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Firefighter daytime visibility: trim properties and conspicuity

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Abstract

Conspicuity enhancing trims on turnout gear promote firefighters' abilities to (1) reduce the possibility of struck-by accidents, (2) be located and recognized by others, and (3) coordinate their work with colleagues. Firefighting personal protective equipment (PPE) ensemble standards specify technical requirements for new visibility materials. A better understanding of the relation between laboratory measures of material properties and behavioral measures of conspicuity can be used to evaluate existing and newly developed turnout gear trim designs. The current paper examined how photometric luminance measures (%Y) of fluorescent trims on firefighter turnout gear relate to daytime conspicuity in two naturalistic field experiments (distance detection and identification, peripheral detection). The test samples consisted of lime yellow and orange-red fluorescent trims, including traditional solid trims and more recently developed segmented trims. We found overall strong relations between measured luminance and (1) observers' detection of a firefighter from afar, and (2) observers' identification of the color of a firefighter's clothing in their peripheral view. A relation did not exist between %Y and peripheral detection. Additionally, the experiments demonstrated that traditional solid and newer segmented trim designs showed little conspicuity performance difference, with the only observed difference being in peripheral color identification. This suggests that the impact of luminance on conspicuity may be overestimated when evaluating a trim's daytime performance. Our results further support that luminance measures alone are not sufficient to evaluate the conspicuity of turnout gear in naturalistic settings.

Keywords: Conspicuity, Luminance, Fluorescence, NFPA 1971, Turnout gear, Visibility trim

Introduction

Firefighters are too often injured or killed by vehicles when tending to persons at motor vehicle incidents, directing traffic around crash sites, crossing highways to reach victims, and when coordinating work team operations on fire grounds (Fahy 2014). Between the years 2000 and 2013, 61 firefighters were killed when struck by a vehicle (Fahy 2014). A failure of drivers to detect and identify firefighters is a major factor in these incidents (Fahy 2014).

Conspicuity refers to the attention capturing capacity of a visual stimulus, such as a firefighter's turnout gear or other high visibility clothing or device, so that an observer can more easily detect and identify the object of importance. Conspicuity in naturalistic conditions depends on the characteristics of a stimulus (e.g., a firefighter in turnout gear), the background (e.g., the incident), the task (e.g., detecting the presence of a firefighter while driving), and perceivers' expectations [e.g., do they expect to see a person on the road (Shinar 1985; Wickens et al. 2004; Zwahlen and Schnell 1997; Zwahlen and Vel 1994; Tuttle et al. 2009)].

For firefighters responding to traffic incidents, multiple factors contribute to reduced visibility even in favorable daylight conditions. A rising number of roadway infrastructure reconstruction projects, attention grabbing commercial signs, higher traffic volumes, and more powerful emergency lighting increase visual complexity, and, as a result, decrease the relative conspicuity of pedestrians on the road (e.g., Sayer and Buonarosa 2008). Furthermore, driver demographics impact conspicuity. The maturing drivers' population has less contrast sensitivity, less visual acuity, and slower reaction times on average, reducing drivers' abilities to detect persons and react to events (Jenssen and Brekke 1998; Luoma et al. 1996; Sayer and Mefford 2000; Tyrrell et al. 2009; Wood et al. 2014; Wood et al. 2012). Finally, the phenomenon of distracted driving is becoming a greater factor in traffic accidents (see for example, http://www.distraction.gov/index.html).

Protective turnout clothing, a firefighter's "first line of defense," can enhance visibility with fire trims (Barker et al. 2013 p. 110, Cotterill and Easter 2010 p. 601), and the resulting increase in conspicuity of turnout gear can improve safety against being struck by vehicles. Additionally, visual saliency facilitates firefighters' abilities to locate colleagues and coordinate operationally with each other. Indeed, systematic patterns of high visibility elements on clothing can be used purposefully to differentiate groups and ranks of firefighters and other first responders. Thus, understanding how well firefighter turnout gear enhances conspicuity is a factor of importance to improve firefighter safety and operations.

As reviewed below, a growing body of research has examined the daytime and nighttime conspicuity of visibility enhancing clothing, but few studies have focused on firefighter turnout gear. The goal of the current paper was to assess the relation of different measures of conspicuity, and to evaluate and compare the daytime conspicuity of current turnout gear trim designs.

Conspicuity enhancing elements for firefighter turnout gear are technically limited to attached trims, in contrast to the variety of safety garments worn by, for example, road maintenance workers. The National Fire Protection Agency (NFPA) 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity to Fire Fighting has required high visibility trim materials on turnout gear in their current design since its 1997 edition. The NFPA pattern prescribed in the standard consists of trims that are at least 50 mm wide on the chest, wrists, and ankles (NFPA 2013 section 6.2), Fig. 1a, b.

