RESEARCH & DEVELOPMENT

Does the color of construction workers safety vests affect worker conspicuity in simulated construction work zones?

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16. Abstract

The construction industry is known to be one of the most dangerous employment industries worldwide. Research has demonstrated that traffic accidents in work zones are on the rise, contributing to both heavy incident-related costs to the industry and, more importantly, to fatal and serious non-fatal injuries of construction workers. With construction workers being twice as likely to be killed by a motor vehicle as the average worker, adoption of methods to improve worker visibility is becoming increasingly important. The fluorescent yellow/green color and fluorescent orange/red color of safety vests are generally considered as the most distinctive colors for high visibility vests. However, there is very limited research to date examining the effects of the presence of safety vest and their colors on worker conspicuity in the context of construction safety. To test these effects, 49 participants from eastern North Carolina navigated a series of 3 construction work zone driving tracks in a commercial driving simulator while fitted with a mobile head mounted eye tracker. Eye tracking data were collected and analyzed to examine participants visual acuity and determine the proportion of worker characters in the simulator tracks which were seen by the research participants. The results suggest that the provision of safety vests did increase the proportion of workers characters observed across all and within each track (p = 0.0002). However, there was no variability in proportion data for safety vest colors indicating that vest color had no effect on worker character conspicuity (all $p > 0.05$). This study departs from the current body of literature by being the first quasi-experimental procedure to examine the effects of the presence of worker safety vests on worker conspicuity in simulated construction work zones. Additionally, this is the first quasi experimental study to investigate the effects of the presence of a worker safety vests on worker conspicuity in simulated construction work zones using an interactive driving simulator and eye tracking technology.

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Executive Summary

The construction industry is known to be one of the most dangerous employment industries worldwide. Research has demonstrated that traffic accidents in work zones are on the rise, contributing to both heavy incident-related costs to the industry and, more importantly, to fatal and serious non-fatal injuries of construction workers. With construction workers being twice as likely to be killed by a motor vehicle as the average worker, adoption of methods to improve worker visibility is becoming increasingly important. The fluorescent yellow/green color and fluorescent orange/red color of safety vests used by NCDOT employees are generally considered as the most distinctive colors for high visibility vests. Although much research has been conducted in the context of cyclist and pedestrian safety (xx), there is very limited research to date examining the effects of the presence of safety vest and their colors on worker conspicuity in construction safety. To test these effects, 49 participants from eastern North Carolina navigated a series of 3 construction work zone driving tracks in a commercial driving simulator while fitted with a mobile head mounted eye tracker. Participants were seated in a commercial driving simulator, fitted with the eye tracking hardware, and asked to drive 3 separate driving tracks in a counterbalanced and randomized pattern according to a blocked experimental design. Eye tracking data were collected and analyzed to examine participants visual acuity and determine the proportion of worker characters in the simulator tracks which were seen by the research participants. When participants visual attention was cast onto or over a worker in the simulator environment, the worker was considered to be seen by the participant. The two null research hypotheses were tested to examine these effects include:

Ho1) The color of worker safety vest does not affect conspicuity in simulated construction work zones and

Ho2) The presence of a worker safety vest does not affect conspicuity in simulated construction work zones.

Analysis of Variance (i.e., ANOVA) analysis suggests there was no statistically significant difference in the proportion of workers seen between the orange ($\mu = 0.5255$) and yellow ($\mu = 0.5340$) safety vest groups (all $p > 0.05$) (see Table 3.0). These results suggest the color of worker safety vest does not affect conspicuity in simulated construction work zones. Therefore, the authors fail to reject hypothesis Ho1 and conclude that either vest would be appropriate as tested in this research. This result was cross validated with mean and dispersion t-testing with the same hypothesis rejection decision. However, ANOVA analysis suggests there was a significant difference in the proportion of workers seen by the participants across all garment colors and driving tracks presented to the research participants. In fact, workers wearing safety vests (μ orange vest = 0.5255 and μ yellow vest = 0.5340) were seen a higher percentage of times when compared to those wearing only white t-shirts ($\mu = 0.3741$) ($p = 0.0002$). Therefore, the authors reject hypothesis Ho2 and conclude that the presence of a worker safety vest does affect conspicuity in simulated construction work zones. Please see section 5.0 for further details.

The objective of the current study was to explore the effect of the color of worker safety vests on worker conspicuity in simulated construction work zones. The two goals of this study were (1) to determine if the presence of a worker safety vest improves worker conspicuity; and (2) to determine which color, ANSI lime-yellow or ANSI fluorescent orange-red, is most conspicuous for both daytime and nighttime conditions. The results indicate that there was no

significant difference in the proportion of workers seen for the Orange Vest and Yellow Vest garment groups. The orange and yellow vests were provided by the research team at NCDOT and were modelled by STISIM Inc. personnel and were used as worker character clothes (i.e., skins) in the simulator models. This was done to ensure the worker vests used in the simulator environments were a replica of those used by NCDOT employees. The eye tracking results of this study suggest that either vest is appropriate for workers to don in construction work zones. Additionally, the results indicate that the presence of a safety vest, in either color, does improve worker conspicuity. When observing the eye tracking data across all driving tracks, drivers did cast their visual attention to workers wearing safety vests at a higher percentage rate for worker characters skinned with vest compared to worker characters skinned with white t-shirts.

This study departs from the current body of literature by being the first quasi-experimental procedure to examine the effects of the presence of worker safety vests on worker conspicuity in simulated construction work zones. Additionally, this is the first quasi experimental study to investigate the effects of the presence of a worker safety vests on worker conspicuity in simulated construction work zones using an interactive driving simulator and eye tracking technology. Future research is warranted in a few areas. First, an examination into the signal detection of screen based stimuli from peripheral vision as compared to the point of visual acuity is needed to understand the potential for participants to obtain visual screen based information from areas in the eye tracking data that lie outside the point of visual acuity. Second, research is needed in a real world and controlled track environment to determine if these results hold true outside of the simulator environment. Third, a study replicating actual NCDOT construction work zones in simulated and controlled real world settings would increase the ecological validity of these results. The recommendations for NCDOT moving forward are to continue to provide high visibility safety garments for employees in a manner which complies with safety standards of the authority having jurisdiction.

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1. Introduction

The construction industry is known to be one of the most inherently dangerous employment industries, warranting the adoption of a positive safety culture for improvement in overall safety performance (Dester & Blockely, 1993 and Abudayyeh et al., 2006). In 2018, there were 1,038 workplace fatalities in the construction industry (Bureau of Labor Statistics, n.d.). When considering only highway construction worker deaths, statistics show that from 2003 to 2017, 1,844 workers lost their lives at road construction sites with an average of 123 fatal work-related injuries at highway construction sites per year (Centers for Disease Control [CDC], 2019). Highway and street construction zones pose unique risks to workers as they are subject not only to the hazards on the construction site itself, but also to vehicular traffic outside of the work zone including public motorists, construction vehicles, and heavy machinery or equipment (Hinze & Teizer, 2011; Pratt et al., 2001). Transportation events accounted for 76% of roadway work zone fatal occupational injuries during the period of 2011-2017, with 60% of cases being that the worker was struck by a vehicle in the work zone (CDC, 2019). Prior research has demonstrated that traffic accidents in work zones are on the rise, contributing to both heavy incident-related costs to the industry and, more importantly, to fatal and serious non-fatal injuries of construction workers (Mohan & Zech, 2005 and Pratt et al., 2001).

Research has demonstrated that the identification of hazards is essential for management and adoption of effective safety interventions (Idris, 2016; Albert et al., 2014). Worker conspicuity is a known highway/road construction work zone hazard and has been identified as such by the Occupational Safety and Health Administration (OSHA). From 1985-1989, 22% of all construction fatalities were struck-by accidents, with the most common cause being related to lack of visibility of workers (Hinze & Teizer, 2011; OSHA, 2009). With construction workers being twice as likely to be killed by a motor vehicle as the average worker, adoption of a safety culture that improves worker visibility, particularly for flaggers and laborers, is becoming increasingly important (Ore & Fosbrooke, 1997; Romano et al., 2008). The American National Standards Institute (ANSI, 2015) stipulates that wearing high-visibility safety vests is mandatory for construction workers to reduce the likelihood of accidents. It is even suggested that workers confidence in safety garment effectives may influence compliance with their usage (Arditi et al., 2005). The fluorescent yellow/green color and fluorescent orange/red color of safety vests are generally considered as the most distinctive colors for high visibility vests. However, there is very limited research to date examining the effects of safety vest colors on worker conspicuity specifically in the context of construction safety. Even fewer studies have utilized eye tracking technology to examine the effects of vest color and design on driver's visual attention allocation in the construction work zone setting.

At present, there is concern in regard to understanding the visual attributes that drivers cast their visual attention to when navigating construction work zones. Traffic routes, traffic density, and environmental and construction conditions all have the potential to influence driver attention and behaviors in work zones. To successfully navigate through work zones, drivers must obtain visual information from their surroundings for decision making processes including the identification of onsite workers. Therefore, the following research question is presented: *Does the donning of worker safety vests increase the conspicuity of workers who operate in roadway construction work zones?*

This paper focuses on the intersection of participants visual scan of construction work zones and their visual attention to roadside workers.

2. Result of Literature Review

To accomplish the papers objectives, a literature review was conducted of peer-reviewed journals and conference proceedings from the following search databases: Google Scholar, ECU Laupus Library Data Base, IEEE Explore, Science Direct, and PubMed. Key search phrases included "construction work zone safety, construction worker conspicuity, pedestrian work zone safety, pedestrian conspicuity, worker visibility, pedestrian visibility, worker reflectivity, pedestrian reflectivity, reflectivity and worker conspicuity, reflectivity and pedestrian conspicuity, eye tracking, visual attention, signal detection, driving simulator, and driving simulation." The sections below connect industrial work zone fatalities, high visibility apparel, and the use of eye tracking technology in the context of work zone safety; define the context in which this study has been conducted; and provide necessary background to establish the authors' epistemological positioning for each of the variables under investigation. A full literature review can be found in Appendix A.

2.1 Highway Construction Work Zones

Each year, over 100 workers are killed and over 20,000 are injured in the street and highway construction industry (Pratt et al., 2001). Mohan and Zech (2005) performed a detailed analysis of the fatalities and severe injuries to construction workers on New York State Department of Transportation (NYSDOT) projects during the period of 1990-2001. They discovered that there were five common types of traffic accidents including: workspace intrusion, worker struck-by vehicle inside workspace, flagger struck-by vehicle, worker struck-by vehicle entering/exiting the workspace, and construction equipment struck-by vehicle inside workspace. These accidents fall into two types including (1) accidents occurring in the work area and (2) traffic accidents involving motorists and construction workers. Ore and Fosbroke (1997) found that laborers represented 41% of pedestrian fatalities and that flaggers account for 50% of pedestrian accidents. Additionally, Bryden and Andrew (1999) found that traffic accidents accounted for 22% of serious injuries and 43% of all fatalities to workers in construction work zones when 240 work zone accidents within NYSDOT, between 1993 and 1997, were analyzed. In later work, Bryden and Andrew (2000) evaluated 290 fatalities from 1993 to 1998. They found that on-foot workers are involved in 10% of all intrusion accidents, which were severe. Research by Hinze and Tiezer, (2011) evaluated 659 fatality accidents from a data pool of 13511 OSHA-investigated cases. It was discovered that blind spots, obstructions, and lighting conditions were the most common factors contributing to vision-related fatalities. Of the U.S. construction fatalities experienced in 2012, 17% (135 fatalities) resulted from workers being struck-by an object or a piece of construction equipment (BLS, 2013). Accidents in which a vehicle enters the work zone and strikes a construction worker tends to be the most severe due to the heavy impact of vehicles traveling at high speeds (Mohan & Zech, 2005). With North Carolina driving crashes increasing steadily over the last five years, it is becoming increasingly important to explore and improve on methods currently used to protect workers in order for the state to adhere to one of its core values: enhancement of worker safety (North Carolina Department of Transportation (NCDOT), 2019).

Though OSHA currently requires workers to wear high visibility apparel when they work as flaggers and when they are exposed to public vehicular traffic (United Sates Department of Labor, 2009), injuries from motor vehicle traffic are still likely to occur, with more than 87% of visibility-related fatalities being "struck-by" accidents (Hinze & Teizer, 2011). The highway construction industry faced an average of 773 lives lost per year between 1982-2017 (CDC, 2019), indicating a potential gap in OSHA requirements and employee use of proper high-visibility apparel. With the ever-accumulating risks to workers and the increase of vehicular traffic in work zones (Pratt et al., 2001), increasing worker visibility is essential to reduce accidents occurring in the work area and traffic accidents involving motorists and construction workers (Mohan and Zech, 2005; Golovina et al., 2016).

2.2 Conspicuity and High-Visibility Apparel

It is well known that high-visibility apparel improves the conspicuity of pedestrians and workers. In fact, the American National Standards Institute (ANSI, 2015) stipulates that wearing high-visibility safety vests is mandatory for construction workers to reduce the likelihood of accidents, and, based on a fatality investigation, NIOSH recommends that all workers on foot in roadway work zones should be required to wear a high-visibility safety garment (Romano et al., 2008). Defined as clothing that "incorporates combinations of luminescent and retro-reflective surfaces that combine to provide brilliant contrast against relatively obscure daytime and nighttime backgrounds," safety vests are commonly used in highway construction zones (Atallah & Blauer, 2006, p. 9). The fluorescent yellow/green color and fluorescent orange/red color of safety vests are generally considered as the most distinctive colors for high visibility vests, likely due to the fact that the colors red and orange have the longest wavelengths, closely followed by yellow and green on the visible light spectrum. Thus, these can be detected from further distances away. The concept of conspicuity or visibility has been explored extensively in research (Olson et al., 1981; Blomberg et al., 1986; Chen and Shen, 2016; Lahrmann et al., 2018; Shoji and Lovegrove, 2019) and several studies have specifically looked at evaluations of varying color effects (Kwan and Mapstone, 2004; Sayer and Mefford, 2004; Tuttle et al., 2009; Roge et al., 2011; Roge et al., 2019). Though very few have explored color and contrast combinations in different environmental contexts.

2.3 Construction Worker Conspicuity

Though perhaps not as extensively researched as cyclist and pedestrian conspicuity, there are some studies that have examined high-visibility apparel and its effects on conspicuity and safety of construction workers. Most of this research has taken place at night, however other studies have examined this topic in other contexts. In early laboratory research, Michon et al., (1969) analyzed several fluorescent and non-fluorescent colors to determine which should be recommended to improve conspicuity for those who work in on or near the road. The results suggest that fluorescent orange resulted in the shortest reaction times followed by yellow, fluorescent yellow, and white (Michon et al., 1969). Later, Turner et al., (1997) examined the conspicuity of safety clothing color in daytime construction work zone environments. In their study, subjects were required to look through a shutter and indicate the point at which they first identified safety clothing in a scene. These detection distances were recorded for each color in each of the work zones. Of 11 colors employed, red-orange was found to have the highest detection distance (Turner et al., 1997).

In a nighttime study, Arditi et al., (2004) measured the luminance of six commonly used safety vests in nighttime construction/maintenance work areas. The results suggest that yellow vests with silver 3M Scotchlite reflective material were more visible than the other four vests in nighttime conditions. This study also shows that the performance of safety vests in nighttime conditions is dependent not only on the characteristics of the vests (e.g., amount of retroreflective material, design of the vest, etc.) but also on the characteristics of the construction/maintenance sites (e.g., weather, lighting, traffic volume, etc.) (Arditi et al., 2004). In another field study, Sayer and Mefford, (2004) solicited ten licensed drivers to navigate a series of construction work zones in a controlled environment to investigate the effects of various attributes of retroreflective personal safety garments on worker conspicuity. Overall, the results suggest that the presence of a safety garment did improve pedestrian detection. Furthermore, blaze orange retroreflective trim color was found to be the most conspicuous color followed by white/silver. The red trimmed garment was found to be the lease conspicuous. In addition, the difference in retroreflective trim on the Class 2 and Class 3 vests did not have a significant effect on the conspicuity of pedestrians in the work zone. However, the Class 3 jacket was more conspicuous than the Class 3 vest. The difference in detection distance associated with the Class 3 jacket is suggested to be a result of how the retroreflective trim was positioned on the garment (Sayer and Mefford, 2004).

Sayer and Buonarosa, (2008) conducted a field study to examine the effects of high-visibility garment design on daytime pedestrian conspicuity in work zones. Specifically, they examined garment color, scene complexity, and other factors using naturalistic conditions on public roads in real traffic. In their study, sixteen drivers drove a 31 km route while searching for workers wearing a high-visibility safety garment along the side of the road. A total of four high visibility garments were used including a yellow-green Class 2 vest, a yellow-green Class 2 jacket, a red-orange Class 2 vest, and a red-orange Class 2 jacket. Detection distances between the fluorescent yellow-green and the fluorescent red-orange garments were not significantly different, nor were there any significant two-way interactions involving garment color (Sayer and Buonarosa, 2008).

