, there are a few reasons why this study's experimental design choice is an appropriate first step.

A nighttime roadway environment is dark, but not entirely scotopic. Streetlights, vehicle's headlights, and ambient illumination from the moon (among other factors) prevent an observer from achieving full dark adaptation while driving at night. As a result of the large range of luminance values in typical nighttime scenes, the rods and cones are both active in these conditions. With this in mind, it is important to understand that the retina's rods are most sensitive to wavelengths approximately 500 nm on the visible light spectrum—corresponding to green and blue-green hues. In other words, objects that are blue and green appear ‘brighter’ than objects that are red and violet at night when other factors (including luminance) are held constant. Therefore, if any one color had to be chosen to make an EL garment with the highest luminance possible while also creating the highest contrast possible between itself and a nighttime background, it would be ideal to use green or blue-green lamps. The EL lamps used in this experiment satisfy both this high luminance and high contrast criteria better than any of the other EL lamp color options. The impact of other colors of EL lamps on pedestrian conspicuity remains open for further empirical testing.

There were a number of limitations in this study. The experimental design compared the response distances of two garment configurations: retro and EL+retro. However, the current study did not incorporate an ‘EL-only’ garment. This option was considered but ultimately excluded due to limited time and resources. Thus, it is important to note that it remains unclear how participants would respond to EL without retroreflectors. In other words, the current study's results can only speak to EL’s effectiveness as a *supplement* to retroreflectors as a conspicuity-enhancing material and not as a *replacement* for retroreflectors. Testing EL’s effectiveness independent from retroreflectors should be a priority for any future research investigating EL in the context of nighttime pedestrian conspicuity.

Another limitation is that the participants in this study were passengers (not drivers) and that their only task was to search for pedestrians. By limiting the participants’ workload and by alerting them to the presence of pedestrians it seems likely that the response distances measured in the present study are optimistic. That is, ‘naturalistic’ response distances from drivers are likely to be shorter than the ones reported here. Future research should address this issue.

This study demonstrated one advantage of EL panels in the nighttime roadway environment– namely, its effectiveness in increasing pedestrians’ conspicuity when they are poorly illuminated. This apparent benefit means that EL may be advantageous in situations other than those tested in the current study, though. The data show that EL is particularly useful in highlighting the pedestrian’s form and motion when they are not near the roadway, and by association, not within an oncoming vehicle’s headlight beam. However, a pedestrian does not necessarily need to be far from the shoulder of the roadway in order to receive insufficient illumination from headlights. Changes in the roadway geometry, such as elevation changes and curvature, can create a situation where a pedestrian is poorly illuminated despite being in the ‘ideal’ position on the shoulder of the road. One example would be a pedestrian walking on the right shoulder of an uphill road which curves sharply to the left (i.e., the pedestrian is located on the outside edge of the curved road). In this scenario, the pedestrian is actually located up and to the left of the vehicle’s path for most of the vehicle’s approach to him. Because the vehicle’s headlamps direct light downward and to the right of the vehicle (i.e., the opposite direction), the pedestrian does not receive sufficient illumination until the vehicle is just about to pass and a collision would be difficult to avoid. Although the current study’s data cannot speak directly to EL’s effectiveness in such scenarios, this does suggest that EL’s benefits may be observable in future research incorporating variations in roadway geometry.