Fire trims are made of flame-resistant fluorescent and retroreflective materials. Fluorescent materials increase conspicuity in daylight by absorbing invisible energy in the near-ultraviolet and then re-emitting it as additional longer wave-length visible light (Burns and Pavelka 1995). Most common high visibility fire trims consist of alternating parallel stripes of fluorescent, retroreflective, and fluorescent material (Fig. 1c).

Laboratory and field studies have repeatedly demonstrated that fluorescent materials enhance daytime conspicuity (Zwahlen and Schnell 1997; Zwahlen and Vel 1994;

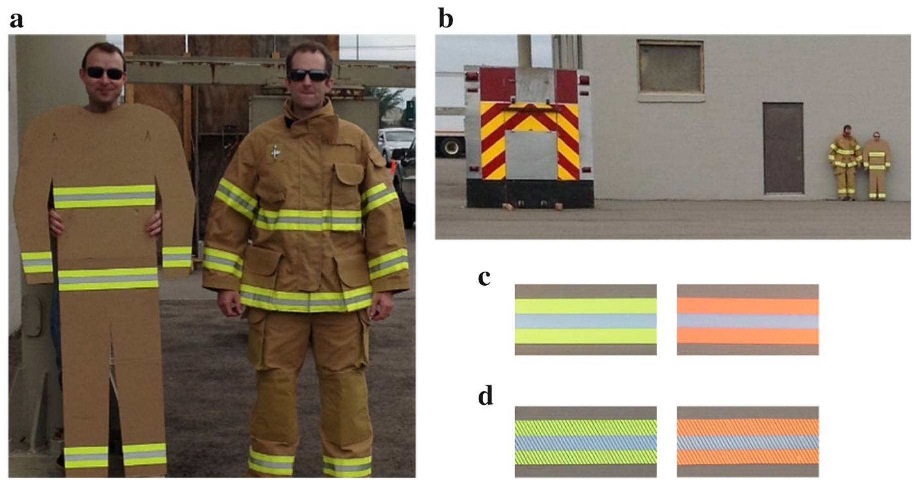

Fig. 1 **a** An experimenter holding a trim stimulus used in study 1 with the minimal trim pattern prescribed by the NFPA 1971–2013 standard (left) and an experimenter wearing firefighter turnout gear (right); **b** trim stimulus and turnout gear when viewed from afar; **c** traditional solid lime yellow and orange-red trim samples with alternating bands of fluorescent, retroreflective, and fluorescent material; **d** more recently developed segmented lime yellow and orange-red trim samples

Jenssen and Brekke 1998; Hanson and Dickson 1963; Kwan and Mapstone 2004; Michon et al. 1969) for differing findings, see (Tyrrell et al. 2009). For example, fluorescent stimuli were detected before green or black garments in an eye-tracking laboratory study (Isler et al. 1997), and a simulated work zone study found that subjects in the daytime detected fluorescent orange-red and fluorescent lime yellow safety vests at longer distances than non-fluorescent orange or yellow vests (Turner et al. 1997). Similarly, studies of nighttime conspicuity have shown a consistent and substantial conspicuity performance advantage for retroreflective materials e.g., (Jenssen and Brekke 1998; Luoma et al. 1996; Wood et al. 2012; Blomberg et al. 1986; Sayer and Mefford 2004). Less research has examined the conspicuity of firefighter turnout gear, specifically as described in NFPA 1971–2013, section 6 (Cassidy et al. 2005). To our knowledge, no published study has systematically tested the daytime conspicuity of firefighter turnout gear with different types of high visibility trims.

Multiple correlative predictors of daytime conspicuity have been suggested in previous research, such as photometric laboratory measures of luminance: %Y (also called big-Y or cap-Y). It is measured as the luminance ratio between a colored fabric sample and a highly reflective white reference tile, when illuminated with a reference light source. Generally, higher luminance should result in greater conspicuity due to the perceivable luminance contrast it can create (Sayer and Mefford 2000).

Measured %Y, however, may not be a reliable indicator of conspicuity in naturalistic conditions. Measures of luminance disregard the interactions between stimulus, perceiver, and context that result in perceptible contrast. For example, a viewer may perceptually not be sufficiently sensitive to see differences in %Y values measurable in the laboratory.

The conspicuity of a stimulus can be more directly and accurately assessed with behavioral measures that capture when perceivers detect and identify a stimulus located in their focal and/or peripheral views in a relevant scene. Behavioral studies have examined "visual search conspicuity", defined as the tendency of a stimulus to be easily detected when an observer is scanning a scene to locate a stimulus, and "attention conspicuity", defined as the attention-grabbing effect of a stimulus in the absence of visual search (Cole and Hughes 1984).