In summary, this beneficial research on construction worker visibility suggests a few key themes. It was found that the presence of safety vests has been found to improve worker conspicuity in controlled studies (Michon, 1969; Sayer and Mefford, 2004). Furthermore, the color of the safety garment does affect conspicuity in nighttime conditions (Arditi et al., 2004). However, research suggests color alone may be insignificant in some conditions as tested in the studies included in this review (Buonarosa and Sayer, 2007; and Sayer and Buonarosa, 2008). Alternatively, it was found that the class garments (Sayer and Mefford, 2004) and the complexity of the driving scene (Sayer and Buonarosa, 2008) affect detection distances. This is supported by Arditi et al., (2004) who found that the characteristics of the construction site also affect conspicuity (Arditi et al., 2004), which can logically be linked to scene complexity. It was also found that the color of reflective striping affects detection distance (Michon, 1969; Turner et al., 1997; Sayer and Mefford, 2004;). Research into nighttime work suggests that night work poses threats to workers as they are not as easily identifiable at nighttime than during the day. This created challenges in improving worker visibility and conspicuity. However, work zone lighting could increase the distance at which workers could be detected (Finley et al., 2014 and Jafarnejad et al., 2018). Overall, it was found that retroreflective safety garments are necessary for both daytime and nighttime conditions (Michon, 1969; Turner et al., 1997; Arditi et al., 2004; Sayer and Mefford, 2004; Buonarosa and Sayer, 2007; Sayer and Buonarosa, 2008; Finley et al., 2014 and Jafarnejad et al., 2018) and pedestrians as well as workers can benefit from incorporating reflective strips on their ankles, knees, wrists, and elbows (Wood et al., 2014).

2.4 Eye Tracking Technology

One tool that may be underutilized in supplementing hazard recognition on road and highway construction sites is use of eye tracking technology. Eye tracking is a research technique used to model how subjects acquire information from visual stimuli (Bass et al. 2016 and Ashraf et al., 2018). Eye tracking systems capture data related to eye-movement that explain information acquisition, decision making processes, and attentional processes. Additionally, eye-tracking data provides evidence relating to eye position and movements of individuals as they process visual stimuli in real time (Duchowski 2002 and Bass et al. 2016). These systems have been accepted as a viable method to test for usability of human-computer interfaces (Goldberg and Kotval 1999; and Rashid et al. 2013), text-based reading research (Rayner 1998), scene perception research (Henderson and Hollingworth 1998), and investigations into the patterns of visual search processes (Findlay and Gilchrist 1998). Eye tracking is also an established research tool in several clinical settings, and the data it provides can indicate clinical skills, provide solutions for training individuals in different contexts, and aid in giving feedback and reflection (Ashraf et al., 2018).

Eye tracking technology is used to measure fixations, saccades, and eye scan paths of research participants (Vidal et al., 2012 and Bass et al. 2016). Fixations are defined as aggregations of eye gaze points and saccades are defined as rapid eye movements between fixations. Scan paths are thereby defined as the sequence of alternating fixations and saccades. These measurements are useful for determining what stimuli participants view, how long they view them, and the order in which the stimuli are viewed. Heat maps can also be generated from eye tracking data to show researchers the density of fixations over a general area of interest. These heat maps are used as a quantitative evaluation metric to identify the information within visual stimuli that is viewed the most times and/or for the longest periods. (Blascheck et al. 2014). For this research, focal attention is the primary metric of investigation. Focal attention occurs when a user focuses on a location within a visual stimulus with the intent of acquiring information. Eye tracking technology provides a platform for researchers to identify the proportion of a user's focal attention within redetermined locations of visual stimuli. This allows for the evaluation of eye gaze locations over time and can be used to generate a variety of inferences. Eye tracking technology is incredibly versatile and has been used across many disciplines to understand ocular and attentional behavior. It has been shown to be informative in construction research.

2.5 Interactive Driving Simulation

It is well known that highway work zones are particularly dangerous construction sites for both construction workers and drivers. The high hazard and dynamic nature of construction work zones make them particularly difficult to systematically analyze and control for experimental confounds in studies with high ecological validity. Interactive driving simulation is one method to reduce the risks of researchers, the public, and construction workers during work zone testing and allows for systematic control and evaluation of simulated work zone environments.

Interactive driving simulators are tools that allow the assessment of driving skills without involving the risks of on-road testing. Driving simulators offer many advantages for assessing on-road driving skills including providing a safe environment for the driver and evaluator, cost-effectiveness and time efficiency of testing, the ability to present situations that might not be available on the road or would potentially put the driver in danger, flexibility of scheduling driving sessions, and reproducibility of scenarios (Bédard et al., 2010; Cochran, 2015). Interactive driving simulators have been tested in relation to driving performance and are becoming increasingly popular (Owsley & McGwin, 2010). They can also be used to compare performance metrics across varied driver populations, or track performance of the same individual over time (Campos et al., 2017). Campos et al., (2017) discussed the usefulness of driving simulators as tools for identifying specific driving skills for intervention development and administration. In addition to increased safety in comparison to on-road testing, simulators are also more easily controlled and standardized, and can assess more challenging environmental and demanding task-based conditions. Multiple styles of driving simulators exist and have been found to have good external and ecological validity (Dickerson et al., 2018), producing results that can be generalized to on-road testing of the same driving conditions (Lee, 2006; Shechtman et al., 2009).

2.6 Driving Simulation and Eye Tracking

Eye tracking technology has also been used in field and simulated driving research as research has provided evidence of the ecological validity of using eye trackers to monitor driver behavior during driving tasks (Owsley and McGwin Jr., 2010; Chan et al., 2010; Mackenzie and Harris, 2015; Kunishige et al., 2019; and Robbins et al., 2019). For example, Owsley and McGwin Jr., 2010 found that interactive driving simulators could be used to uncover relationships between human vision and driving performance and that simulation aids drivers with visual impairments to improve critical driving skills before being exposed to actual on-road situations. For example, Chan et al. (2010) examined use of driving simulation as a tool for evaluating novice drivers' hazard anticipation, speed management, and attention maintenance skills in comparison to experienced drivers. They found that driving simulators capture behavioral differences between new and experienced drivers in the areas of anticipation of hazard, speed management, and attention maintenance. In another study, Mackenzie and Harris, 2015 assessed visual attention in both non-driving and driving hazard perception tasks. In their study, 34 participants either drove on a driving simulator for eight courses or watched a series of eight video clips of driving simulations while wearing eye-tracking technology to record eye movements. Results of the study showed that participants searched more of the road during non-driving condition, indicated by the small fixation distribution across horizontal and vertical planes in the driving condition.

Additionally, Kunishige et al., 2019 used driving simulation and eye tracking glasses (i.e., Tobii Glasses 2) together to quantify gaze behaviors to assess environment navigation and eye movements for younger and older drivers. Significant between-groups differences were found for these tests with older participants scoring significantly lower on attention, including visual search. These results show that eye tracking and driving simulation can be used to assess driving behaviors, particularly visual performance in relation to interacting with dynamic driving environments. Recently, Robbins et al., 2019 used Tobii Pro Glasses 2 to look at visual attention in both real and simulated driving environments. In their study, drivers' visual attention was measured at six intersections where maneuvers were controlled by the driver, and in six on-road situations where traffic was controlled by traffic signals and the road environment. Participants wore eye tracking glasses both on-road and in simulated conditions. Conditions in each scenario varied between low and medium demand driving situations Results showed that drivers had longer fixation durations in the simulator compared to on-road conditions. Additionally, the distances between drivers' fixations were shorter in low demand driving situations compared to medium demand driving situations. Additionally, results indicate that simulators and eye tracking technology can be useful in examining drivers' visual attention, particularly at intersections. Results of these studies validate the use of employing eye tracking technology and interactive driving simulators to understand the visual attention of drivers in simulated construction work zone environments.

Report Body

3.0. Research Objectives and Point of Departure

The two goals of this study were (1) to determine if the presence of a worker safety vest improves worker conspicuity; and (2) to determine which color, ANSI lime-yellow or ANSI fluorescent orange-red, is most conspicuous for both daytime and nighttime conditions. The six primary steps conducted to achieve these goals included the following:

(1) Develop experimental protocol
(2) Develop simulator pedestrian models for testing
(3) Construct simulator environments
(4) Recruit subjects for testing
(5) Conduct experimental testing by manipulating the safety vest presence and color, track condition, and environmental condition
(6) Examine the influence of the presence of and color of safety vest on the proportion of workers viewed across experimental conditions.

The corresponding null hypotheses are presented below:

Ho1: The color of worker safety vest does not affect conspicuity in simulated construction work zones.
Ho2: The presence of a worker safety vest does not affect conspicuity in simulated construction work zones.

This study departs from the current body of literature by being the first quasi-experimental procedure to examine the effects of the presence of worker safety vests on worker conspicuity in simulated construction work zones. Additionally, this is the first quasi experimental study to investigate the effects of the presence of a worker safety vests on worker conspicuity in simulated construction work zones using an interactive driving simulator and eye tracking technology. By addressing the identified gap in literature, the research community can better understand how to improve worker conspicuity inside live construction work zones.

4.0. Research Methods

The first step to accomplish the study objectives encompassed creating a series of simulated construction work zones in STISIM Drive software to be used for experimental testing. The second step of the study included conducting a series of quasi-experimental trials to identify the proportion of workers gazed upon in each scenario and investigate the variability of workers gazed upon across the study's experimental groups: one in which workers were wearing safety vests and one in which workers were not. A description of the research protocol and data processing and analysis methods are provided in the sections below.

4.1. Development of Simulated Construction Work Zones and Pedestrian Models

The first step of the research consisted of developing a series of simulated construction work zone driving tracks for experimental testing. For this study, a driving track is the game-based simulated environment that participants were asked to navigate through for the research trial. STISIM Drive software was used to create realistic game-based simulated construction work zone driving tracks. This software was selected as it is the host software for the physical driving simulator used in this study. The STISIM Drive software allows users to manipulate the parameters of simulated driving tracks including the time of day, fog conditions, traffic and pedestrian density, and simulated crash and hazardous conditions. The ability to control these track parameters is what allows researchers to manipulate the simulated track, control for potential confounding factors, and increase the experimental rigor of the study.

A series of driving tracks were created to simulate 2 and 4-lane, 2-way rural roads with construction work zones within each track. A total of three tracks were created for both day and nighttime conditions. This was done to effectively balance the experimental factors of track count and worker color conditions. Tracks were identified in the software as *Track 1*, *Track 2*, and *Track 3*. Each track was designed to be as realistic to United States road construction as practically feasible. Each construction work zone was developed to meet the 2009 Manual on Uniform Traffic Control Devices specs for signage and channeling devices. This was done to ensure that simulated construction work zones would meet realistic driving conditions and ensure uniformity of traffic control signage and devices across all the construction work zones developed. Each track contained only one work zone. Each work zone was of similar size and complexity to reduce potentially negative effects of confounds arising from track complexity and signage/device density within the work zones.

Once the driving tracks were developed, three-dimensional non player characters of construction workers were placed into each track for each included worker garment color. A total of 12 characters were placed into each track in the same locations regardless of garment color. Worker garment colors include white t-shirts, yellow safety vests, and orange safety vests. A total of ten worker characters were developed for this study. Eight of the ten characters were created by STISIM Drive Systems Technologies, Incorporated in the post award phase of the project. They include one of each of the following: 1) a tan skin male with orange ANSI Class II safety vest with yellow reflective striping, 2) a tan skin male with yellow ANSI Class II safety vest with orange striped reflective striping, 3) a light skin male with orange ANSI Class II safety vest with yellow reflective striping, 4) a light skin male with yellow ANSI Class II safety vest with orange striped reflective striping, 5) a tan skin female with orange ANSI Class II safety vest with yellow reflective striping, 6) a tan skin female with yellow ANSI Class II safety vest with orange striped reflective striping, 7) a light skin female with orange ANSI Class II safety vest with yellow reflective striping, and 8) a light skin female with yellow ANSI Class II safety vest with orange striped reflective striping. Safety vests were designed to the older NCDOT vest and the newer 2018 version currently being used by NCDOT employees. Once developed, these characters were uploaded into the STISIM software remotely and coded for research purposes. Additionally, two of the ten worker characters including existing tan and light skin males wearing only a white t-shirt and blue jeans were employed for this study to serve as baseline non player characters similar to research conducted by Blomberg et al. (1986) to serve as a control group. The models of worker characters with vests donned can be seen in Figure 1.0 below. The models of pedestrians without donned vests and white t-shirts can be seen in Figure 2.0 below. Figure 3.0 shows a front and back view of the Orange vest and Yellow vests.

Figure 1.0: Worker Characters with Donned Vests

Figure 2.0: Worker Characters with White T-Shirts

Figure 3.0: Front and Back view of Orange (Left) and Yellow (Right) Safety Vests.

4.2. Quasi Experimental Testing

4.2.1. Participant Selection

A total of 49 participants from the public of Eastern North Carolina and East Carolina University students were selected for this study. The public was selected as the target population as they may commonly encounter roadway construction work zones during routine driving activities. Students were solicited as a convenient sample. Participants were only allowed to participate if they had active drivers' licenses. All practical efforts were made to equally balance male to female drivers and younger to older drivers. However, COVID-19 restrictions did make sampling difficult due to participant and researcher interactions. Participants were provided $20.00 for participation via Walmart and Target gift cards. The sample population was selected to ensure the results of the study are generalizable to a broader population. An ANOVA sample size calculation ($\alpha = 0.05$) yielded $N = 27$ as a minimum number of observations for each experimental group in testing. This yields a total of $N=81$ minimum observations for testing. Once participants are identified, they were randomly assigned to a research module as outlined below. Table 1.0 below presents the participant demographic characteristics.

Table 1.0: Participant Demographic Characteristics

Demographic Characteristic	Count	Mean	Median	Standard Deviation	Minimal Value	Maximum Value
Age	-	24.35	23.00	5.45	20.00	50.00
Years of Driving Experience	-	9.11	8.00	5.35	4.00	34.00
Gender (Female/Male)	42 / 7	-	-	-	-	-
<u>Ethnicity Category</u> 1. African American 2. White Asian 3. Caucasian 4. White Latino	N = 49 3 1 44 1	-	-	-	-	-

4.2.2. Research Design

To study the effects of safety vest color on visual attention allocation, a counterbalanced and blocked research design, inspired by traditional Latin square designs, was developed. A Latin square is an experimental design that controls for the negative effects of multiple variable interactions by blocking the treatment and independent variables. Latin square designs are used to cross the treatment factors with the independent variables to assess the variability in the data of an independent variable for a single population group (Edwards, 1951 and McNemar, 1951). Latin square designs have been used in a wide variety of research including agriculture (Mead et al., 2003), metallurgy (Peng et al., 2016), and psychology (Edwards, 1951; McNemar, 1951; Birney et al., 2006; Baracz et al., 2016; and Daniel, 2016). Within Latin square designs, the number of levels of independent variables must equal the number of levels of the treatment factor. This creates an orthogonal (n x n) matrix in which no single treatment and independent variable combination can occur more than once in the experimental design. In traditional human research, each participant is typically randomly assigned to one cell within an intersecting row and column of independent and treatment variables. These designs are used to cross the treatment factors with the independent variables to ensure that negative effects of repeated observations are minimized and to assess the variability in the data of an independent variable for a single population group over a series of sequential research trials (Edwards, 1951; McNemar, 1951).

An adapted 3x3 counterbalanced and blocked design (see Table 2.0) was developed to cross the 3 treatment factors (i.e., garment colors) with the 3 independent variables (i.e., track ID) for both day and nighttime environmental conditions. This resulted in a counterbalanced 3-factor blocked design; factors of primary investigation include worker character garment color, track ID, and order or the research trials. By doing so, any experimental error potentially occurring through these variables was controlled. The worker character garments colors include *White T-Shirt*, *Yellow Vest*, and *Orange Vest*, respectively. The track ID's include *Track 1*, *Track 2*, and *Track 3*. Finally, the dependent variable is proportion of worker characters gazed upon for each of the treatment variables crossed with the independent variables. Furthermore, environmental conditions such as day and nighttime conditions are balanced equally throughout each treatment and independent variable as they are investigated outside of primary hypothesis testing.

For the experimental design, participants were randomly assigned to a research module consisting of 3 sequential experimental trials. During experimental trials, each participant was asked to navigate 3 tracks in a predetermined order as defined by the randomly assigned research module. Research modules were created to facilitate the experimental trials by indicating the correct arrangement of track ID, worker garment color, and environmental condition for each of the three experimental trials. For this experiment, the research modules were designed around track ID and garment color. Research design ensures the tracks in which participants drove were counterbalanced across the sequential research trails to reduce confounds arising from any gained navigation experience the participant may have acquired during the sequence of research trials. In total, there were six unique arrangements in which the three track IDs could be arranged in a sequential manner (i.e., 3 x 2 x 1 = 6). Additionally, each of the three worker garment colors were arranged into six unique arrangements within each individual track arrangement. This yielded a total of 36 unique and mutually exclusive research modules in which participants were randomly assigned to.