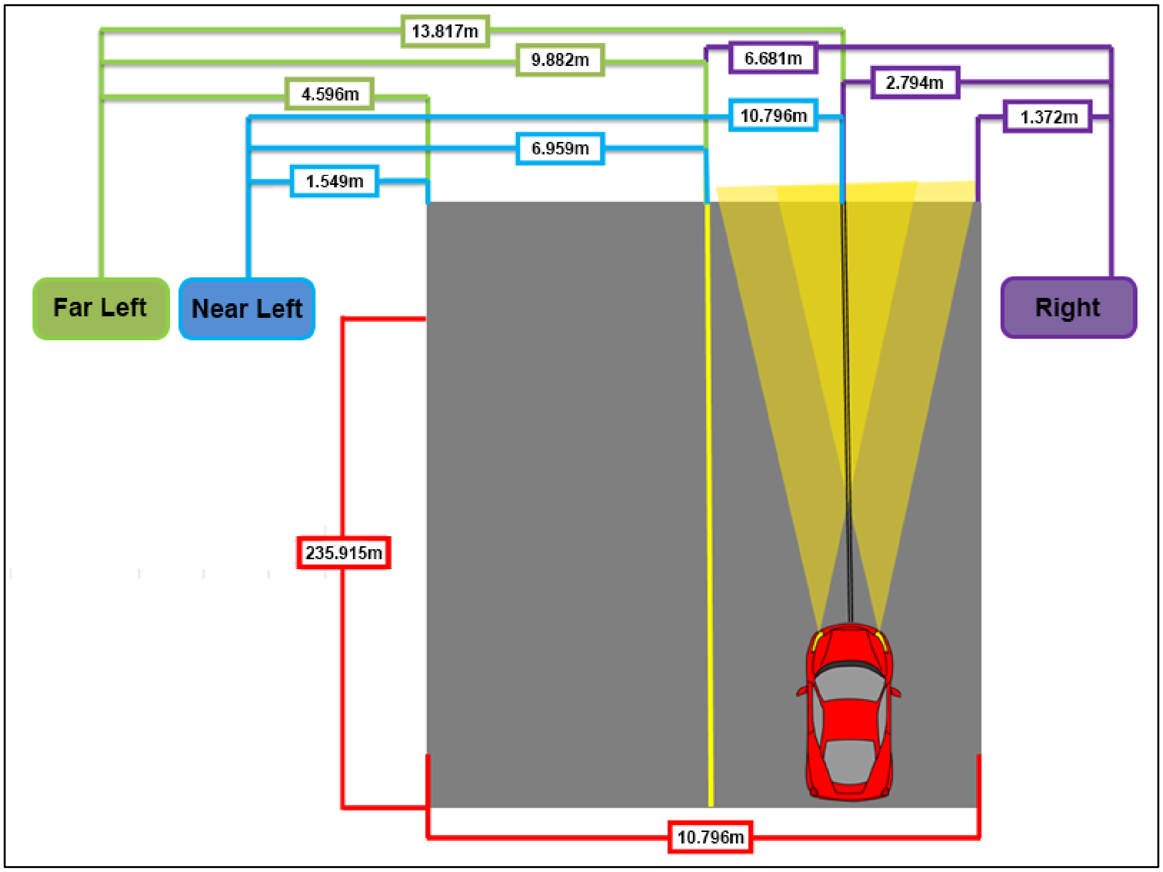
There is evidence to suggest that pedestrians neither understand nor appreciate the conspicuity problems that they face at night. Pedestrians typically overestimate how visible they are to drivers, (Tyrrell, Wood, & Carberry, 2004; Whetsel Borzendowski, Rosenberg, Stafford Sewall, & Tyrrell, 2013; Balk, Brooks, Klein, & Grygier, 2012) and typically do not wear conspicuity-enhancing clothing. Unfortunately, the purpose of retroreflective materials and their conspicuity benefits are not always as impressive (or even apparent) when viewed on a computer screen or in a brightly illuminated retail clothing store. However, electroluminescent garments may be more marketable or fashionably appealing than retroreflectors because their functionality is more apparent indoors and in photographs. If electroluminescent materials are as effective in enhancing nighttime conspicuity of pedestrians as the current study suggests, then their more appreciable benefits (or simply, their ‘coolness’) may also prove useful in helping pedestrians become more aware of this safety issue. Because of its novelty, wearable electroluminescence may not require those who adopt it to be knowledgeable about pedestrian safety in order for them to reap the benefits of its usage.