A variety of behavioral paradigms associated with quantifying pedestrian conspicuity have been used in past research (Sayer and Mefford 2000; Burns and Pavelka 1995; Kwan and Mapstone 2004; Hughes and Cole 1986; Langham and Moberly 2003; Lesley 1995; Wood et al. 2011). A common behavioral paradigm to assess conspicuity is to measure the distance at which perceivers can detect and recognize (identify) a stimulus (Tuttle et al. 2009; Sayer and Buonarosa 2008; Jenssen and Brekke 1998; Wood et al. 2014; Wood et al. 2012; Burns and Pavelka 1995; Michon et al. 1969; Blomberg et al. 1986; Sayer and Mefford 2004; Moberly and Langham 2002; Buonarosa and Sayer 2007). Alternative non-driving paradigms concern the measured angle (referred to as conspicuity angle) at which viewers can detect a stimulus or identify its color when the stimulus is presented in viewers' peripheral view (Zwahlen and Schnell 1997; Zwahlen and Vel 1994; Isler et al. 1997). These paradigms simulate situations in which a perceiver may need to detect approaching stimuli from the side regions beyond the immediate focal viewpoint. Because of the nonuniform distribution on the retina of the cone photoreceptors responsible for color perception, color vision is notably less sensitive at peripheral rather than at focal viewpoints.

Previous research does not clearly indicate the strength of the relation between laboratory luminance and behavioral conspicuity measures. Generally, daytime fluorescent materials are dependably more conspicuous than non-fluorescent materials of the same color, and laboratory luminance measures have been reported to correlate strongly with behavioral measures of conspicuity, e.g., (Sayer and Mefford 2000).

Studies in naturalistic driving contexts, however, indicate that luminance may not always predict conspicuity performance (Zwahlen and Vel 1994; Michon et al. 1969; Turner et al. 1997; Sayer and Mefford 2004). For example, (Turner et al. 1997) found that a subset of variously colored safety vests ranging in luminance values between 66.1 and 102.3 %Y did not differ significantly in behavioral measures of conspicuity, and that luminance and conspicuity were not linearly related.

The main objective of the present paper was to better understand the relation between photometric laboratory measures and behavioral measures of daytime conspicuity of firefighter turnout gear using samples of current and more recently developed high visibility trims. Insights on how well luminance measures predict conspicuity are particularly important given the different advantages between laboratory and behavioral measures. Photometric laboratory measures may be faster, more convenient, and less costly, but behavioral measures have higher ecological validity. Understanding whether photometric luminance measures can reliably predict conspicuity in field studies remains an important question given expected material degradations in turnout gear due to wear and tear over its service life (Cotterill and Easter 2010). Furthermore, ongoing updates either in NFPA requirements or in technology development lead to new turnout gear designs that need to be evaluated, such as recent examples of segmented trims.

Changes to the 2013 edition of the NFPA 1971 standard impacted the implementation of visibility trim on firefighters' turnout gear. Sections 7.2.6 and 8.71 of the standard require that all materials attached to the outer shell of turnout gear sleeves meet a stored thermal energy test standard (ASTM F2731) to a defined performance level. These changes are intended to help reduce risks to firefighters from long-duration radiant heat exposure which may cause thermal energy to build up within the layers of their protective clothing.

Two approaches to meet the new performance requirements are adding additional material layers within the turnout construction or perforating exterior accessories such as fire trims and identification panels. Both have been deployed successfully and each offer certain performance, manufacturing, and cost advantages.

Another recent solution to meet the NFPA stored energy requirement is a segmented trim design (Fig. 1d). In this approach, the retroreflective and fluorescent materials are arranged as separated striped segments. Compared to solid trims (Fig. 1c), the segmentation permits increased moisture vapor transport and improved performance in the stored energy test method (ASTM F2731). Further, breaks between the segments allow for greater flexibility of the material, reduced trim weight, and a thinner heat-applied film, which offers a threadless attachment process. These advantages, however, come at the expense of reducing the visual density of the optical elements of the structure, leading to questions about possible impacts to conspicuity performance.

Although certified segmented trims successfully conform with NFPA physical property requirements of geometry, size, stored energy measurements, and photometric indices, no reported studies have behaviorally verified the daytime conspicuity performance of fluorescent segmented trim designs. For example, segmented trim conspicuity may be influenced by the area reduction of fluorescent material, lowering daytime luminance, which could in turn degrade conspicuity performance. As reviewed above, measured luminance values are associated with increased conspicuity in some studies, but not in other studies. Therefore, a direct assessment of the daytime conspicuity of segmented trims in naturalistic environments is needed.