Table 2.0: Block Design and Participant Observations by Experimental Condition

Track ID	Experimental Condition								
	Orange Vets			Yellow Vest			White T-Shirt		
	Day	Night	Total	Day	Night	Total	Day	Night	Total
1	N = 9	N = 8	N = 16	N = 8	N = 8	N = 16	N = 8	N = 8	N = 16
2	N = 8	N = 8	N = 16	N = 9	N = 8	N = 16	N = 8	N = 8	N = 16
3	N = 8	N = 8	N = 16	N = 8	N = 8	N = 16	N = 8	N = 9	N = 16
Total Observations	N = 25	N = 24	N = 49	N = 25	N = 24	N = 49	N = 24	N = 25	N = 49

4.2.3. Conducting Experimental Trials

The experimental trials were conducted in a controlled laboratory setting at East Carolina University’s Allied Health Science Campus. In the beginning of the experiment, participants were briefed about the experimental procedure in a manner to not introduce any potential confounds or biases into the experiment. Once briefed, participants signed the consent form and completed a brief demographic questionnaire. Participant demographic data included participant age, years of driving experience, gender, ethnicity, and education level. The demographic questionnaire can be found in Appendix A. Once the participant completed the demographic questionnaire, they were placed into the driving simulator and were fitted with a head mounted Tobii 2 eye tracker. The researcher then informed the participant of the simulator controls and instructed the participant to complete a navigation scenario of a “free drive” that allowed the participant to practice and accommodate to the driving simulator and demonstrate navigational abilities and skills without specific directions or guidance.

Once the “free drive” was complete, the researcher performed calibration procedures for the Tobii 2 Pro Glasses unit. Calibration is the process whereby the geometric characteristics of a subject’s eyes are estimated as the basis for a fully customized and accurate gaze point calculation (Tobii, 2018). After calibration, the researcher initiated the correct sequence of experimental trials as dictated by the module ID. For the experiment, participants were provided screen-based instructions which stated to “*Successfully navigate the road conditions without vehicular crashes and maintain compliance with all roadway rules*.” Participants were not informed of roadway work zones or pedestrian details to avoid any potential bias. In the event of crashes, participants were allowed to restart the simulation from the crash location until successful completion is achieved. Participant time was not limited, reducing any feeling of being rushed to complete the tasks as a distraction. However, the total time of the research trial was recorded including the time from the beginning of the research trial until the participant passed the finish line at the end of the track. This time was collected for each of the three individual tracks navigated by the participant. Post calibration procedures were also conducted to ensure the glasses were collecting data representative of the participants actual gaze point and the glasses had not shifted on the participants face and/or head compromising the quality of the data. Once the last track was completed, the researcher doffed the eye tracking glasses and instructed the participant to step out of the simulator. At this time, the participant was debriefed about the experiment and was provided the monetary incentive for participation. All research trials were recorded and coded for downstream analysis. All data was kept in accordance with East Carolina University's Institutional Review Board requirements.

4.2.3.1 Trans-Sit Driving Simulator

The Trans-Sit simulator used in this study was manufactured by Advanced Therapy Products and is a 48-by-60-in. mock-up of a car with a moveable steering wheel, functional doors, handles, locks, seat belts, moveable seats, a gas pedal, and a brake pedal (Advanced Therapy Products, 2014). It has been fitted with three 27" LCD screens that portray animated images of an on-road environment. The simulator software, STISIM Drive (Systems Technology, n.d.), has demonstrated accessibility and transferability between simulator and on-road performance (Lee et al., 2006; Shechtman et al., 2009). Box fans were positioned in front of the participant to blow cool air across the simulator body to reduce the ambient temperature and help with participant comfort. The Trans-Sit simulator can be seen in Figure 4.0 below.

Figure 4.0: Trans-Sit Simulator and Driver View with Gaze Point

4.2.3.1 Tobii Eye Tracking

For this experiment, Tobii Pro Glasses 2 were employed for data collection and analysis. The Tobii Pro Glasses 2 is a head mounted eye tracking system that records binocular gaze direction, pupil size, and the 3D orientation of each eye in a coordinate system. The system includes a head and hip mounted recording unit that captures what the participant sees, relevant eye tracking data, and participants verbal comments and simultaneously saves the data to an SD card. The controller software allows the researcher to control the recording functions, apply calibration techniques, and observe what the participant sees and all surrounding visual stimuli in real time. The output of the eye-tracking setup consists of the video of the scene camera along with gaze direction which is reported in the video frame of the scene camera. Tobii Pro Glasses 2 recording data are analyzed on Tobii closed commercial software, Tobii Pro Lab. Some researchers have suggested that Pro Lab offers insufficient flexibility and control over the various analysis steps as the software is suggested to be limited in its functionality (Benjamins et al., 2018 and Neihorster et al., 2020). However, Pro lab does offer a workflow for manually mapping gaze data and observing gaze locations for each video frame recorded within each of the recorded research trials. This was found to be sufficient to answer the research hypotheses presented and thereby supports the use of Tobii Pro lab as a standalone analysis tool. An image of the Tobii Pro Glasses 2 is in figure 5.0 below.

Figure 5.0: Tobii Pro Glasses 2 Head and Recording Unit

4.3. Data Processing and Analysis

The raw eye tracking data were sampled using Tobii Pro Lab software. Initially, the raw data were stored on the hip mounted controller unit and were transferred to a desktop computer. Once uploaded into the Tobii Pro Lab software, the research analyzed the data for each experimental trial individually. To analyze each track, the researcher observed each research trial recording, which were recorded at a 50 Hz sampling rate. Thereby, recording 50 samples of video frame for each second of recording. Each recording was played back in the analyzer software frame-by-frame. The location of the participants eye gaze was represented in the software within each frame of the recording as an opaque red circle displayed as an overlay to in the video recording. This overlay represents a person's attentional focus at any point in time. The Tobii software allows for the tracking circle to be exported at varying sizes. A tracking circle size was selected to ensure the circle was large enough to be detected by the researcher and not too large to cover up or wash out the background worker characters of interest. Additionally, the overlay was set to an opaque factor of 25% to ensure the researcher could observe both the circle and the object behind the overlay. The researcher played the video in the analysis software by advancing through the frames individually and indicating if the overlay circle was overlaying a worker. This analysis process was completed 3 times for each trial to ensure accuracy of the recorded data. If the circle was overlaying a worker, the frame was considered to be a "hit" indicating the worker was seen by the participant. However, if the circle was not overlaying a worker, the frame was considered to be a "miss" indicating the worker was not seen by the participant. Each worker's position on the roadway was predetermined in the development of the driving tracks and remained consistent throughout the track for all garment colors and environmental conditions. Therefore, researchers were able to code each worker consistently and accurately as being seen or unseen in each of the research trials. Although being seen by the participant was of interest, no analysis was conducted to determine the count of frames each of the workers was either seen or unseen. An observation of participants post-calibration procedure was observed by the researcher to ensure accurate and precise data with each research trial.

The resulting "hit" and "miss" data yielded the total number of workers in each of the experimental trials that were seen and unseen by the participants. Next, proportion data were calculated for each of the research trials based on the number of worker characters seen versus the total number of workers in each driving track. This proportion data is thereby referred to as the Conspicuity index (C_{index}). Therefore, the numerator in equation 1 is the total number of worker characters, in which a single overlay circle "hit" the worker character. The denominator is the total number of worker characters in the driving track, which was set to 12. This proportion simply allows for the quantification of the number of worker characters seen within each of the experimental conditions. The (C_{index}) is presented below in [Eq. (1)].

$$[1]C_{index} = \frac{\text{Total \# of Worker Characters Seen in Each Track}}{12}$$

Findings and Conclusions

5.0. Results

5.1. Analysis of Variance

An Analysis of Variance (i.e., ANOVA) statistical approach was used to test Ho1: *The color of worker safety vest does not affect conspicuity in simulated construction work zones*. Additionally, ANOVA analysis was used to test hypothesis Ho2: *The presence of a worker safety vest does not affect conspicuity in simulated construction work zones*. Specifically, ANOVA analysis was applied to examine the variability of the Conspicuity Index or C_{index} (i.e., proportion of worker characters seen) across the independent variables (i.e., worker character garment colors). All data come from a normal distribution (all $p > 0.05$). The ANOVA statistical test determines whether there is a difference between means of independent variables. This test estimates statistically significant differences between the means using an F value while measuring the variability of the dependent variable that is explained by the independent variable. Table 3.0 below provides the sample size, C_{index}, F, and p values of ANOVA analysis. This analysis is independent of driving track ID and the order of research trial as these variables were blocked in the adapted Latin square design and their effects controlled.

Table 3.0: ANOVA Results

Garment Color	Sample Size	C_{index}	*F*	p
Orange Vest	49	0.5255	8.635	0.0002*
Yellow Vest	49	0.5340		
White T-Shirt	49	0.3741		

Note: F = variance of the group mean; p = significance.
Asterisk (*) = Statistically significant difference beyond 95% confidence.

The results of the ANOVA analysis suggest there is a significant difference in the proportion of workers seen by the participants across all garment colors and driving tracks presented to the research participants ($p = 0.0002$). From the ANOVA results in Table 1.0 above, the mean values and standard deviation of the C_{index} are ($\mu = 0.5255$, SD = 0.2206) for the Orange Vest garment color, ($\mu = 0.5340$, SD = 0.2482) for the Yellow Vest garment color, and ($\mu = 0.3741$, SD = 0.1962) for the workers with White T-Shirts. There is a statistically significant difference between the C_{index} of the White T-Shirt group garment color group and the overall group mean ($F = 8.635$, $p = 0.0002$). However, the C_{index} are relatively equal between the Orange Vest ($\mu = 0.5255$) and Yellow Vest ($\mu = 0.5340$) garment group. There is no significant difference between the C_{index} for the Orange Vest and Yellow Vest garment group. Due to the blocking of the experiment design, these results are independent of track ID or the experimental trial. Therefore, the authors fail to reject Ho1 and conclude that the color of worker safety vest does not affect conspicuity in simulated construction work zones.

These results were also used to test research hypothesis Ho2. ANOVA results were used to determine if the presence of a safety vest improved worker conspicuity. The results suggest the C_{index} for the Orange Vest ($\mu = 0.5340$) and Yellow Vest ($\mu = 0.5340$) were significantly higher than the White T-Shirt group ($\mu = 0.3741$) ($F = 8.635$, $p = 0.0002$). Therefore, the authors reject hypothesis Ho2 and conclude that the presence of a worker safety vest does affect conspicuity in simulated construction work zones. Figure 6.0 below provides a box and whisker plot of C_{index} across worker garment color categories.

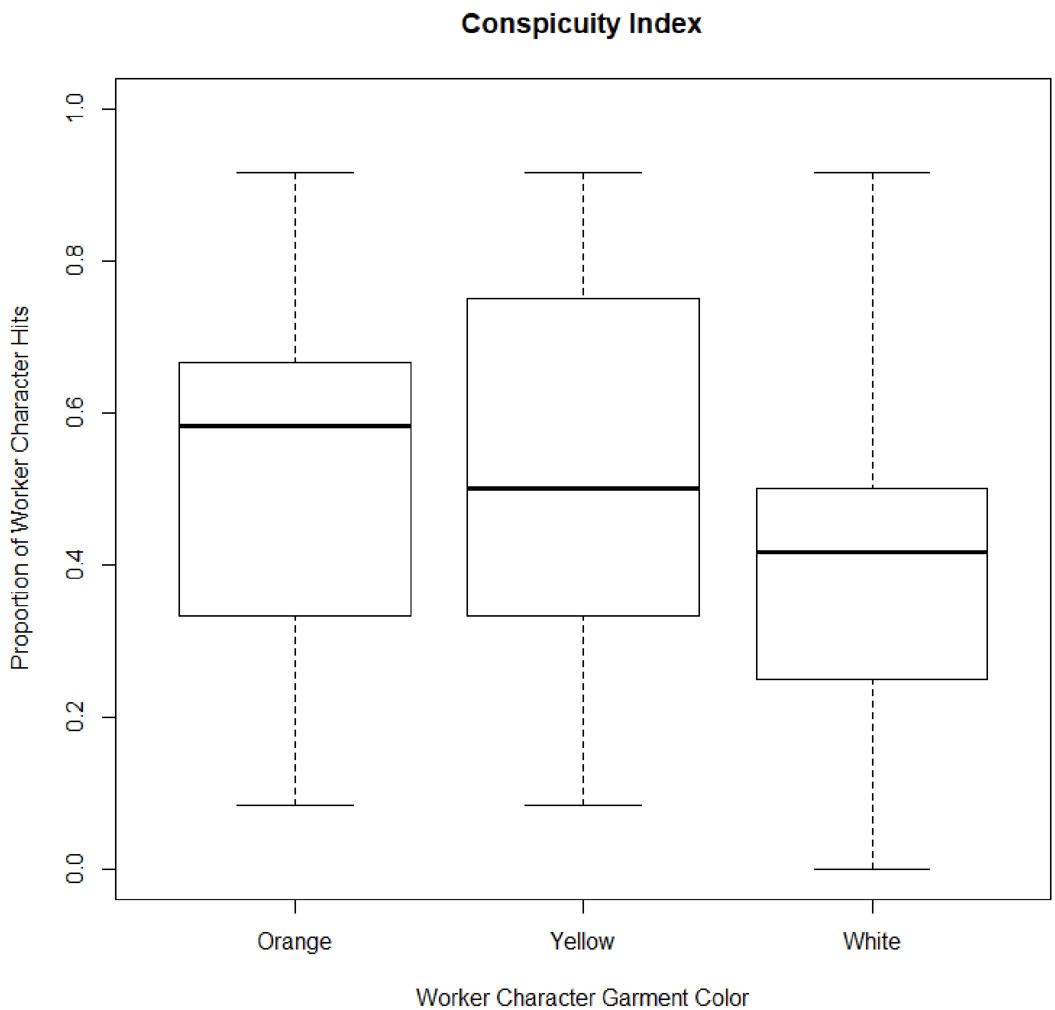

Figure 6.0: Box and Whisker Plot of Conspicuity Index across Worker Garment Color Categories

5.2. Mean and Dispersion t tests (Proportion Across and Within All Tracks)

A mean and dispersion t-test was performed in the statistical software MVPStats to further examine hypothesis Ho2: *The presence of a worker safety vest does not affect conspicuity in simulated construction work zones*. A mean and dispersion t-test was performed to evaluate the differences of C_{index} between the aggregate of all treatment (i.e., orange and yellow safety vest colors) and control (i.e., white t-shirt) across and within each track. Specifically, t-tests were used to examine the differences in C_{index} between the aggregate of worker characters with donned orange and yellow safety vests and worker characters skinned with white t-shirts. This test was completed across and within each track ID. Table 4.0 below provides the driving track condition, worker character category, sample size, mean C_{index}, and *t*, and *p* values.

Table 4.0: C_{index} Two-Sample Independent Mean and Dispersion Test Results

Driving Track Condition	Worker Character Category	Sample Size	C_{index}	Percent Difference	t	P
All Tracks	Orange and Yellow Vests	98	0.5298	15.56%	4.007	0.000*
	White T-Shirts	49	0.3742			
Track 1	Orange and Yellow Vests	33	0.4495	11.62%	1.917	0.061**
	White T-Shirts	16	0.3333			
Track 2	Orange and Yellow Vests	33	0.5177	17.92%	3.305	0.002*
	White T-Shirts	16	0.3385			
Track 3	Orange and Yellow Vests	32	0.6250	17.89%	2.607	0.012*
	White T-Shirts	17	0.4461			

Note: t = t-test statistic; p = significance.
Asterisk (*) = Statistically significant difference beyond 95% confidence.
Asterisk (**) = Statistically significant difference beyond 90% confidence.

As can be seen from Table 4.0 above, the pairwise t-test results suggest there is a significant difference in the mean C_{index} for the Orange and Yellow Vests ($\mu = 0.5298$) and White T-Shirts ($\mu = 0.3742$) garment color groups across all track conditions ($t = 4.007$, $p = 0.000$). Due to these results, it is suggested that the provision of worker safety vest does affect worker conspicuity in simulated construction work zones. In fact, there was a 15.56% increase in the C_{index} for the Orange and Yellow Vests garment color group when analyzed across all tracks. A within track assessment was also conducted to determine if this result is consistent within each track. The pairwise t-test results for Track 1 suggest there was an 11.62% increase in the C_{index} for the Orange and Yellow Vests ($\mu = 0.4495$) when compared to the White T-Shirts ($\mu = 0.3333$) garment color groups. The results suggest there is a significant difference (at 90% confidence) in the C_{index} within Track 1 ($t = 1.917$, $p = 0.061$). Additionally, the pairwise t-test results for Track 2 suggest there was an 17.92% increase in the C_{index} for the Orange and Yellow Vests ($\mu = 0.5177$) when compared to the White T-Shirts ($\mu = 0.3385$) garment color groups. The results suggest there is a significant difference in the C_{index} within Track 2 ($t = 3.305$, $p = 0.002$). Furthermore, the pairwise t-test results for Track 3 also suggest there was an 17.89% increase in the C_{index} for the Orange and Yellow Vests ($\mu = 0.6250$) when compared to the White T-Shirts ($\mu = 0.4461$) garment color groups. The results suggest there is a significant difference in the C_{index} within Track 3 ($t = 2.607$, $p = 0.012$). These results indicate that the provision of a safety vest improves the C_{index} across and within all tracks and cross validates the ANOVA analysis results. Therefore, the authors reject hypothesis Ho2 and conclude that the presence of a worker safety vest does affect and improve worker conspicuity in simulated construction work zones.