One potentially exciting application of EL materials is to enhance the nighttime conspicuity of those referred to as ‘professional pedestrians.’ These include roadway workers, emergency responders, and traffic control officers (Sayer & Mefford, 2004a; Tyrrell, et al., 2009; Wood, et al., 2014). People in these professions are not typically found in one roadside location, and are more likely to be crossing or entering the roadway compared to other types of pedestrians (e.g., police officers and EMTs surveying a crash site before traffic control is in place). In these situations, the effectiveness of retroreflective markings may be limited by variable illumination from headlamps. Future research should explore the extent to which electroluminescence can be a valuable supplement to retroreflectors in this context. Further, designing electroluminescent garments for this subset of pedestrians could be advantageous in that it would somewhat alleviate the need to ‘force’ or educate pedestrians to use conspicuity-enhancing clothing through interventions, which is a tactic with promising results in recent literature but is sometimes difficult to implement on a large scale (Tyrrell, Patton, & Brooks, 2004). Since these types of professions typically involve the use of uniforms that are prescribed by government agencies it may be possible to integrate active lighting into standard uniforms. Garments that provide conspicuity advantages in variable illumination conditions (e.g., the EL+retro garment and other materials that include active lighting) may be particularly cost-effective in these settings.

APPENDICES

Appendix A

Pedestrian Location Dimensions



Appendix B

Headlight Illumination Reaching the Test Pedestrian

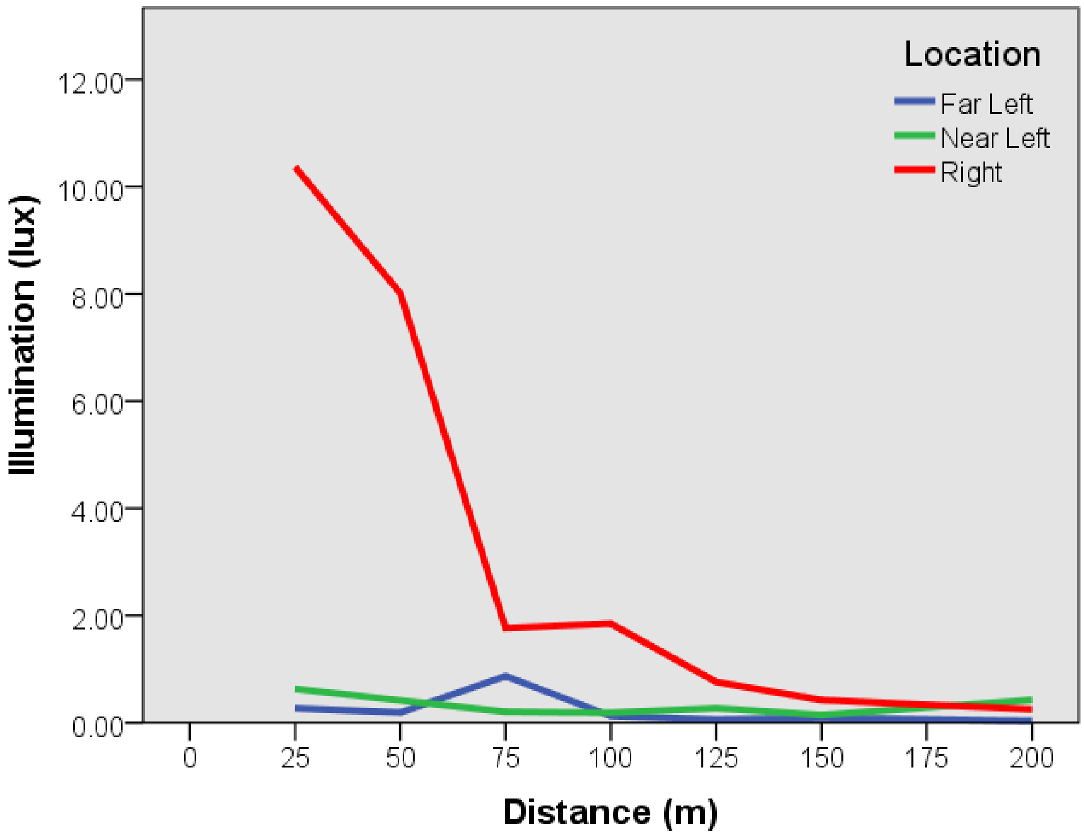


Figure B-1: Illumination measurements observed at the 50th percentile male's knee height.

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