The main objective of the current studies was to investigate and better understand the relation between laboratory photometric measures of fluorescence and two common behavioral measures of conspicuity. Experiment 1 used a distance detection paradigm, and Experiment 2 used a peripheral view detection paradigm. To assess the relation between the different measurements, performance evaluations of eight (study 1) and 10 (study 2) trim samples were compared (Table 1).

A second objective of the current study was to compare performance of the daytime conspicuity of traditional solid trims with more recently developed segmented trims for firefighter turnout gear in a naturalistic driving context. We compared the conspicuity of compliant NFPA 1971–2013 solid and segmented fluorescent lime yellow and fluorescent orange-red trims which were the same size visually but differed in the amount of material removed from the gaps between segments.

Methods

Study 1: detection distance

Study 1 used a detection distance paradigm to examine the relation of %Y and conspicuity, and the impact of a segmented trim design on daytime conspicuity. In this

Table 1 Trim characteristics (%Y and chromaticity coordinates at illumination D65 and 45/0 geometry with 2° standard observer and a black underlay) and conspicuity measures (person detection distance, peripheral person detection angle, and peripheral color recognition angle) of trims 1–8 (study 1) and trims 1–10 (study 2)

Trim	%Y	x	y	Person detection distance in meters (study 1)	Peripheral person detection in degrees (study 2)	Peripheral color recognition in degrees (study 2)
1: Solid fl. lime yellow 1[a]	119.26	.3959	.5445	303.51 (63.93)	25.70 (7.37)	15.00 (7.44)
2: Solid fl. orange-red[a]	54.16	.6085	.3487	263.87 (59.28)	25.75 (6.96)	10.25 (4.90)
3: Segmented fl. lime yellow[a]	88.79	.3942	.5259	301.18 (60.59)	24.27 (7.22)	11.25 (6.71)
4: Segmented fl. orange-red[a]	52.16	.5560	.3723	273.66 (58.57)	25.35 (8.03)	10.40 (6.03)
5: Solid fl. lime yellow 2[a]	79.71	.4020	.5618	286.57 (71.12)	26.06 (8.57)	14.91 (7.22)
6: Solid fl. lime yellow, filter 1[a]	104.29	.4062	.5472	286.85 (69.49)	24.50 (7.20)	12.18 (5.73)
7: Solid fl. lime yellow, filter 2	65.3	.3998	.5439	268.85 (134.14)	24.67 (7.57)	10.03 (6.12)
8: Blank	25.25	.3863	.3788	238.15 (54.49)	24.85 (7.47)	8.28 (5.20)
9: Solid fl. lime yellow, filter 3	30	.3942	.5469		24.81 (6.86)	5.24 (4.17)
10: Solid fl. lime yellow, dirty	58	.3923	.5223	–	24.32 (7.11)	9.67 (5.21)

Standard deviations are indicated in parentheses

[a] Indicates conformance to NFPA 1971 performance requirements. Filter descriptions for samples 6, 7, and 9 are found in "Study 1 trim stimuli and placement" section paragraph 5 (filters 1 and 2) and 2.2.4 paragraph 1 (filter 3)

paradigm, a participant was seated in the passenger seat of a vehicle approaching a road scene including ecologically valid distracters such as construction zone barrels, a stationary automobile, realistic fire truck mockups, road-worker signs, and a visual target stimulus wearing turnout gear with different high visibility trims. The distance at which the participant observer detected and recognized a person in the scene was the dependent variable.

In a within-subjects design using eight trim conditions, we examined the relation between luminance indicator %Y and detection distance. Four of the trims were used to examine how well traditional solid and newer segmented trims could be detected in a 2 (trim design: solid, segmented) × 2 (trim color: lime yellow, orange-red) study design.

Study 1 participants

Thirty-two individuals (22 men) with a mean age of 33 years (range 20–54 years) participated in the study. All participants were of legal driving age and had normal or corrected-to-normal acuity and normal color vision. Volunteers for the study were recruited from a large company campus. They provided written consent and received gift certificates ($20 value) as compensation prior to participating in the experiment.

Study 1 experimental site

Study 1 was conducted on a closed track without incidental traffic, from July 14 to 18, 2014 between 8:30 a.m. and 6:00 p.m. (i.e., at least 2 h after sunrise and 3 h before sunset). Daytime lighting conditions included direct sun with intermittent clouds and measured above 100,000 cd/m^2 (the highest reading for the meter employed) for all trials.

The surrounding area of the test track contained green foliage, a brown brick building, an overhead sign support structure, and a green overpass sign. A straight 250 m stretch of the roadway was used for simulating a roadway accident scene (Fig. 2). As viewed by the participant, the scene included orange construction zone barrels, an SUV facing the observer, an overhead sign post, a building, and two mock fire truck rear ends made of painted plywood, retroreflective colored chevron sheathing, and functioning LED emergency lights. The scene additionally included two portable roll-up fluorescent road worker signs at either side of the road. To increase the generalizability of the findings, the fire truck and the SUV lights were turned on in half the trials, and the roadway signs were changed from lime yellow to orange-red in half the trials.