5.3. Mean and Dispersion Testing for C_{index} Across Driving Tracks for Orange and Yellow Vest Colors.

A mean and dispersion t-test was performed to examine the effect of safety vest garment color on the C_{index} across all and within each driving track. Specifically, t-tests were used to examine the differences in C_{index} between the aggregate of orange and yellow vest colors by removing the data from the data set in which worker characters were skinned with white t-shirts. As a result, the sample size is reduced but sufficient sample size remains for testing. This test was completed across and within each track ID. Table 5.0 below provides the driving track condition, safety vest color category, sample size, mean C_{index}, and *t*, and *p* values.

Table 5.0: C_{index} Two-Sample Independent Mean and Dispersion Test Results

Driving Track Condition	Safety Vest Color	Sample Size	C_{index}	Percent Difference	t	P
All Tracks	Orange Vest	49	0.5255	1.60%	-0.179	0.858
	Yellow Vest	49	0.5340			
Track 1	Orange Vest	17	0.5098	27.79%	2.113	0.043*
	Yellow Vest	16	0.3854			
Track 2	Orange Vest	17	0.4948	8.58%	-0.516	0.610
	Yellow Vest	16	0.5392			
Track 3	Orange Vest	16	0.5729	16.67%	-1.211	0.235
	Yellow Vest	16	0.6771			

Note: t = t-test statistic; p = significance.
Asterisk (*) = Statistically significant difference beyond 95% confidence.
Asterisk (**) = Statistically significant difference beyond 90% confidence.

As can be seen from Table 5.0 above, the pairwise t-test results suggest there is no significant difference in the mean C_{index} for the Orange Vest ($\mu = 0.5255$) and Yellow Vest ($\mu = 0.5340$) conditions across all driving tracks ($t = -0.179$, $p = 0.858$). Due to these results, it is suggested that the color of safety vest does not affect worker conspicuity in simulated construction work zones across all driving tracks. There was only a slight 1.60% difference in the C_{index} between the orange and yellow vest colors when analyzed across all tracks. A within track assessment was also conducted to determine if this result is consistent within each track. The pairwise t-test results for Track 1 suggest there was a 27.79% difference in the C_{index} for the Orange Vest ($\mu = 0.5098$) compared to the Yellow Vest ($\mu = 0.3854$) condition for Track 1. The results suggest there is a significant difference at 95% confidence in the C_{index} within Track 1 ($t = 2.113$, $p = 0.043$*) suggesting orange vests are more conspicuous in Track 1. The pairwise t-test results for Track 2 suggest there was an 8.58% difference in the C_{index} for the Orange Vest ($\mu = 0.4948$) compared to the Yellow Vest ($\mu = 0.5392$). The results suggest there is no significant difference in the C_{index} within Track 2 ($t = -0.516$, $p = 0.610$). Furthermore, the pairwise t-test results for Track 3 suggest there was a 16.67% difference between the Orange Vest ($\mu = 0.5729$) when compared to the Yellow Vest ($\mu = 0.6771$) within Track 3 ($t = -1.2119$, $p = 0.235$).

The results suggest there is no significant difference in the C_{index} between Orange Vests and Yellow Vests across all tracks ($t = -0.179$, $p = 0.858$). However, within Track 1, there was a significant difference in the C_{index} for the Orange Vest ($\mu = 0.5098$) compared to the Yellow Vest ($\mu = 0.3854$) condition ($t = 2.113$, $p = 0.043$*) indicating orange vests are more conspicuous in Track 1. However, track 2 and 3 lacked significance to suggest either color improved worker conspicuity within these tracks. In Track 3, there was a 16.67% percent difference between the yellow and orange colors. However, this percent difference was found to be insignificant ($p > 0.05$).

5.4. Mean and Dispersion Testing for C_{index} Across Environmental Condition for All Garment Colors.

A mean and dispersion t-test was performed to examine the effect of daylight conditions on the C_{index} across all and within each track. Specifically, t-tests were used to examine the differences in C_{index} between the aggregate of Daytime and Nighttime environmental conditions. The effect of garment color is not analyzed. Only the proportion of worker hits across all garment colors is evaluated. This test was completed across and within each track ID. Table 6.0 below provides the driving track condition, environmental condition category, sample size, mean C_{index}, and *t,* and *p* values.

Table 6.0: C_{index} Two-Sample Independent Mean and Dispersion Test Results

Driving Track Condition	Environmental Condition	Sample Size	C_{index}	Percent Difference	t	P
All Tracks	Daytime	74	0.4741	2.16%	-0.198	0.844
	Nighttime	73	0.4817			
Track 1	Daytime	25	0.4000	5.73%	-0.401	0.690
	Nighttime	24	0.4236			
Track 2	Daytime	25	0.4667	3.33%	0.231	0.818
	Nighttime	24	0.4514			
Track 3	Daytime	24	0.5590	1.36%	-0.109	0.913
	Nighttime	25	0.5667			

Note: t = t-test statistic; p = significance.
Asterisk (*) = Statistically significant difference beyond 95% confidence.
Asterisk (**) = Statistically significant difference beyond 90% confidence.

As can be seen from Table 6.0 above, the pairwise t-test results suggest there is no significant difference in the mean C_{index} for the Daytime ($\mu = 0.4741$) and Nighttime ($\mu = 0.4817$) conditions across all track conditions ($t = -0.198$, $p = 0.844$). Due to these results, it is suggested that daylight conditions not affect worker conspicuity in simulated construction work zones across all garment colors. In fact, there was a 2.16% difference in the C_{index} for Nighttime condition when analyzed across all tracks. A within track assessment was also conducted to determine if this result is consistent within each track. The pairwise t-test results for Track 1 suggest there was a 5.73% difference in the C_{index} for the Daytime ($\mu = 0.4000$) compared to the Nighttime ($\mu = 0.4236$) condition across all garment colors. The results suggest there is no significant difference in the C_{index} within Track 1 ($t = -0.401$, $p = 0.690$). Additionally, the pairwise t-test results for Track 2 suggest there was an 3.33% difference in the C_{index} for the Daytime ($\mu = 0.4667$) condition compared to the Nighttime ($\mu = 0.4514$) condition. The results suggest there is no significant difference in the C_{index} within Track 2 ($t = 0.231$, $p = 0.818$). Furthermore, the pairwise t-test results for Track 3 suggest there was only a slight 1.36% difference between the Daytime ($\mu = 0.5590$) when compared to the Nighttime ($\mu = 0.5667$) condition across all garment colors ($t = -0.109$, $p = 0.913$). The results suggest there is no significant difference in the C_{index} between Daytime or Nighttime conditions across and within all tracks. Therefore, the authors suggest the presence of daylight does not affect worker conspicuity regardless of garment color. More investigation is needed to determine if removing the worker characters which are skinned with white t-shirts may change the results of this data.

5.5. Mean and Dispersion Testing for C_{index} Across Environmental Condition for Orange and Yellow Vest Garment Colors.

A mean and dispersion t-test was performed to examine the effect of daylight conditions on the C_{index} across all and within each track for only the orange and yellow vest garment colors. Specifically, t-tests were used to examine the differences in C_{index} between the aggregate of Daytime and Nighttime environmental conditions for vest colors by removing the data from the data set in which worker characters were skinned with white t-shirts. As a result, the sample size is reduced but sufficient sample size remains for testing. This test was completed across and within each track ID. Table 7.0 below provides the driving track condition, environmental condition category, sample size, mean C_{index}, and *t*, and *p* values.

Table 7.0: C_{index} Two-Sample Independent Mean and Dispersion Test Results

Driving Track Condition	Environmental Condition	Sample Size	C_{index}	Percent Difference	t	P
All Tracks	Daytime	50	0.5450	6.16%	0.681	0.497
	Nighttime	49	0.5124			
Track 1	Daytime	17	0.4510	0.68%	0.049	0.962
	Nighttime	16	0.4479			
Track 2	Daytime	17	0.5392	8.58%	0.516	0.610
	Nighttime	16	0.4948			
Track 3	Daytime	16	0.6510	8.32%	0.595	0.556
	Nighttime	16	0.5990			

Note: t = t-test statistic; p = significance.
Asterisk (*) = Statistically significant difference beyond 95% confidence.
Asterisk (**) = Statistically significant difference beyond 90% confidence.

As can be seen from Table 7.0 above, the pairwise t-test results suggest there is no significant difference in the mean C_{index} for the Daytime ($\mu = 0.5405$) and Nighttime ($\mu = 0.5124$) conditions across all track conditions ($t = 0.681$, $p = 0.497$). Due to these results, it is suggested that daylight conditions not affect worker conspicuity in simulated construction work zones across safety vest garment colors. However, there was a 6.16% difference in the C_{index} between the daytime and nighttime conditions when analyzed across all tracks. A within track assessment was also conducted to determine if this result is consistent within each track. The pairwise t-test results for Track 1 suggest there was a 0.68% difference in the C_{index} for the Daytime ($\mu = 0.4510$) compared to the Nighttime ($\mu = 0.4479$) condition across all garment colors. The results suggest there is no significant difference in the C_{index} within Track 1 ($t = 0.049$, $p = 0.962$). Additionally, the pairwise t-test results for Track 2 suggest there was an 8.58% difference in the C_{index} for the Daytime ($\mu = 0.5392$) condition compared to the Nighttime ($\mu = 0.4948$) condition. The results suggest there is no significant difference in the C_{index} within Track 2 ($t = 0.516$, $p = 0.610$). Furthermore, the pairwise t-test results for Track 3 suggest there was a 8.32% difference between the Daytime ($\mu = 0.6510$) when compared to the Nighttime ($\mu = 0.5990$) condition across safety vest garment colors ($t = -0.109$, $p = 0.913$). The results suggest there is no significant difference in the C_{index} between Daytime or Nighttime conditions across and within all tracks for orange or yellow vest colors. However, these was an increase in the percent difference for daytime conditions across all and within each track. Although percent differences exist, the consistent levels of non-significance of the pairwise t-test results suggest presence of daylight does not affect worker conspicuity regardless of safety vest garment color. More investigation is needed to determine if removing the worker characters which are skinned with white t-shirts may change the results of this data.

6. Discussion

This investigation primarily explores the effects of the color of worker safety vests on worker conspicuity in simulated construction work zones. Additionally, this is the first quasi experimental study to investigate the effects of the presence of a worker safety vests on worker conspicuity in simulated construction work zones using an interactive driving simulator and eye tracking technology. The two goals of this study were (1) to determine if the presence of a worker safety vest improves worker conspicuity; and (2) to determine which color, ANSI lime-yellow or ANSI fluorescent orange-red, is most conspicuous for both daytime and nighttime conditions. Analysis of Variance (i.e., ANOVA) statistical results found that there is a significant difference in the proportion of workers seen by the participants across all garment colors and driving tracks presented to the research participants ($p > 0.0002$). From the ANOVA results in Table 3.0 above, the mean values and standard deviation of the C_{index} are ($\mu = 0.5255$, SD = 0.2206) for the Orange Vest garment color, ($\mu = 0.5340$, SD = 0.2482) for the Yellow Vest garment color, and ($\mu = 0.3741$, SD = 0.1962) for the workers with White T-Shirts. There is a statistically significant difference between the C_{index} of the White T-Shirt group garment color group and the overall group mean ($F = 8.635$, $p = 0.0002$). However, the C_{index} are relatively equal between the Orange Vest ($\mu = 0.5255$) and Yellow Vest ($\mu = 0.5340$) garment group. There is no significant difference between the C_{index} for the Orange Vest and Yellow Vest garment group.

These results indicate that there was no significant difference in the C_{index} for the Orange Vest and Yellow Vest garment groups. The orange and yellow vests were provided by the research team at NCDOT and were modelled by STISIM Inc. personnel and were used as worker character clothes (i.e. skins) in the simulator models. This was done to ensure the worker vests used in the simulator environments were a replica of those used by NCDOT employees. The eye tracking results of this study suggest that either vest is appropriate for workers to don in construction work zones. Additionally, the results indicate that the presence of a safety vest, in either color, does improve worker conspicuity. When observing the eye tracking data across all driving tracks, drivers did cast their visual attention to workers wearing safety vests at a higher percentage rate (C_{index}) for worker characters skinned with vest compared to worker characters skinned with white t-shirts.

Additional exploratory analysis was conducted to examine the effects of safety vest garment color on worker conspicuity across all and within each track. Mean and dispersion t-test procedures were performed to evaluate the differences of C_{index} between the aggregate of all treatment (i.e., orange and yellow safety vest colors) and control (i.e., white t-shirt) across and within each track. The pairwise t-test results suggest there is a significant difference in the mean C_{index} for the Orange and Yellow Vests ($\mu = 0.5298$) and White T-Shirts ($\mu = 0.3742$) garment color groups across all track conditions ($t = 4.007$, $p = 0.000$). These results cross-validate the results of the ANOVA analysis. Within track pairwise t-test analysis results show a significant difference for Track 1 at 90% confidence ($p = 0.061$), Track 2 at 95% confidence ($p = 0.002$), and Track 3 at 95% confidence ($p = 0.012$) indicating higher mean values C_{index} for the safety vest colors. Details can be found in Table 4.0 above.

Further exploratory analysis was conducted to examine the variability in C_{index} for orange safety vests and yellow safety vests across all and within each track. This was completed by using the same pairwise t-test procedures and removing the white t-shirt color data from the data set. The results suggest there was no significant difference in C_{index} for orange safety vests and yellow safety vests across all tracks or within Tracks 2 and 3 ($p > 0.05$). However, there was a significant difference in C_{index} for Track 1 ($p = 0.043$) with the C_{index} for orange safety vests being 27.79% higher than yellow safety vests. It remains inappropriate to make assumptions as to why the C_{index} for orange safety vests is higher in Track 1 than in Track 2 or 3. The counterbalanced blocked design appropriately controls the potential confounds from trial ID or track ID. However, there may be some underlying characteristic of Track 1 that promotes greater visibility of orange safety vests.

A mean and dispersion t-test was performed to examine the effect of daylight conditions on the C_{index} across all and within each track. Specifically, t-tests were used to examine the differences in C_{index} between the aggregate of Daytime and Nighttime environmental conditions. This was completed independent of all worker garment colors (i.e. data included orange vest, yellow vest, and white t-shirts) across and within each track. This t-test procedure was also completed independent of worker safety vest garment colors (i.e. data included orange vest and yellow vest colors) across and within each track. The results suggest there was no significant difference in the C_{index} for Daytime and Nighttime environmental conditions across all and within each track for both sets of data which included: (1) all worker garment colors and (2) only worker safety vest colors (all $p > 0.05$). These results indicate that daylight conditions had no effect on the conspicuity of workers in simulated construction environments. See tables 6.0 and 7.0 for more details.

Overall, there were 49 research participants who completed the study. Of these, 42 (85.71%) were female and 7 (14.29%) were male. The average age of the research participant was 24.35 years. A total of 44 (89.80%) participants were white, 3 (6.12%) were African American, 1 (2.04%) was White Asian, and 1 (2.04%) identified as White Latino. Please see table 1.0 for additional demographic information. Exploratory analysis was conducted to determine if participant age and years of driving experience were related to the C_{index} across all research trials for both orange and yellow safety conditions independent of Track ID. The results from the Pearson-r correlation suggest that neither participant age or experience were related to the C_{index} for the orange safety vest or yellow safety vest condition independent of Track ID (all $p > 0.05$). This suggests that participant age and driving experience will not affect the proportion of workers that participants cast their visual attention to regardless of safety vests color. Lastly, at the end of each experiment, each participant was debriefed and asked a follow question to identify which vest color the participant thought was more conspicuous. Specifically, participants were asked the following question:

Color Preference (Check One): In this experiment, you may have noticed that the construction workers in the work zones along the road were wearing safety vests. There were different color vests present in the tracks that you drove. The colors were yellow and orange. Which one stood out to you the most? Which one was most visible to you?

[ ] Yellow [ ] Orange

In total 35 (71.42%) of the 49 participants indicated that the orange safety vest color stood out the most and was most visible. This result conflicts with the eye tracking data which collects eye movement data which is calibrated to collect the focal point of visual acuity. It remains technically infeasible for the eye tracking device employed in this research to collect visual acuity data encompassing stimuli viewed through peripheral vision. There may be some underlying characteristic of the orange and/or yellow safety vests used that may affect participants abilities to collect and process visual stimuli data gathered through peripheral vision.