Study 1 procedure

Participants sat in the front passenger seat of one of two four-door Nissan Altimas (2009 and 2010) with functioning headlights and clean windshields. Experimenters drove the cars to ensure a uniform speed of 50 kmph across trials and participants. Participants were informed that on any given trial a pedestrian could be present positioned on or near the road. Participants were asked to look downward prior to the onset of each trial while the driver accelerated to 50 kmph (30 mph). When the driver reached the start location at 585 m, a laser sensor triggered an initial time stamp, and an auditory tone

Fig. 2 Overview of the roadway scene. Each trial started at 587 meters (not indicated in the figure). The trim locations (approximately indicted by numbered circles) were at 378 m, 408 m, 426 m, 430 m, 527 m, 541 m, 565 m, and 569 m from the trial starting location. Orange construction zone barrels were located between 362 and 466 meters, an SUV faced the observer at 574 m, fluorescent road worker signs were at 411 and 561 m, and two mock fire truck rear ends were at 580 and 587 m

within the car indicated that the participant should look up and begin to regard the road. Upon recognizing a target stimulus, participants pressed a button on the response box, sending a response trigger signal to a radio receiver (recognition distance). Participants were instructed to respond only when they were confident that the object they viewed was a person. The driver then returned to the trial start location. Prior to the beginning of each session, participants were given a training session of less than 20 min. The total duration of a session was ~ 1.5 h per subject.

Study 1 trim stimuli and placement

We created two-dimensional cutouts to represent firefighter stimuli (Fig. 1a), similar to previous research using highway worker dummies (Turner et al. 1997). Trims were placed on cardboard cutouts in the shape of a 1.83-m man (75th percentile human man) from foot to neck. At each trial, an experimenter would hold the cutout in front of him just below his head facing the road.

The appearance of the cardboard approximated the color of commonly used tan turnout gear (Fig. 1a). A previous field study comparing the daytime conspicuity of tan and black turnout jackets with lime yellow fire trim in a uniform standardized pattern found no performance difference between the colors (Tuttle et al. 2009). Based on this previous result, only tan cutouts were used as targets.

Trims were placed on the cutouts conforming as closely as possible to the specifications of the NFPA structural firefighting ensemble standard (1971–2013): a horizontal band around the waist, a horizontal band around the chest under the arms, horizontal bands around each wrist cuff, and horizontal bands around each ankle (Fig. 1a). In the "blank" condition, no trim was placed on the cutout.

Eight trim conditions were compared in this study, including a blank control condition. See Table 1 for %Y values and chromaticity coordinates. All trim samples were selected based on commercially available materials certified to NFPA 1971 component conformance for use on turnout gear, including samples from different manufacturers.

To better assess the relation of %Y with distance detection, the range of luminance differences represented among the trim samples was expanded by adding neutral density optical filter over layers on two samples, to attenuate the %Y value controllably. The manipulations aimed to reduce the trims' luminance values while maintaining the trims' color space coordinate values. One sample was generated by adhering a Lee 298 .15 neutral density filter (Table 1, sample no. 6, filter 1). Another sample was created by adhering a selective wavelength multi-layer optical notch filter film (blocking wave lengths from 440 to 490 nm) over the fluorescent yellow triple trim, resulting in a trim substandard to luminance requirements based on the NFPA 1971 Standard (Table 1, sample no. 7, filter 2).

Four trims were used to test differences in conspicuity between solid and segmented orange and yellow trims (Fig. 1c, d). All samples were triple trims with a silver retroreflective middle band. The solid and segmented trims of the same color were of the same material and produced by the same manufacturer and had similar chromaticity coordinates. Fluorescence measures showed that the solid lime yellow trim had a higher %Y value than the segmented lime yellow trim, whereas there was little difference in %Y between the solid and segmented orange-red trims (Table 1).

During each trial, stimuli were presented at one of eight possible locations, four to the left and four to the right side of the road. Stimulus locations ranged from 380 to 570 meters from the trial starting location (Fig. 2). Participants saw each of the eight trim conditions on the roadway scene twice (16 trials). Additionally, there were four trials with no person in the scene, resulting in a total of 20 trials. To reduce total trial number, session time, and respondent fatigue, trim conditions were counterbalanced across eight roadway locations using a Latin Square design. Participants were randomly assigned to a trial order. To familiarize themselves with the task before the experiment proper, participants saw one practice trial with a person with one of the trims in the roadway scene and one practice trial with no person in the scene.