7. Limitations

This study has three notable limitations. First, care was taken to ensure the results would be generalizable to the United States and North Carolina population. However, due to COVID-19 restrictions and scheduling issues post-pandemic, participants were mostly recruited from the public of Eastern North Carolina and East Carolina University students. The resulting participant demographic is comprised of mostly female participants (85.71%) with an overall mean age of 24.35 years and standard deviation of 5.45 years. Although this demographic does not appropriately externally generalize to the broad North Carolina and United States demographic, it does have strong external generalizability to the homogenous study population. For this reason, future research is needed to test the hypotheses in this study across a larger and more externally generalizable study population.

The second limitation lies with the use of simulators. While simulators offer many advantages, they do have some limitations. One limitation being it is not possible to exactly replicate a real-road driving experience on a simulator due to limitations in technology and cost, so often some aspects of reality are disregarded on the simulator (Shechtman et al., 2009). In other words, driving simulators have relative validity of certain driving measures, but do not exactly replicate on-road driving behavior meaning they lack absolute validity (Matowicki & Přibyl, 2017). Although this limitation to ecological validity exists, the authors consider the ability to place participants in consistent simulations important in increasing the internal validity of the study and reducing confounds that can arise from the ever-evolving nature of construction road work.

Lastly, eye tracking hardware and software is limited in its ability to examine true signal detection. With eye tracking technology, the primary data of interest is the focal point of visual acuity. Eye tracking systems track the location of visual acuity through calibrated hardware and software methods. The eye tracking data shows real time indication of the position of the eye and the location of visual attentional allocation on a stimulus of interest. This data does not include any visual information that may be obtained through a participant's peripheral vision. Simply, a participant may detect the presence of a worker through their peripheral vision and the eye tracking data show that the participant never cast their visual attention in that direction. This would lead the researcher to identify that worker character as a miss, when it was in fact a hit but unrecognizable in the eye tracking data. Additionally, there may be characteristics of the human eye and light waves that may play a physiological role in conspicuity.

8. Conclusions

The objective of the current study was to explore the effect of the color of worker safety vests on worker conspicuity in simulated construction work zones. Additionally, this is the first quasi experimental study to investigate the effects of the presence of a worker safety vests on worker conspicuity in simulated construction work zones using an interactive driving simulator and eye tracking technology. In total, 49 participants completed a series of 3 independent driving tasks in a driving simulator while fitted with a head mounted eye tracker. Participants were seated in a commercial driving simulator, fitted with the eye tracking hardware, and asked to drive 3 separate driving tracks in a counterbalanced and randomized pattern according to a blocked experimental design. Twelve construction workers, each skinned in a variety of clothing garments (i.e., orange safety vests, yellow safety vests, and white t-shirts) were placed into the simulator tracks according to the blocked design. As participants navigated the driving track, eye tracking data was collected to determine the participants location of focal attention and was used to determine if the workers in the track were seen by the participant or not. When participants visual attention was cast onto or over a worker, the worker was considered to be seen by the participant. No analysis of peripheral vision was collected as it lies outside of the capabilities of the eye tracking system.

An Analysis of Variance (i.e., ANOVA) statistical approach was used to test Ho1: *The color of worker safety vest does not affect conspicuity in simulated construction work zones* and hypothesis Ho2: *The presence of a worker safety vest does not affect conspicuity in simulated construction work zones*. ANOVA analysis suggests there was a significant difference in the proportion of workers seen by the participants across all garment colors and driving tracks presented to the research participants ($p = 0.0002$). In fact, it was found that workers wearing safety vests (μ orange vest = 0.5255 and μ yellow vest = 0.5340) were seen a higher percentage of times when compared to those wearing only white t-shirts ($\mu = 0.3741$). ANOVA analysis suggests there was no statistically significant difference in the C_{index} between the orange ($\mu = 0.5255$) and yellow ($\mu = 0.5340$) safety vest groups (all $p > 0.05$) (see Table 3.0). These results suggest the color of worker safety vest does not affect conspicuity in simulated construction work zones. Therefore, the authors fail to reject hypothesis Ho1. Alternatively, the results suggest that the presence of a worker safety vest does improve worker conspicuity. There was a significant difference in the C_{index} between the white t-shirt group and the vests groups ($p = 0.0002$). Therefore, the authors reject hypothesis Ho2 and conclude that the presence of a worker safety vest does affect conspicuity in simulated construction work zones.

Additionally, mean and dispersion t-testing was used to further assess Ho2 and determine if the presence of a safety vest improved worker conspicuity in the simulated construction work zones. The pairwise t-test results suggest there is a significant difference in the mean C_{index} for the Orange and Yellow Vests ($\mu = 0.5298$) and White T-Shirts ($\mu = 0.3742$) garment color groups across all track conditions ($t = 4.007$, $p = 0.000$) (see Table 4.0). Due to these results, it is suggested that the provision of worker safety vest does affect worker conspicuity in simulated construction work zones. In fact, there was a 15.56% increase in the C_{index} for the Orange and Yellow Vests garment color group when analyzed across all tracks. Additional pairwise t-test analyses were conducted to examine the effect of daylight conditions on the C_{index} across all and within each track for conditions including: 1) all garment colors and 2) only the orange and yellow vest garment colors. Details of these analyses can be found in Tables 6.0 and 7.0.

The two safety vests of interest in this study were the orange ANSI Class II safety vest with yellow reflective striping and the yellow ANSI Class II safety vest with orange reflective striping. These vests can be seen in Figure 3.0. The findings of this research indicate that neither of these vests are superior in terms of increasing worker conspicuity in simulated construction work zone settings. This is true regardless of environmental condition or track driven. However, when compared to workers skinned with white t-shirts, the workers skinned with these safety vests were observed a higher percentage of times. The counterbalancing of the blocked experimental design, proper calibration and procedural protocol with the participants driving experience and eye tracking hardware, adequate sample size, and accurate and precise measurement of the eye tracking data provide strong foundations for these conclusions.

Overall, there were 49 research participants who completed the study. The results from Pearson-r correlation tests suggest that neither participant age or experience were related to the C_{index} for the orange safety vest or yellow safety vest condition independent of Track ID (all $p > 0.05$). This suggests that participant age and driving experience will not affect the proportion of workers that participants cast their visual attention to regardless of safety vests color. A more diverse population may alter these results in additional studies. However, the homogenous participant population employed in this study does increase external generalizability for the population recruited.

Future research is warranted in a few areas. First, an examination into the signal detection of screen based stimuli from peripheral vision as compared to the point of visual acuity is needed to understand the potential for participants to obtain visual screen based information from areas in the eye tracking data that lie outside the point of visual acuity. Such an examination may uncover the characteristics of a subject's background and target object that yield signal detection via peripheral vision. This may help to uncover certain attributes of safety clothing, chevron designs, etc. that lead to a higher percentage of signal detection through peripheral vison and design changes to these objects to lead to faster detection times. Second, research is needed in a real world and controlled track environment to determine if these results hold true outside of the simulator environment. The research team noted that some participants only casted their visual gaze into the center of the simulator computer screen to successfully navigate the environment in the simulator. As with a standard first person driving video game, it may not be necessary for some to cast their visual gaze away from the center of the screen to successfully navigate the course as the gamer/participant simply uses the hand controls to pull the simulator environment into the center of the screen rather than needing to use the controls to physically move the vehicle. Additionally, the risk of crash has no real world consequence. This may have affected the participants emotions and reduced their encouragement to act as if they were in a real world environment. Third, a study replicating actual NCDOT construction work zones in simulated and controlled real world settings would increase the ecological validity of these results. More investigation into these areas is warranted.

Recommendations

Primary recommendation is to continue to provide worker protection consistent with the authority having jurisdiction. Additionally it is recommended that NCDOT make purchase decisions for high visibility garments based on safety requirements rather than color alone.

Implementation and Technology Transfer Plan

- Research Products – None
- Affected Parties – None
- Training Needed - None

Cited References

Abudayyeh, O., Fredericks, T.K., Butt., S.E., & Shaar, A. (2006). An investigation of management's commitment to construction safety. *International Journal of Project Management, 24*(2). https://doi.org/10.1016/j.ijproman.2005.07.005

Albert, A., & Hallowell, M. R. (2012). Hazard recognition methods in the construction industry. In Construction Research Congress: (pp. 407-416)

Albert, A., Hallowell, M. R., & Kleiner, B. M. (2014). "Experimental field testing of a real-time construction hazard identification and transmission technique." *Constr. Manage. Econ., 32*(10). https://doi.org/10.1080/01446193.2014.929721

ANSI/International Safety Equipment Association (ISEA) (2015). American national standard for high-visibility safety apparel and headwear, ANSI/ISEA 107–2015, Washington, DC., United States.

Ashraf, H., Sodergren, M.H., Merali, N., Mylonas, G., Singh, H., & Darzi, A. (2018). Eye-tracking technology in medical education: A systematic review. *Medical Teacher*, *40*(1), 62-69. https://doi.org/10.1080/0142159X.2017.1391373

Atallah, T.G., & Blauer, S.J. (2006). United States patent for high visibility clothing. https://patents.google.com/patent/US7058982B2/en

Arditi, D., Ayrancioglu, M. A., & Shi, J. (2004). Effectiveness of safety vests in nighttime highway construction. Journal of transportation engineering, 130(6), 725-732.

Arditi, D., Ayrancioglu, M., & Shi, J. J. (2005). Worker safety issues in night-time highway construction. Engineering, Construction and Architectural Management.

AZO Materials. (2018, February 20). *How does the human eye perceive light? Photopic and scoptopic vision.* https://www.azom.com/article.aspx?ArticleID=14971

Baracz, S. J., Everett, N. A., McGregor, I. S., & Cornish, J. L. (2016). Oxytocin in the nucleus accumbens core reduces reinstatement of methamphetamine-seeking behaviour in rats. Addiction biology, 21(2), 316-325.

Bass, S. B., Gordon, T. F., Gordon, R., & Parvanta, C. (2016). Using eye tracking and gaze pattern analysis to test a "dirty bomb" decision aid in a pilot RCT in urban adults with limited literacy. BMC medical informatics and decision making, 16 (1), 1-13.

Bédard, M., Parkkari, M., Weaver, B., Riendeau, J., & Dahlquist, M. (2010). Assessment of driving performance using a simulator protocol: Validity and reproducibility. The American Journal of Occupational Therapy, 64(2). http://dx.doi.org.jproxy.lib.ecu.edu/10.5014/ajot.64.2.33

Benjamins, J. S., Hessels, R. S., & Hooge, I. T. C. (2018). GazeCode: Open-source software for manual mapping of mobile eye-tracking data. In Proceedings of the 2018 ACM symposium on eye tracking research & applications.

Birney, D. P., Halford, G. S., & Andrews, G. (2006). Measuring the influence of complexity on relational reasoning: The development of the Latin Square Task. Educational and Psychological Measurement, 66(1), 146-171.

Blascheck, T., Kurzhals, K., Raschke, M., Burch, M., Weiskopf, D., & Ertl, T. (2014). State-of-the-art of visualization for eye tracking data. In Proceedings of Eurographics Conference on Visualization (2014).

Blomberg, R.D., Hale, A., & Preusser, D.F. (1986). Experimental evaluation of alternative conspicuity-enhancement techniques for pedestrians and bicyclists. *Journal of Safety Research*, *17*(1). https://doi.org/10.1016/0022-4375(86)90002-2

Buonarosa, M. L., & Sayer, J. R. (2007). Seasonal Variations in Conspicuity of high-visibility garments. Universit of Michigan. Transportation Research Institute, UMTRI-2007-42, Ann Arbor, MI.

Bureau of Labor Statistics. (n.d.)., Industry at a Glance: Construction United States Bureau of Labor Statistics. Retrieved from: http://www.bls.gov/iag/tgs/iag23.htm

Bryden, J. E., & Andrew, L. (1999). Serious and fatal injuries to workers on highway construction projects. *Transportation Research Record, 1657*(1). https://doi.org/10.3141/1657-06

Bryden, J. E., Andrew, L.B., & Fortuneiewicz, J.S. (2000). Intrusion accidents on highway construction projects. *Transportation Research Record, 1715*

Campos, J. L., Bédard, M., Classen, S., Delparte, J. J., Hebert, D. A., Hyde, N., Law, G., Naglie, G., & Yung, S. (2017). Guiding Framework for Driver Assessment Using Driving Simulators. *Frontiers in psychology*, *8*, 1428. 10.3389/fpsyg.2017.01428

Carter, G. & Smith, S.D. (2006). Safety hazard identification on construction projects. *Journal of Construction Engineering and Management, 132*(2). https://doi.org/10.1061/(ASCE)0733-9364(2006)132:2(197).

Centers for Disease Control and Prevention (2019, October 3). *Highway work zone safety*. https://www.cdc.gov/niosh/topics/highwayworkzones/default.html

Chan, E., Pradhan, A. K., Pollatsek, A., Knodler, M. A., & Fisher, D. L. (2010). Are driving simulators effective tools for evaluating novice drivers' hazard anticipation, speed management, and attention maintenance skills. *Transportation research. Part F, Traffic psychology and behaviour*, *13*(5), 343-353. 10.1016/j.trf.2010.04.001

Chen, P. & Shen, Q. (2016). Built environment effects on cyclist injury severity in automobile-involved bicycle crashes. *Accident Analysis & Prevention, 86*. https://doi.org/10.1016/j.aap.2015.11.002

Classen, S. & Brooks, J. (2014). Driving simulators for occupational therapy screening, assessment, and intervention. *Occupational Therapy in Health Care: A Journal of Contemporary Practice*, *28*(2), 154-162. 10.3109/07380577.2014.901590

Cochran, L.M. (2015*). Driving performance while wayfinding on-road and in an interactive driving simulator* [Master's Thesis, East Carolina University]. The Scholarship Institutional Repository.

Dan Turner, J. D., Simmons, C. J., & Graham, J. R. (1997). High-visibility clothing for daytime use in work zones. Transportation Research Record, 1585(1), 1-8.

Daniel, E. (2016). Motivational and cognitive correlates of avoidance of ambiguity: The role of values and relational complexity. Personality and Individual Differences, 102, 149-152.

Dester, W.S. & Blockley, D.I. (1993). Safety — behaviour and culture in construction. *Engineering, Construction, and Architectural Management*, *2*(1). https://doi.org/10.1108/eb021000

Dickerson, A., Schold Davis, E., & Carr, D. B. (2018). Driving decisions: Distinguishing evaluations, providers and outcomes. Geriatrics, 3(2), 25.

Duchowski, A. T. (2002). A breadth-first survey of eye-tracking applications. Behavior Research Methods, Instruments, & Computers, 34 (4): 455-470.

Dzeng, R. J., Lin, C. T., & Fang, Y. C. (2016). Using eye-tracker to compare search patterns between experienced and novice workers for site hazard identification. Safety science, 82, 56-67.

Edwards, A. L. (1951). Balanced latin-square designs in psychological research. The American journal of psychology, 64(4), 598-603.

Fahy, R. (2014). US firefghters killed when struck by vehicles, 2000–2013 (NFPA Index No. 2443). Quincy: Fire analysis and research division, NFPA

Feng, Y. (2013). Effect of safety investments on safety performance of building projects. *Safety Science, 59.* https://doi.org/10.1016/j.ssci.2013.04.004

Findlay, J. M., & Gilchrist, I. D. (1998). Eye guidance and visual search. In G. Underwood (Ed.), Eye guidance in reading and scene perception (pp. 295-312).

Finley, M. D., Weimert, K. D., & Miles, J. D. (2014). Impact of work zone lighting on driver's detection of objects. Transportation Research Record, 2458(1), 56-64.

Goldberg, J. H., & Kotval, X. P. (1999). Computer interface evaluation using eye movements: Methods and constructs. International Journal of Industrial Ergonomics, (24): 631-645

Golovina, O., Teizer, J., & Pradhananga, N. (2016). Heat map generation for predictive safety planning: Preventing struck-by and near miss interactions between workers-on-foot and construction equipment. Automation in construction, 71, 99-115.

Hardison, D., Sears, M., Hallowell, M., & Goodrum, P. (2017). Using eye tracking technology to evaluate focal attention location and its relationship to hazard recognition. In CSCE Annual Conference, Vancouver, Canada.

Hasanzadeh, S., Esmaeili, B., & Dodd, M. D. (2016). Measuring Construction Workers' Real-Time Situation Awareness Using Mobile Eye-Tracking. In Construction Research Congress (2016): (2894-2904).

Henderson, J. M., & Hollingworth, A. (1998). Eye movements during scene viewing: An overview. In G. Underwood (Ed.) Eye guidance in reading and scene perception (pp. 269-294).

Pinheiro, R. D. O., Pradhananga, N., Jianu, R., & Orabi, W. (2016). Eye-tracking technology for construction safety: A feasibility study. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 33, p. 1). IAARC Publications.

Hills, B. L. (1980). Vision, visibility, and perception in driving. *Perception*, *9*(2), 183–216. https://doi.org/10.1068/p090183

Hinze, J. W., & Teizer, J. (2011). Visibility-related fatalities related to construction equipment. *Safety Science*, *49*(5), 709-718. http://dx.doi.org/10.1016/j.ssci.2011.01.007

Hohorst, W.H., Kinder, C.M., Lodha, N., & Smith, B.W. (2019). *Is simulator-based driver rehabilitation missing motion feedback?* [Conference paper]. 2019 16th IEEE International Conference on Rehabilitation Robotics (ICORR). Toronto, Canada. 10.1109/ICORR.2019.8779414.

Idris, J. (2016). Personalized hazard recognition training for construction workers [Unpublished master's thesis]. North Carolina State University.

Jafarnejad, A., Gambatese, J. A., & Nnaji, C. (2018, March). Illumination and visibility of workers in nighttime highway work zones. In Construction research congress.

Kahl, J. T., Anderson, N. J., Casner, G., Shuman, V., & Gardner, T. J. (2019). Firefighter daytime visibility: Trim properties and conspicuity. *Fashion and Textiles, 6*(1), 1-18. http://dx.doi.org/10.1186/s40691-019-0173-5

Kartam, N.A. (1997). Integrating safety and health performance into construction CPM. *Journal of Construction Engineering and Management*, *123*(2). https://doi.org/10.1061/(ASCE)0733-9364(1997)123:2(121)

Katz, E.Z., & Bothwell, R. (2019). Working with elders who have vision impairments. In H.L. Lohman, S. Beyers-Connon, & R.L. Padilla (Eds.), *Occupational therapy with elders: Strategies for the COTA* (4th ed., pp. 217-233). Elsevier.

Keshavarz, B., Hecht, H., & Lawson, B.D. (2014). Visually induced motion sickness: Characteristics, causes, and countermeasures. In K.S. Hale & K.M. Stanney (Eds.), *Handbook of virtual environments: Design, implementation, and applications* (648-697). CRC Press.

Kunishige, M., Fukuda, H., Iida, T., Kawabata, N., Ishizuki, C., & MIyaguchi, H. (2019). Spatial navigation ability and gaze switching in older drivers: A driving simulator study. *Hong Kong Journal of Occupational Therapy, 32*(1), 22-31. https://doi.org/10.1177/1569186118823872

Kwan, I., & Mapstone, J. (2004). Visibility aids for pedestrians and cyclists: A systematic review of randomized controlled trials. *Accident Analysis & Prevention, 36*(3). https://doi.org/10.1016/S0001-4575(03)00008-3

Lahrmann, H., Madsen, T. K. O., Olesen, A. V., Hels, T., & Madsen, J. C. O. (2018). The effect of a yellow bicycle jacket on cyclist accidents. *Safety Science, 108*, 209. Retrieved from https://search.proquest.com/docview/2088807825?accountid=10639

Langham, M., & Moberly, N. (2003). Pedestrian conspicuity research: a review. Ergonomics, 46(4), 345-363.

Lee, H. C. (2006). Virtual driving tests for older adult drivers?. British Journal of Occupational Therapy, 69(3), 138-141.

Lu, Y., Hinze, J., and Li, Q. (2011). “Developing fuzzy signal detection theory for workers’ hazard perception measures on subway operations.” Safety Science, 49 (3): 491–497.

Luoma, J., Schumann, J., & Traube, E. C. (1996). Effects of retroreflector positioning on nighttime recognition of pedestrians. *Accident Analysis & Prevention, 28*(3), 377-383. https://doi.org/10.1016/0001-4575(96)00004-8

Mackenzie, A. K., & Harris, J. M. (2015). Eye movements and hazard perception in active and passive driving. *Visual cognition*, *23*(6), 736-757. 10.1080/13506285.2015.1079583.

Maniglia, M., Thurman, S. M., Seitz, A. R., & Davey, P. G. (2018). Effect of varying levels of glare on contrast sensitivity measurements of young healthy individuals under photopic and mesopic vision. *Frontiers in psychology*, *9*(899). 10.3389/fpsyg.2018.00899

Masuda, K., & Uozato, H. (2014). Effect of color illumination from street lights on scotopic visual acuity [Abstract]. *Investigative Ophthalmology & Visual Science, 55*(6238). https://iovs.arvojournals.org/article.aspx?articleid=2271921

Matowicki, M., & Přibyl, O. (2017). Cross-study research on utility and validity of driving simulator for driver behavior analysis. *Acta Polytechnica CTU Proceedings*, 12, 68-73. 10.14311/APP.2017.12.0068

McNemar, Q. (1951). On the use of latin squares in psychology. Psychological Bulletin, 48(5), 398.

Mead, R., Curnow, R. N., & Hasted, A. M. (2017). Statistical methods in agriculture and experimental biology. Chapman and Hall/CRC.

Michon, J. A., Eernst, J. T., & Koutstaal, G. A. (1969). Safety clothing for human traffic obstacles. Ergonomics, 12(1), 61-69.

Mohan, S., & Zech, W. C. (2005). Characteristics of worker accidents on NYSDOT construction projects. Journal of Safety Research, 36(4), 353-360.

Mullen, N., Charlton, J., Devlin, A., & Bédard, M. (2011). Simulation validity: Behaviors observed on the simulator and on the road. In D. L. Fisher, M. Rizzo, J. K. Caird, & J. D. Lee (Eds.), *Handbook of Driving Simulation for Engineering, Medicine and Psychology* (1st ed., pp. 1 - 18). CRC Press.

National Institute for Occupational Safety and Health (2019). *Construction program.* Centers for Disease Control and Prevention. https://www.cdc.gov/niosh/docs/2019-151/pdfs/2019-151.pdf

Niehorster, D. C., Hessels, R. S., & Benjamins, J. S. (2020). GlassesViewer: Open-source software for viewing and analyzing data from the Tobii Pro Glasses 2 eye tracker. Behavior research methods, 52(3), 1244-1253.

North Carolina Department of Transportation: Safety Rates. (2019). Retrieved from: https://www.ncdot.gov/about-us/our-mission/Performance/Pages/safety-rates.aspx

Occupational Safety and Health Administration (2005). *Worker safety series: Construction.* https://www.osha.gov/Publications/OSHA3252/3252.html

Occupational Safety and Health Administration (2009). *Inspections within Industry*. https://www.osha.gov/pls/imis/industry.html

Olson, P. L., Halstead-Nussloch, R., & Sivak, M. (1981). The effect of improvements in motorcycle/motorcyclist conspicuity on driver behavior. *Human Factors, 23*(2), 237-248. doi:http://dx.doi.org/10.1177/001872088102300211

Ore, T., & Fosbroke, D. (1997). Motor vehicle fatalities in the United States construction industry. *Accident Analysis and Prevention, 29*(5), https://doi.org/10.1016/S0001-4575(97)00013-4

Owsley, C., & McGwin, G. (2010). Vision and driving. *Vision research, 50*(23), 2348-2361. doi:10.1016/j.visres.2010.05.021.

Parasuraman, R., Masalonis, A. J., & Hancock, P. A. (2000). Fuzzy signal detection theory: Basic postulates and formulas for analyzing human and machine performance. Human Factors: The Journal of the Human Factors and Ergonomics Society, 42 (4): 636-659.

Peng, Y. H., Lee, C. H., Popuri, S. R., & Kumar, K. N. (2016). Preparation of high-purity ultrafine copper powder in mass-production by chemical reduction method: Taguchi robust design optimization. Powder Metallurgy and Metal Ceramics, 55(7), 386-396.

Pratt, S., Fosbroke, D., & Marsh, S. (2001, April). *Building safer highway work zones: Measures to prevent worker injuries from vehicles and equipment*. Centers for Disease Control and Prevention. [PDF]. https://www.cdc.gov/niosh/docs/2001-128/pdfs/2001-128.pdf?id=10.26616/NIOSHPUB2001128

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. Psychological Bulletin, (124): 372-422.

Rashid, S., Soo, S. T., Sivaji, A., Naeni, H. S., & Bahri, S. (2013). Preliminary usability testing with eye tracking and FCAT analysis on occupational safety and health websites. Procedia-Social and Behavioral Sciences, (97): 737-744.

Robbins, C.J., Allen, H.A., & Chapman, P. (2019). Comparing drivers' visual attention at junctions in real and simulated environments. *Applied Ergonomics*, *80*, 89-101. https://doi.org/10.1016/j.apergo.2019.05.005

Roge, J., Douissembekov, E., & Vienne, F. (2011). Low conspicuity of motorcycles for car drivers : Dominant role of bottom-up control of visual attention or deficit of top-down control? *Human Factors: The Journal of the Human Factors and Ergonomics Society, 54*(1). https://doi.org/10.1177/0018720811427033

Rogé, J., Laurent, S., Ndiaye, D., Aillerie, I., & Vienne, F. (2019). Does a yellow jacket enhance cyclists' sensory conspicuity for car drivers during daylight hours in an urban environment?. Safety Science, 119, 385-391.

Romano, N., Fosbroke, D., & Ruff, T. (2008). Improving work zone safety. *Professional Safety, 53*(4), 46-48. Retrieved from https://search.proquest.com/docview/200341199?accountid=10639

Sawacha, E., Naoum, S., & Fong, D. (1999). Factors affecting safety performance on construction sites. *International Journal of Project Management, 17*(5). https://doi.org/10.1016/S0263-7863(98)00042-8

Sayer, J. & Mefford, M. (2004). High visibility safety apparel and nighttime conspicuity of pedestrians in work zones. *Journal of Safety Research, 35*(5). 10.1016/j.jsr.2004.08.007

Sayer, J. R., & Buonarosa, M. L. (2008). The roles of garment design and scene complexity in the daytime conspicuity of high-visibility safety apparel. Journal of safety research, 39(3), 281-286.

Shechtman, O., Classen, S., Awadzi, K., & Mann, W. (2009). Comparison of driving errors between on-the-road and simulated driving assessment: A validation study. *Traffic Injury Prevention, 10*(4), 379-385. 10.1080/15389580902894989.

Shoji, T., & Lovegrove, G. (2019). Integrating communication with conspicuity to enhance vulnerable road user safety: ArroWhere case study. *Sustainability, 11*(10). http://dx.doi.org/10.3390/su11102761

Tuttle, S.J., Sayer, J.R. & Buonarosa, M.L. (2009). The conspicuity of first-responder safety garments. *Journal of safety research*, *40*(3), 191-196. https://doi.org/10.1016/j.jsr.2009.03.002

United States Department of Labor (2009). Standard Interpretations. Retrieved from https://www.osha.gov/laws-regs/standardinterpretations/2009-08-05:

Vidal, M., Turner, J., Bulling, A., & Gellerson, H. (2012). Wearable eye tracking for mental health monitoring. *Computer Communications*, *35*(11), 1306-1311. https://doi.org/10.1016/j.comcom.2011.11.002

Wood, J. M., Marszalek, R., Lacherez, P., & Tyrrell, R. A. (2014). Configuring retroreflective markings to enhance the night-time conspicuity of road workers. Accident Analysis & Prevention, 70, 209-214.

Appendix A: Literature Review

To accomplish the papers objectives, a literature review was conducted of peer-reviewed journals and conference proceedings from the following search databases: Google Scholar, ECU Laupus Library Data Base, IEEE Explore, Science Direct, and PubMed. Key search phrases included "construction work zone safety, construction worker conspicuity, pedestrian work zone safety, pedestrian conspicuity, worker visibility, pedestrian visibility, worker reflectivity, pedestrian reflectivity, reflectivity and worker conspicuity, reflectivity and pedestrian conspicuity, eye tracking, visual attention, signal detection, driving simulator, and driving simulation." The reference sections of papers identified from this search were then used to locate additional relevant literature. The sections below connect industrial work zone fatalities, high visibility apparel, and the use of eye tracking technology in the context of work zone safety; define the context in which this study has been conducted; and provide necessary background to establish the authors' epistemological positioning for each of the variables under investigation.

A.1 Construction Site Safety

According to OSHA, approximately 6.5 million people work at 252,000 construction sites across the United States (U.S.) every day. Due to the exposure of many potential hazards, the fatal injury rate for the construction industry in higher than other professions with U.S. construction workers being over three times more likely to be killed than the all-industry average (Kartam, 1997; Carter & Smith, 2006; OSHA, 2005). With a consistently poor safety record in the industry (Carter & Smith, 2006), The National Institute for Occupational Safety and Health (NIOSH) has outlined several areas of priority in prevention of injuries and fatalities. A few of these areas include the reduction of hazardous respiratory exposures, reduction of hearing loss among workers, reduction of injuries and musculoskeletal disorders related to emerging or new technologies, and prevention of injuries and fatalities related to falls and struck-by incidents. (NIOSH, 2019).

A.2 Highway Construction Work Zones

Each year, over 100 workers are killed and over 20,000 are injured in the street and highway construction industry (Pratt et al., 2001). Mohan and Zech (2005) performed a detailed analysis of the fatalities and severe injuries to construction workers on New York State Department of Transportation (NYSDOT) projects during the period of 1990-2001. They discovered that there were five common types of traffic accidents including: workspace intrusion, worker struck-by vehicle inside workspace, flagger struck-by vehicle, worker struck-by vehicle entering/exiting the workspace, and construction equipment struck-by vehicle inside workspace. These accidents fall into two types including (1) accidents occurring in the work area and (2) traffic accidents involving motorists and construction workers. Ore and Fosbroke (1997) found that laborers represented 41% of pedestrian fatalities and that flaggers account for 50% of pedestrian accidents. Additionally, Bryden and Andrew (1999) found that traffic accidents accounted for 22% of serious injuries and 43% of all fatalities to workers in construction work zones when 240 work zone accidents within NYSDOT, between 1993 and 1997, were analyzed. In later work, Bryden and Andrew (2000) evaluated 290 fatalities from 1993 to 1998. They found that on-foot workers are involved in 10% of all intrusion accidents, which were severe. Research by Hinze and Tiezer, (2011) evaluated 659 fatality accidents from a data pool of 13511 OSHA-investigated cases. It was discovered that blind spots, obstructions, and lighting conditions were the most common factors contributing to vision-related fatalities. Of the U.S. construction fatalities experienced in 2012, 17% (135 fatalities) resulted from workers being struck-by an object or a piece of construction equipment (BLS, 2013). Accidents in which a vehicle enters the work zone and strikes a construction worker tends to be the most severe due to the heavy impact of vehicles traveling at high speeds (Mohan & Zech, 2005). With North Carolina driving crashes increasing steadily over the last five years, it is becoming increasingly important to explore and improve on methods currently used to protect workers in order for the state to adhere to one of its core values: enhancement of worker safety (North Carolina Department of Transportation (NCDOT), 2019).

Some of the methods currently in place for road and highway construction zone worker safety include use of flaggers during movement of large equipment with blind spots, speed enforcement outside the work zone, equipment maintenance, illumination of the work zone for night construction, use of clear signage to identify the limits of construction zone, and use of high-visibility apparel (Pratt et al., 2001). Exploration of the factors affecting safety performance on construction sites has revealed that many accidents may occur due to lack of knowledge or training, lack of supervision, error in judgment, and unsafe acts and conditions (Sawacha et al., 1999; Abudayyeh et al., 2006). In many cases, lack of adherence to standards and lack of improvement of the methods put in place to protect workers in highway construction zones contributes to a poor safety culture and ultimately puts workers at risk of injury or death. Contractor investment in implementation of interventions that increase physical protection as well as cultivate a positive safety culture can help to reduce financial costs to construction companies and personal costs to workers (Feng, 2013). One such intervention to increase worker safety is the use of high-visibility apparel.

Though OSHA currently requires workers to wear high visibility apparel when they work as flaggers and when they are exposed to public vehicular traffic (United Sates Department of Labor, 2009), injuries from motor vehicle traffic are still likely to occur, with more than 87% of visibility-related fatalities being “struck-by” accidents (Hinze & Teizer, 2011). The highway construction industry faced an average of 773 lives lost per year between 1982-2017 (CDC, 2019), indicating a potential gap in OSHA requirements and employee use of proper high-visibility apparel. With the ever-accumulating risks to workers and the increase of vehicular traffic in work zones (Pratt et al., 2001), increasing worker visibility is essential to reduce accidents occurring in the work area and traffic accidents involving motorists and construction workers (Mohan and Zech, 2005; Golovina et al., 2016).