Study 1 detection distance measurement

Radio sensors measured the distance at which participants detected a person relative to the starting point of each trial. We installed an infrared laser with a reflective marker such that a laser beam ran perpendicular to the road. At the beginning of a trial, the car disrupted the laser beam, a radio signal transmitted a signal to a receiver radio, and the receiver radio sent a time stamp to a response time measurement device. Times were recorded in milliseconds. To compute the distance at which respondents perceived a stimulus relative to the starting location, we multiplied the average velocity of the vehicle by response time. By subtracting this score from the stimulus location distance value (Fig. 2), we computed distance detection scores.

Study 2: peripheral person detection and color recognition

To substantiate the results from study 1 with alternate means, study 2 examined the performance of solid and segmented trims of varying %Y using a peripheral viewing methodology. This paradigm focuses on individuals' abilities to detect a person and identify the garment's color when viewed outside one's focal viewpoint, such as when a driver focuses on the road ahead but needs to notice firefighters in adjacent lanes or off the road. We added two trims with additional luminance attenuation (Table 1, samples 9 and 10) to the sample set in study 2 to better assess the relation between luminance and behavioral conspicuity measures.

Study 2 participants

Thirty-two individuals (24 men, all individuals different from experiment 1) with a mean age of 34 years (range 24–57 years) participated in the study. All participants were of legal driving age and had normal or corrected-to-normal acuity and normal color vision. Volunteers for the study were recruited from a large company campus. They provided written consent and received gift certificates ($20 value) as compensation prior to participating in the experiment.

Study 2 experimental site

Twenty-eight cones were placed at an 8-m radius, 2.9° apart, spanning an arc of 80.248°. Trims were presented at two locations at 30 m distance (same distance used in previous research, e.g., (Zwahlen and Schnell 1997; Zwahlen and Vel 1994; see also Fig. 3). The scene also included at assigned locations in the background two mock firetruck

Fig. 3 Experimental set-up of study 2. Trims were presented at two angle locations, 60.19 or 77.38° from the left most cone at a distance of 30 m. Mock firetruck rear ends were located behind the trims at 54.45° and at 71.65° from the left most cone. A road sign was located at 48.72°, and an SUV at 65.92° from the left most cone

rear-facing silhouettes, an SUV, a road sign, an overhead road sign installation, and a building. Cones were labeled with numbers and letters in a fixed pseudo-randomized order.

Study 2 procedure

A four-door Nissan Altima was placed at an 8-m distance from 28 evenly spaced cones arranged in an arc. Participants were seated in the driver seat. At the beginning of each trial, a windshield blind blocked participants' view. Once the windshield blind was removed by an experimenter, participants looked at the far-left cone. To ensure that participants focused on this cone, they were asked to read and report the number or letter indicated on the cone. Participants then stated whether they detected the presence of a person in their peripheral vision. Further, participants were asked to recognize the color of the trim worn by the individual. If participants were not able to discern the presence of a person and/or the color of the trim, they were asked to attend to the next cone in the arch and read aloud the indicated letter or number. Participants were instructed to move at a constant, fast pace and to avoid peeking ahead. The duration of a session was about 1 h per subject.

Study 2 trim stimuli and placement

The same cutout human shapes and eight trim stimuli were used as in study 1. To expand the represented range of luminance of the trims, we created two additional samples. One stimulus was generated by adding a Lee 209 .3 neutral density filter on a solid lime yellow trim (Table 1, sample no. 9, filter 3). Another stimulus was created by attenuating a solid lime yellow trim with charcoal and ash to simulate naturalistic soiled wear conditions (Table 1, sample no. 10).

During each trial, trim stimuli were presented at 30 meters distance at one of two angle locations, 60.186° or 77.382° from the left most cone. There were two blocks in which participants saw each of the ten trim conditions (20 trials). Additionally, there were five trials with no person in the scene, resulting in a total of 25 trials. Trim conditions were fully counterbalanced across the two location conditions across participants. Participants were randomly assigned to a pseudo-randomized trial order. To familiarize

Table 2 Correlation coefficients of luminance, chromaticity, distance person detection (study 1, n = 8), and peripheral person detection and color recognition scores (study 2, n = 10)

	Person detection distance (study 1)	Peripheral person detection (study 2)	Peripheral color recognition (study 2)
%Y	.92**	.12	.86**
Distance detection		.03	.83*
Peripheral person detection			.45

** p < .05, ** p ≤ .01*

themselves with the task, participants saw one practice trial with a person in the scene and one practice trial with no individual in the scene before the experiment proper.

Study 2 peripheral person detection and color recognition measurement

We computed a peripheral person detection score by subtracting the angle of the cone participants focused on from the angle of the trim location in any one trial. Similarly, we computed a peripheral color recognition score by subtracting the angle at which participants correctly identified a trim's color in their peripheral view from the angle of the trim location. Catch and null trials, blank trials, and a number/letter-reading task were included in the design. No color identification errors were observed in this experiment.