A.3 Conspicuity and High-Visibility Apparel

Driving is a complex task that challenges a driver’s motor skills, cognition, and vision. However, it is estimated that over 90% of the information input to the driver is visual (Hills, 1980), thus effectively increasing worker visibility requires a basic understanding of the visual system. The human eye relies on rods to see under varying levels of luminance (scotopic vision), while cones make it possible to visually distinguish between colors (photopic vision), and the combination of the vision types, mesopic vision, is used in most scenarios (AZO Materials, 2018). Though the eye is unable to detect individual wavelengths, it is sensitive to different parts of the spectrum, and the colors seen are influenced by the level of light present (AZO Materials, 2018). Changes in luminance are known to decrease visual acuity and contrast sensitivity, which is the ability to detect small spatial changes of luminance or how we distinguish objects from a background (Maniglia et al., 2018; Katz & Bothwell, 2019). One study demonstrated that scotopic visual acuity is affected by different luminance and color wavelength, with a decrease in visual acuity under colors with shorter wavelengths, such as blue light (Masuda & Uozato, 2014). Though this study was specific to streetlights, understanding which color wavelengths are better seen by the eye in varying street conditions can assist in creating the most effective high-visibility apparel.

It is well known that high-visibility apparel improves the conspicuity of pedestrians and workers. In fact, the American National Standards Institute (ANSI, 2015) stipulates that wearing high-visibility safety vests is mandatory for construction workers to reduce the likelihood of accidents, and, based on a fatality investigation, NIOSH recommends that all workers on foot in roadway work zones should be required to wear a high-visibility safety garment (Romano et al., 2008). Defined as clothing that "incorporates combinations of luminescent and retro-reflective surfaces that combine to provide brilliant contrast against relatively obscure daytime and nighttime backgrounds," safety vests are commonly used in highway construction zones (Atallah & Blauer, 2006, p. 9). The fluorescent yellow/green color and fluorescent orange/red color of safety vests are generally considered as the most distinctive colors for high visibility vests, likely due to the fact that the colors red and orange have the longest wavelengths, closely followed by yellow and green on the visible light spectrum. Thus, these can be detected from further distances away. The concept of conspicuity or visibility has been explored extensively in research, and several studies have specifically looked at evaluations of varying color effects. Though very few have explored color and contrast combinations in different environmental contexts.

A.3.1. Cyclist Conspicuity

Much research has been conducted to determine if high-visibility apparel aids in cyclist safety while bicycling on public roads. For example, in a study of 9 years of cycling accidents, Chen and Shen, (2016) observed a lower likelihood of injuries for bicyclists wearing reflective clothing. Earlier research examining conspicuity enhancement for nighttime cyclists was conducted to examine cyclist detection distances. Specifically, four experimental conditions were analyzed including: (1) a baseline bicyclist in blue jeans and a white t-shirt; (2) a cyclist with retroreflective strips on the sides, cranks, and spokes of the bicycle; (3) a cyclist wearing a small light on the left ankle; and (4) a cyclist wearing fluorescent ankle bands and an equilateral fluorescent triangle over his posterior. Results suggest that the cyclist wearing the light on their ankle was detected at statistically significant distances away compared to all of the other conditions (Blomberg et al., 1986). Another study examining the effects of increasing motorcyclist conspicuity on driver behavior during the daytime and nighttime found that both daytime and nighttime conspicuity of a motorcycle is improved if the cyclist has their lights on and is wearing a high-visibility fluorescent vest and helmet cover (Olson et al., 1981). These results suggest a motion light may help increase NCDOT worker conspicuity if used in the appropriate setting.

Additionally, a literature review conducted by Kwan and Mapstone, (2004) found a total of 37 individual studies that showed fluorescent materials in yellow, red, and orange colors improved drivers' detection of pedestrians and cyclists during the day; while lamps, flashing lights, and retroreflective materials in red and yellow colors improved the detection at night. Researchers posited that public acceptability of use of visibility aids and strategies would assist in further development and implementation. Lahrmann et al., (2018) conducted a randomized controlled trial of 8,042 cyclists and analyzed results of self-reported personal cycling accidents in Denmark during 2012-2013. Participants in the control group did not wear a reflective garment while those in the test group did, and over the course of the year, results showed that the accident rate for personal injury accidents in the test group was 38% lower for those who wore the garment. Results of this study demonstrate strong evidence that cyclists who wear high-visibility apparel are better protected from motor vehicle accidents than those who do not (Lahrmann et al., 2018).

In a 2011 study, Roge et al. found that a high level of color contrast enhanced the visibility of motorcycles from a further distance away when participants on a driving simulator were asked to flash their headlights as soon as they detected a motorcycle on the road. More recently, Roge et al., (2019) performed a test where 43 participants used a driving simulator to evaluate whether the presence of a safety vest on a simulated bicyclist improved driver detection based on variations in color contrast. They found that cyclists with yellow vests were identified more quickly and at greater distances than those simulated cyclist without vests. However, they concluded that the yellow vest was an insufficient visibility aid due to lack of significant reduction in collisions between the cyclist and vehicle. Roge et al., (2019) thereby suggest the use of eye tracking glasses to examine the localization of the cyclist in the motorists' field of view and determine if the cyclist was actually focused upon by the driver. This sentiment was shared by Shoji & Lovegrove (2019), who concluded that high-visibility apparel alone is not enough to truly improve their safety after studying conspicuity of cyclists. They instead focused on improvement of other dimensions of high-visibility wear aside from color, focusing their preliminary research on the effects of a chevron (i.e., ArroWhere) design on conspicuity from a driver's perspective as well as combinations of the colors and types of arrows used. Results of this case study showed that participants felt safer while wearing ArroWhere designs, and that there was a significant association between ArroWhere and vulnerable road user safety.

A.3.2 Pedestrian Conspicuity

Research with pedestrians has also been conducted to determine if high-visibility apparel aids in pedestrian conspicuity when on or near the road, predominantly at night as this is when visibility is of greatest concern (Langham & Moberly, 2003). Early research examining conspicuity enhancement for pedestrians at night for detection distances for five experimental conditions including: (1) a baseline pedestrian in a white tee shirt and blue jeans walking in place; (2) a pedestrian wearing retroreflective dangle tags at the waist; (3) a flashlight in the hand of the pedestrian that swung around when walking in place; (4) a retroreflective and fluorescent jogger's vest; and (5) retroreflective rings (i.e., belt, headband, ankle band, and headband). In this experiment, the flashlight in condition (3) was detected from the furthest distance away (Blomberg et al., 1986). Researchers concluded that use of the jogging vest showed "promise" due to improvements in detection over the baseline pedestrian wearing only a white tee shirt and blue jeans.

Luoma et al., (1996) studied the effects of retroreflector positioning on the recognition of pedestrians during nighttime conditions. They found that the visibility distance of pedestrians in dark clothing is approximately one-third of the stopping distance of vehicles at normal highway speed. Therefore, researchers wanted to know if a certain configuration of retroreflectors had a higher level of visibility so drivers may react faster and reduce the chance of pedestrian collision. During the study, participants were passengers in a slow-moving vehicle with its low beams on. They were asked to press a button each time they recognized a pedestrian on or alongside a dark road. Retroreflector conditions included: (1) no retroreflectors; (2) retroreflectors on the torso and shoulders; (3) retroreflectors on the wrists and ankles; and (4) retroreflectors on the hips, knees, ankles, wrists, elbows, and shoulders. The results show that pedestrians wearing retroreflective stripes were seen from further distances than pedestrians who wore nothing, and those that wore the stripes on their limbs were detected 60-80% further away than those who wore stripes on their torso. Since these early studies, research has further examined visibility aids for improving pedestrian conspicuity. For example, pedestrian conspicuity research has been explored using a variety of different methods and in many situations, indicating that measurements from one study may not generalize to other settings (Langham & Moberly, 2003). Though the review showed varied results, one thing was evident: retroreflective markings made pedestrians more recognizable from greater distances and were most effective when positioned in ways that highlighted the shape of the human body.

The use of high-visibility safety apparel has been studied extensively in combination with driving due to the risks it poses to pedestrians. Sayer & Mefford (2004) examined the conspicuity of pedestrians wearing three types of retroreflective garments at night while drivers drove in a real car on the road. Results examined if level of complexity of the night driving scene affected pedestrian conspicuity. The findings suggest scene complexity did affect pedestrian conspicuity. Participants were able to spot pedestrians from 21 meters – or 30% farther away – in lower complexity scenes than in medium complexity night scenes. Researchers also found that arm motion had a significant effect on conspicuity, finding that participants were able to spot pedestrians from an additional 22 meters – or 62% farther away – when compared to conditions where their arms were stationary. Although no significant effects of type of retroreflective garments were found, participants did see the Class 3 jacket garment from the furthest distance away, followed by a standard Class 2 vest, followed by a Class 2 vest with reflective half sleeves (Sayer & Mefford, 2004). The use of high-visibility apparel has also been researched with pedestrian firefighters who are frequently present in on-road environments as part of their job and are frequently injured or killed due to motor vehicle collisions while attending to accidents (Fahy, 2014). Firefighter turnout gear, which has been labeled as a firefighter's "first line of defense" is relied upon to enhanced conspicuity (Kahl et la., 2019). Tuttle et al. (2009) compared the conspicuity of four types of fluorescent yellow first-responder PPE including two ANSI/ISEA-compliant vests and two firefighter turnout jackets in a closed track environment. Specifically, eight participants drove on a closed track in day and nighttime conditions and indicated when they could first detect the first-responder pedestrians in a simulated emergency response scene. The distance away from scene was then recorded. Pedestrians stood to the right or left of a simulated fire truck either facing away from or towards traffic and wore one of the four safety garments while moving in place with their arms swinging to simulate walking. Results show that participants saw pedestrians at 495 meters further away during the day than at night when times of day were compared. During the day, pedestrians that faced oncoming traffic were seen at further distances than those who faced away; but at night, pedestrian orientation had no effect on visibility distance. Garment type was not found to be statistically significant, but researchers stated that the most important factors related to conspicuity of first responders were time of day and pedestrian orientation to traffic (Tuttle et al., 2009).

In a more recent two-part study, firefighter visibility was examined during daytime conditions (Kahl et al., 2019). Conspicuity garments consisted of lime yellow and orange-red fluorescent trims. In part one of the study, participants were passengers in a vehicle on a closed track with a 250-meter stretch of road with a simulated emergency scene. The distance at which a participant observer in the passenger seat of a vehicle detected and recognized a person in the scene was measured through radio sensors and an infrared laser. In part two of the study, participants' ability to detect a person and identify the color of their garment when viewed outside their focal viewpoint was measured. Participants sat in a car with a windshield blind over the windshield. When it was removed, cones with numbers and letters on them were in a row right in front of the car. Participants were asked to read and report the number or letter on the cone, fixate on it, and state whether they saw a person in their peripheral vision. If so, they were asked to describe the color; vest trims were lime yellow and orange-red. Part one found no significant difference in performance between types of trim (segmented trim versus solid trim) but found that luminance was strongly associated with detection distance. In the simulated emergency scene, fluorescent lime yellow trims were detected from farther away than fluorescent orange-red trims. The results of part two showed that a color's luminance influenced the observer's abilities to identify color worn by person seen in peripheral view. Conspicuity of these garments is important for overall safety of firefighters, and results can be used to inform improvement of high-visibility apparel for construction road workers (Kahl et al., 2019).

A.3.3 Construction Worker Conspicuity

Though perhaps not as extensively researched as cyclist and pedestrian conspicuity, there are some studies that have examined high-visibility apparel and its effects on conspicuity and safety of construction workers. Most of this research has taken place at night, however other studies have examined this topic in other contexts. In early laboratory research, Michon et al., (1969) analyzed several fluorescent and non-fluorescent colors to determine which should be recommended to improve conspicuity for those who work in on or near the road. A combination of 6 colored chips were placed on a white garment and positioned at a set distance from participants. These including: (1) white, (2) fluorescent green-yellow, (3) yellow, (4) fluorescent orange, (5) fluorescent red-orange, and (6) fluorescent red. During testing, ten subjects were seated in a mock-up vehicle cabin and viewed each of the jackets in a randomized order. The results of the reaction times for jacket detection suggest found that fluorescent orange resulted in the shortest reaction times followed by yellow, fluorescent yellow, and white (Michon et al., 1969).

Later, Turner et al., (1997) examined the conspicuity of safety clothing color in daytime construction work zone environments. In their study, subjects were required to look through a shutter, which opened for 300 msec at 30.5-m intervals, as the researcher drove 32 km/hr toward a work zone. Subjects were instructed to indicate the point at which they first identified safety clothing in the scene. These detection distances were recorded for each color in each of the work zones. There were 11 colors of clothing under investigation. These included: fluorescent [(1) green, (2) yellow-green, (3) yellow, (4) yellow-orange, (5) red-orange, (6) a combination of red-orange with yellow-green, (7) red mesh over white background, and (8) pink]; two non-fluorescent colors [(9) yellow and (10) orange]; and one semi fluorescent color (11) yellow. Overall, red-orange was found to have the highest mean detection distance, and it was significantly different from every color except the fluorescent red mesh, fluorescent yellow-green, and fluorescent red-orange/yellow-green combination. Each of these colors is recommended for use in safety garments with the exception of fluorescent red mesh, because the mesh may not perform well if worn over darker clothing (Turner et al., 1997).

In a nighttime study, Arditi et al., (2004) developed LUMINA, a system used to measure the luminance of six commonly used safety vests in nighttime construction/maintenance work areas. The LUMINA system was used on actual construction sites and to calculate the average luminance of the vests tested. The six vests tested are included in the list below:

1) Mesh, orange vest with yellow 3M Scotchlite reflective material,
2) Mesh, orange vest with yellow PVC prism sheeting,
3) Fabric/Mesh, yellow vest with silver 3M Scotchlite reflective material,
4) Mesh, yellow vest with silver 3M Scotchlite reflective material,
5) Fabric, orange vest with yellow Reflexite retroreflective tape, and
6) Fabric, yellow vest with silver 3M Scotchlite reflective material (Arditi et al., 2004).

The results suggest that vest #3 and vest #6 were more visible than the other four vests in nighttime conditions. The authors suggest that the tie for first in rank may be due to the similarity in vests #3 and #6 as they were similar in most respects. However, Arditi et al., (2004) found it interesting that these two vests did not have the largest amount of retroreflective material on them. This study also shows that the performance of safety vests in nighttime conditions is dependent not only on the characteristics of the vests (e.g., amount of retroreflective material, design of the vest, etc.) but also on the characteristics of the construction/maintenance sites (e.g., weather, lighting, traffic volume, etc.) (Arditi et al., 2004).

In another field study, Sayer and Mefford, (2004) solicited ten licensed drivers to navigate a series of construction work zones in a controlled environment to investigate the effects of various attributes of retroreflective personal safety garments on worker conspicuity. In total, 18 safety garments with yellow-green background material were used with each having its own configuration of trim material and color. Of the eighteen garments, six were class 2 vests, six were class 3 vests, and six were class 3 jackets. Participants drove the closed track in a series of experimental conditions under speed constraints managed by the research administrators. Pedestrians were placed inside the work zone and wore safety garments or dark clad clothing to simulate an experimental control. Pedestrian detection distances were recorded and analyzed using analysis of variance procedures. Overall, the results suggest that the presence of a safety garment did improve pedestrian detection. Furthermore, blaze orange retroreflective trim color was found to be the most conspicuous color followed by white/silver. The red trimmed garment was found to be the lease conspicuous. A full description of trim colors and their effects can be found in Sayer and Mefford (2004). In addition, the difference in retroreflective trim on the Class 2 and Class 3 vests did not have a significant effect on the conspicuity of pedestrians in the work zone. However, the Class 3 jacket was more conspicuous than the Class 3 vest. The difference in detection distance associated with the Class 3 jacket is suggested to be a result of how the retroreflective trim was positioned on the garment (Sayer and Mefford, 2004).

In a daytime field study conducted by Buonarosa and Sayer, (2007), 24 subjects drove a vehicle along a 29-km route once in the summer and again in the fall to examine the effect of seasonal attributes on safety garment conspicuity. Drivers were asked to verbalize their detection of pedestrians wearing high-visibility garments along the roadway. Detection distances at which pedestrians were first detected were recorded. A total of four high visibility garments were used including a yellow-green Class 2 vest, a yellow-green Class 2 jacket, a red-orange Class 2 vest, and a red-orange Class 2 jacket. Pedestrians with safety garments were positioned along the roadway at various locations. Drivers were asked to verbalize when they spotted a pedestrian wearing the safety garment. Results show that in the fall, drivers detected pedestrians at farther distances than they did in the summer by 46 m (12 %). However, this may be a potential confound due to a learning effect (Buonarosa and Sayer, 2007). As for color, detection distances for fluorescent yellow-green and fluorescent red-orange garments were not significantly different across seasons. The final conclusions suggest that to be visible at long distances, garments must contrast with their background, preferably with respect to both brightness and color (Buonarosa and Sayer, 2007).

Sayer and Buonarosa, (2008) conducted a field study to examine the effects of high-visibility garment design on daytime pedestrian conspicuity in work zones. Specifically, they examined garment color, scene complexity, and other factors using naturalistic conditions on public roads in real traffic. In their study, sixteen drivers drove a 31 km route while searching for workers wearing a high-visibility safety garment along the side of the road. As with Buonarosa, (2007), a total of four high visibility garments were used including a yellow-green Class 2 vest, a yellow-green Class 2 jacket, a red-orange Class 2 vest, and a red-orange Class 2 jacket. Pedestrians with safety garments were positioned along the roadway at various locations. Again, drivers were asked to verbalize when they spotted a pedestrian wearing the safety garment. Detection distances between the fluorescent yellow-green and the fluorescent red-orange garments were not significantly different, nor were there any significant two-way interactions involving garment color. However, drivers detected pedestrians 70 meters farther in the low complexity scenes than they did in the medium complexity scenes. These results coincide with the results of Buonarosa and Sayer, (2007) in that color may not have an effect under the conditions tested. However, the complexity of the driving scene may play a role in pedestrian detection (Sayer and Buonarosa, 2008).

Next, Wood et al., (2014) conducted a field study to investigate if the night-time conspicuity of road workers can be enhanced by positioning retroreflective strips on the moveable joints in patterns that convey varying degrees of biological motion. A total of 24 adults drove a passenger car along a closed road encompassing a series of hills, bends, curves, intersections, lengthy straight sections, and standard road signs. No ambient light was present. Roadside pedestrians wore one of four clothing conditions: (1) standard road worker vest; (2) standard vest plus thigh-mounted retroreflective strips; (3) standard vest plus retroreflective strips on ankles and knees; and (4) standard vest plus retroreflective strips positioned on the extremities in a configuration that conveyed biological motion. As they drove along the closed road, participants were instructed to press a button to indicate when they first recognized that a road worker was present. The results demonstrated that regardless of the direction of walking, road workers wearing biomotion clothing were recognized at significantly ($p < 0.05$) longer distances (3×), relative to the standard vest alone. The results suggest the pedestrians and workers can benefit from incorporating reflective strips on their ankles, knees, wrists, and elbows (Wood et al., 2014).

Later, Finley et al., (2014) conducted a closed-course study to evaluate the effect of work zone lighting on the ability of drivers to detect low-contrast objects and workers wearing high-visibility vests. Thirty participants drove a passenger car along a construction work zone course in temporary work zone lighting in three conditions including: (1) no lights (dark or base condition); (2) a portable, trailer-mounted light tower; and (3) a portable balloon light. For the road conditions in which there was no work zone lighting, workers wearing a retroreflective vest could be detected at significantly longer distances than low-contrast objects in head lights alone. For lighted conditions, work zone lighting could increase the distance at which workers and low-contrast objects could be detected. Furthermore, results confirmed that improperly positioned portable light towers decreased pedestrian detection and support the theory that direct illumination by portable light towers could visually wash out workers and thus could make them more difficult to detect (Finley et al., 2014).

In more recent research, Jafarnejad et al., (2018) evaluated the effects of light towers and balloon lights in a controlled situation on the conspicuity of pedestrian workers. Workers were positioned in four conditions on a roadway in a simulated construction work zone. Those four conditions included: (1) a worker located at 100 feet distance under an elevated balloon light, (2) a worker located at 100 feet distance under a light tower, (3) a worker located at 1000 feet distance under an elevated balloon light, and (4) a worker located at 1000 feet distance under a light tower. Photographs were taken of the workers who were each wearing safety garments including: (A) Class 2 vest only, (B) Class 2 vest plus Class E pants, or (C) Class 3 vest only. Only one worker was present in each photograph. Results suggest the location of the worker on the roadway relative to the light location is a significant factor in the visibility of the worker. Additionally, the pilot testing suggests that balloon lights and light towers have the potential to improve worker visibility in actual projects (Jafarnejad et al., 2018).

In summary, this beneficial research on construction worker visibility suggests a few key themes. It was found that the presence of safety vests has been found to improve worker conspicuity in controlled studies (Michon, 1969; Sayer and Mefford, 2004). Furthermore, the color of the safety garment does affect conspicuity in nighttime conditions (Arditi et al., 2004). However, research suggests color alone may be insignificant in some conditions as tested in the studies included in this review (Buonarosa and Sayer, 2007; and Sayer and Buonarosa, 2008). Alternatively, it was found that the class garments (Sayer and Mefford, 2004) and the complexity of the driving scene (Sayer and Buonarosa, 2008) affect detection distances. This is supported by Arditi et al., (2004) who found that the characteristics of the construction site also affect conspicuity (Arditi et al., 2004), which can logically be linked to scene complexity. It was also found that the color of reflective striping affects detection distance (Michon, 1969; Turner et al., 1997; Sayer and Mefford, 2004;). Research into nighttime work suggests that night work poses threats to workers as they are not as easily identifiable at nighttime than during the day. This created challenges in improving worker visibility and conspicuity. However, work zone lighting could increase the distance at which workers could be detected (Finley et al., 2014 and Jafarnejad et al., 2018). Overall, it was found that retroreflective safety garments are necessary for both daytime and nighttime conditions (Michon, 1969; Turner et al., 1997; Arditi et al., 2004; Sayer and Mefford, 2004; Buonarosa and Sayer, 2007; Sayer and Buonarosa, 2008; Finley et al., 2014 and Jafarnejad et al., 2018) and pedestrians as well as workers can benefit from incorporating reflective strips on their ankles, knees, wrists, and elbows (Wood et al., 2014).

A.4. Signal Detection in Construction Work Zones

Previous research by Albert and Hallowell, (2012) suggests construction workers' safety performance depends largely on their ability to recognize hazards in their environment. In the context of the construction work zone, a driver's ability to successfully navigate a construction work zone depends on his ability to detect the presence of hazardous signals in the work zone. This is known as signal detection (Parasuraman et al. 2000; Lu et al. 2011). Signal detection has previously been researched in the arena of construction safety (Parasuraman et al. 2000 and Lu et al. 2011). Traditional signal detection theory places a significant division of real-world truths into two main distinct and non-overlapping categories. These categories are "signal" and "noise." Signals are present when the situation of interest is present. On the other hand, noise occurs when the situation of interest is not present (Hardison et al., 2017). In the context of construction work zone safety as investigated in this study, a signal is the presence of a worker and noise is everything else in the environment or construction work zone (Parasuraman et al. 2000; Lu et al. 2011). Eye tracking technology was used to measure users' attention to signals (i.e., workers in the work zone) by employing traditional signal detection theory via eye tracking technology and interactive driving simulation.

A.5. Eye Tracking Technology

One tool that may be underutilized in supplementing hazard recognition on road and highway construction sites is use of eye tracking technology. Eye tracking is a research technique used to model how subjects acquire information from visual stimuli (Bass et al. 2016 and Ashraf et al., 2018). Eye tracking systems capture data related to eye-movement that explain information acquisition, decision making processes, and attentional processes. Additionally, eye-tracking data provides evidence relating to eye position and movements of individuals as they process visual stimuli in real time (Duchowski 2002 and Bass et al. 2016). These systems have been accepted as a viable method to test for usability of human-computer interfaces (Goldberg and Kotval 1999; and Rashid et al. 2013), text-based reading research (Rayner 1998), scene perception research (Henderson and Hollingworth 1998), and investigations into the patterns of visual search processes (Findlay and Gilchrist 1998). Eye tracking is also an established research tool in several clinical settings, and the data it provides can indicate clinical skills, provide solutions for training individuals in different contexts, and aid in giving feedback and reflection (Ashraf et al., 2018).

Eye tracking technology is used to measure fixations, saccades, and eye scan paths of research participants (Vidal et al., 2012 and Bass et al. 2016). Fixations are defined as aggregations of eye gaze points and saccades are defined as rapid eye movements between fixations. Scan paths are thereby defined as the sequence of alternating fixations and saccades. These measurements are useful for determining what stimuli participants view, how long they view them, and the order in which the stimuli are viewed. Heat maps can also be generated from eye tracking data to show researchers the density of fixations over a general area of interest. These heat maps are used as a quantitative evaluation metric to identify the information within visual stimuli that is viewed the most times and/or for the longest periods. (Blascheck et al. 2014). For this research, focal attention is the primary metric of investigation. Focal attention occurs when a user focuses on a location within a visual stimulus with the intent of acquiring information. Eye tracking technology provides a platform for researchers to identify the proportion of a user's focal attention within redetermined locations of visual stimuli. This allows for the evaluation of eye gaze locations over time and can be used to generate a variety of inferences. Eye tracking technology is incredibly versatile and has been used across many disciplines to understand ocular and attentional behavior. It has been shown to be informative in construction research.

A.5.1. Eye Tracking use in Construction Safety Research

Eye tracking technology has become popular in construction safety research as it provides a method to better understand how individuals acquire safety information from static scenes (Dzeng et al. 2016; Hasanzadeh et al. 2016; and Pinherio et al. 2016). Dzeng et al. (2016) used eye-tracking to evaluate search patterns of novice and experienced workers as they searched for both obvious and unobvious hazards. The results indicated that field experience aided the detection of both obvious ($p < 0.001$) and unobvious hazards ($p = 0.004$) significantly faster than the novice workers. Additionally, eye trackers have been used to evaluate hazard perceptions from real construction photographs and ultra-realistic 3D models (Pinherio et al. 2016). The results show that the use of construction photographs and ultra-realistic 3D models can be used for hazard recognition training (Pinherio et al. 2016). Research conducted by Hasanzadeh et al. (2016) suggests that eye-tracking technology can also be used to investigate situational awareness by using construction photographs. Their results show that workers with high levels of situational awareness spent less time dwelling on one location and more time searching the entire environment for safety hazards (Hasanzadeh et al. 2016). These preliminary results suggest that an optimum proportion of focused to distributed focal attention may be required for workers to assess construction photographs for safety hazards and differentiate hazard signals from noise in the environment. However, research conducted by Hardison et al., 2017 suggests otherwise. In their study, Hardison et al., 2017 examined if the proportion of hazards viewed correlates with hazard recognition performance. To study this topic 18 subjects were fitted with mobile binocular eye tracking glasses, presented with a random sequence of three photographs of construction workspaces, and asked to recognize all of the safety hazards present in each photograph. The results reveal that there is no correlation between the proportion of fixations on hazards and hazard recognition despite assumptions made in previous research. The findings of this study suggest the proportion of safety hazards viewed in construction environments is not a predictor of hazard recognition performance. This is an important research finding as it suggests that simply viewing objects in an environment does not lead to increased hazard recognition (Hardison et al., 2017)

A.6. Interactive Driving Simulation

It is well known that highway work zones are particularly dangerous construction sites for both construction workers and drivers. The high hazard and dynamic nature of construction work zones make them particularly difficult to systematically analyze and control for experimental confounds in studies with high ecological validity. Interactive driving simulation is one method to reduce the risks of researchers, the public, and construction workers during work zone testing and allows for systematic control and evaluation of simulated work zone environments.

Interactive driving simulators are tools that allow the assessment of driving skills without involving the risks of on-road testing. Driving simulators offer many advantages for assessing on-road driving skills including providing a safe environment for the driver and evaluator, cost-effectiveness and time efficiency of testing, the ability to present situations that might not be available on the road or would potentially put the driver in danger, flexibility of scheduling driving sessions, and reproducibility of scenarios (Bédard et al., 2010; Cochran, 2015). Interactive driving simulators have been tested in relation to driving performance and are becoming increasingly popular (Owsley & McGwin, 2010). They can also be used to compare performance metrics across varied driver populations, or track performance of the same individual over time (Campos et al., 2017). Campos et al., (2017) discussed the usefulness of driving simulators as tools for identifying specific driving skills for intervention development and administration. In addition to increased safety in comparison to on-road testing, simulators are also more easily controlled and standardized, and can assess more challenging environmental and demanding task-based conditions. Multiple styles of driving simulators exist and have been found to have good external and ecological validity (Dickerson et al., 2018), producing results that can be generalized to on-road testing of the same driving conditions (Lee, 2006; Shechtman et al., 2009).

For example, Shechtman et al. (2009) used both field driving trials and a STISIM M500W driving simulator to assess the number and type of driving errors of 39 participants for both field driving and simulated driving conditions. Driving errors evaluated included speed, lane maintenance, signaling, visual scanning, adjustment to stimuli, and anterior/posterior vehicle positioning. Drivers were required to navigate a right and left turn at an intersection both on-road and on the simulator. Results showed no significant interactions between on-road versus simulator indicating drivers' behaviors and performance were similar both on-road and on the simulator, contributing to the relative validity of simulators compared to on-road criteria. This study also did not find significant differences between on-road and simulator for driving errors related to lane maintenance, adjustment to stimuli, and visual scanning, indicating absolute validity for these error types (Classen & Brooks, 2014; Shechtman et al., 2009).

A.7. Driving Simulation and Eye Tracking

Eye tracking technology has also been used in field and simulated driving research as research has provided evidence of the ecological validity of using eye trackers to monitor driver behavior during driving tasks (Owsley and McGwin Jr., 2010; Chan et al., 2010; Mackenzie and Harris, 2015; Kunishige et al., 2019; and Robbins et al., 2019). For example, Owsley and McGwin Jr., 2010 found that interactive driving simulators could be used to uncover relationships between human vision and driving performance and that simulation aids drivers with visual impairments to improve critical driving skills before being exposed to actual on-road situations. Additionally, Chan et al. (2010) examined use of driving simulation as a tool for evaluating novice drivers' hazard anticipation, speed management, and attention maintenance skills in comparison to experienced drivers. In this study, researchers asked newly licensed and experienced drivers to drive through rural and city scenes on a driving simulator while wearing eye-tracking technology. Participants had to react to randomly occurring traffic and complete a series of "distraction tasks" designed to visually distract them (Chan et al., 2010). They found that driving simulators capture behavioral differences between new and experienced drivers in the areas of anticipation of hazard, speed management, and attention maintenance. This study was one of the first simulator studies to compare glance patterns and durations of novice and experienced drivers in those areas, as well as to define glance durations during a set interval of time as a dependent variable (Chan et al., 2010).

In another study, Mackenzie and Harris, 2015 assessed visual attention in both non-driving and driving hazard perception tasks. In their study, 34 participants either drove on a driving simulator for eight courses or watched a series of eight video clips of driving simulations while wearing eye-tracking technology to record eye movements. During the experiment, participants in both groups were asked to press a button when they detected a hazardous event, which was defined as a collision between two or more other vehicles. Results of the study showed that participants searched more of the road during non-driving condition, indicated by the small fixation distribution across horizontal and vertical planes in the driving condition. Additionally, they found that overall reaction time to hazard detection was shorter in the non-driving condition, and that individuals often fixated their vision closer to the front of the vehicle in the driving condition rather than further ahead on the road. Researchers attributed the poorer performance in the driving condition to the increased complexities of an on-road drive. During an on-road drive, drivers have a higher cognitive and visual load when behind the wheel of a moving vehicle, and attention must be allocated to multiple tasks such as steering, braking, and maintaining lane position (Mackenzie & Harris, 2015).

Additionally, Kunishige et al., 2019 used driving simulation and eye tracking glasses (i.e., Tobii Glasses 2) together to quantify gaze behaviors to assess environment navigation and eye movements. The simulated condition was that of an urban area during the day with dangerous events occurring such as oncoming cars and children jumping in front of the car (Kunishige et al., 2019). The Benton Judgment of Line Orientation Test (BJLO) was used as a visual recognition evaluation tool; the Card-Placing Test (CPT) for spatial navigation; and the Raven's Colored Progressive Matrices (RCPM) and the Trail Making Test Part A and B (TMT-A and TMT-B) for visual attention and concentration. Significant between-groups differences were found for these tests with older participants scoring significantly lower on attention, including visual search. A negative correlation was found between gaze time and CPT-A and CPT-B scores in the older adult age group, and the increased gaze time for older adults and main effect for age during lane changes and intersection approaches suggest that older adults have poorer control of eye movement in relation to prediction of their driving environment on the road ahead. As a result, their responses may be delayed. These results show that eye tracking and driving simulation can be used to assess driving behaviors, particularly visual performance in relation to interacting with dynamic driving environments.

Recently, Robbins et al., 2019 used Tobii Pro Glasses 2 to look at visual attention in both real and simulated driving environments. In their study, drivers' visual attention was measured at six intersections where maneuvers were controlled by the driver, and in six on-road situations where traffic was controlled by traffic signals and the road environment. Participants wore eye tracking glasses both on-road and in simulated conditions. Conditions in each scenario varied between low and medium demand driving situations. Researchers analyzed mean fixation durations, mean saccade amplitudes, and number of head movements per minute to examine direct attention in a visual scene and visual search. Results showed that drivers had longer fixation durations in the simulator compared to on-road conditions. Additionally, the distances between drivers' fixations were shorter in low demand driving situations compared to medium demand driving situations. Overall, results were consistent with previous research that has shown that drivers' visual attention fluctuates depending on the demand of the task at hand. Robbins et al., 2019 suggest if driving situations are made demanding enough on a simulator, visual behaviors in the simulated environment should be similar to real-world driving. Additionally, results indicate that simulators and eye tracking technology can be useful in examining drivers' visual attention, particularly at intersections. Results of these studies validate the use of employing eye tracking technology and interactive driving simulators to understand the visual attention of drivers in simulated construction work zone environments.