Data analysis

The associations of person detection distance with %Y and participant age were examined with correlation analyses for continuous variables (Spearman's r). The impact of trim design (solid, segmented) and trim color (fluorescent orange-red, fluorescent lime yellow) on person detection distance were examined with repeated measures ANOVAs, with trim design and color as within-subject factors. Significant effects were further examined with pair-wise comparisons (t-tests).

Results

Study 1 results

We examined the relation between detection distance and %Y with a correlation and found that detection distance was strongly associated with %Y, $r\ (8) = .92$, $p = .001$ (Table 2, Fig. 4). Additional analyses by subject demographic showed no effect of age.

To compare the performance of traditional solid and new segmented trims, we conducted a repeated measures ANOVA with trim design (solid, segmented) and trim color (lime yellow, orange-red) as factors. We found a main effect of trim color, $F(1, 31) = 15.69$, $p = .001$, $\eta = .34$, but no main effect of trim design, or interaction effect of trim design and color. Fluorescent lime yellow trims were detected at farther distances than fluorescent orange-red trims (302.34 m, 268.77 m), but no significant performance difference between solid and segmented trims of the same color was found (Fig. 4). Additional analyses showed that all trims, except the lime yellow trim with filter 2 (Table 1 sample no. 7) that did not comply with NFPA-1971 performance standards, were detected earlier than the blank control, all $p\text{s} < .016$.

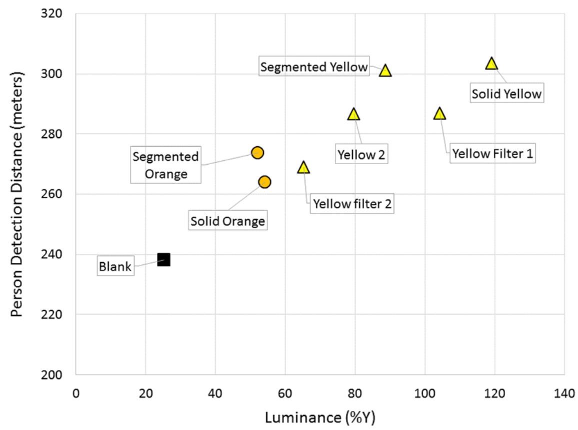

Fig. 4 Scatterplot of mean person detection distance (meters) and luminance (%Y) in Study 1 for lime yellow and orange-red fluorescent trims and a blank control condition

Study 2 results

Correlation analyses showed that %Y scores were strongly associated with peripheral color recognition, $r\ (10) = .86$, $p = .001$, but not with peripheral person detection, $r\ (10) = .12$, $p = .75$ (Table 2). Additional analyses of age effects showed no relation of age with peripheral person detection or color recognition scores. However, participants who were better at detecting the presence of a person were also better at recognizing the person's trim color, $r\ (32) = .82$, $p < .001$.

A repeated measures ANOVA of trim design (solid, segmented) and trim color (fluorescent orange-red, fluorescent lime yellow) for person detection showed no main effects or interaction effect. In other words, the presence of an individual wearing solid and segmented fluorescent lime yellow or orange-red trims was detected at similar peripheral viewing angles (Table 1).

A repeated measures analysis of trim design (solid, segmented) and trim color (fluorescent orange-red, fluorescent lime yellow) for peripheral color recognition showed a main effect of trim color, $F(1, 30) = 13.51$, $p = .001$, $\eta = .31$, and a main effect of trim design, $F(1, 30) = 11.53$, $p = .002$, $\eta = .28$, that were qualified by an interaction effect of trim color and design, $F(1, 30) = 10.61$, $p = .003$, $\eta = .26$. Follow-up pair-wise comparisons showed that the color of the solid lime yellow trim was recognized at larger angles than the color of the segmented lime yellow trim (15.00°, 11.91°), $t(31) = 4.90$, $p < .001$. However, for orange-red trims, solid and segmented trims were recognized at similar angles (10.25°, 10.40°). The color of the solid lime yellow trim was recognized at significantly greater angles than the color of the other three trims, all ps < .001, with no other significant differences between the four trims. Additional analyses showed that all trims, except for the lime yellow trim with filter 2 (Table 1, no. 7) and the dirty lime yellow trim (Table 1, no. 10), differed from the blank control condition, all ps < .019.

An integrated analysis across experiment 1 and 2 showed that distance detection in study 1 was highly correlated with peripheral color recognition in study 2, $r\ (8) = .83$, $p = .012$. However, peripheral person detection was not associated with distance detection or peripheral color detection (Table 2).

Discussion

Study 1 discussion

Study 1 examined the relation between distance detection and firefighter turnout gear trim %Y luminance in a naturalistic daytime driving context. On the one hand, we found that luminance was strongly associated with detection distance in a simple correlation analysis. On the other hand, there was no difference in conspicuity between solid and segmented lime yellow fluorescent trims although these trims differed in luminance (Fig. 4). This suggests that laboratory measures of luminance, though overall strongly related to behavioral measures of conspicuity, may not be a valid indicator of a trim's conspicuity performance in a naturalistic setting.

We found that in this simulated emergency scene, the fluorescent lime yellow trims were detected from farther away than fluorescent orange-red trims. This appears to contrast with research that showed no differences between fluorescent yellow-green and orange-red safety vests (Sayer and Buonarosa 2008; Turner et al. 1997; Buonarosa and Sayer 2007), or research that found that orange was more visible than other colors (Jenssen and Brekke 1998; Michon et al. 1969). Our study, however, differs from previous research in the amount and placement of fluorescent material as well as in background features. Construction worker safety vests have fluorescent background fabric with retroreflective trims, whereas firefighter turnout gear is usually tan or black with fluorescent and retroreflective trims arranged as stripes in a distinct pattern. Additionally, the simulated scene devised for this experiment contained as distractors more orange than yellow competing stimuli (e.g., orange construction barrels, orange signage). It could be speculated that because of an increased color contrast between yellow target stimuli and orange background stimuli, yellow-green trims may have captured attention more readily than orange-red trims. If an increase in the relative amount of yellow in the background were to occur (e.g., vehicles, road worker signs, warning lights, etc.), the saliency of orange-red trimmed turnout gear might become greater, see (Treisman and Gelade 1980). This finding underscores the importance of studying the performance of high visibility clothing in the context for which the clothing is designed.

Study 2 discussion

Study 2 examined the relation between peripheral person detection, peripheral color identification, and luminance (%Y) for turnout gear in a naturalistic daytime scene. We found an overall strong relation of the color luminance measure %Y with observers' abilities to identify the color worn by a person seen in their peripheral view, i.e., the higher the value of %Y, the greater an observer's ability to identify the color. Furthermore, the pattern of differences in luminance was evident in differences in color recognition between traditional solid and new segmented trim designs, i.e., solid fluorescent lime yellow trims had the highest luminance score and their color was better recognized than the color of other trims. We did not see a relation between luminance and perceivers' abilities to detect the presence of a person in their peripheral view. Similarly, we found that differences in luminance associated with either solid or segmented fluorescent lime yellow or fluorescent orange-red trims showed no influence on person detection.

Our results differ from previous research regarding which color was associated with better person detection (here: no difference between orange-red and yellow-green) and color recognition (here: lime yellow). Specifically, previous research reported better peripheral detection for fluorescent lime yellow color targets (Zwahlen and Schnell 1997; Zwahlen and Vel 1994; Isler et al. 1997). However, the authors did not report statistical tests to compare the reliability of the observed differences. Previous research on color recognition led to mixed results, with some studies reporting better color identification for fluorescent orange color targets (Zwahlen and Vel 1994), and other studies showing better color recognition for lime yellow color targets (Zwahlen and Schnell 1997).

Variation in stimuli types, stimulus size, background, and setting may be responsible for inconsistencies across studies. Furthermore, the number of stimuli of different colors in an experiment may affect color recognition due to a higher salience of colors (which color is relatively sparse in the sample?), response tendencies (subjects 'recognize' the color that has a higher chance of being the right color), and burden on respondents (e.g., differentiate yellow from yellow-green; Zwahlen and Schnell 1997, Jenssen and Brekke 1998). Further research analyzing error rates in color recognition studies could shed light on this issue, e.g., (Jenssen and Brekke 1998).

The variety of findings regarding the effect of certain colors on person detection and color recognition underscores the importance of examining the performance of high visibility garments in the context for which they were designed. To our knowledge, our study is the first to examine peripheral daytime conspicuity for firefighter turnout gear.

Conclusions

Visibility enhancing trims on turnout gear play a major role in promoting firefighters' abilities to (1) reduce the possibility of vehicle and equipment struck-by accidents, (2) be located and recognized by others, and (3) coordinate their work with colleagues. Behavioral conspicuity measurements can support the understanding and expectations of gear performance and the development of effective practices in the field. Focusing on firefighter turnout gear, the current studies examined how different measures of conspicuity relate to each other in a naturalistic daytime context.

The first objective of the studies was to better understand the relation between laboratory measures of luminance (%Y) and two behavioral measures of conspicuity (distance detection, experiment 1, and peripheral viewing/detection, experiment 2). We found overall strong relations of the measured %Y luminance values with observers' abilities to detect a target from afar when driving on a road (study 1) and to recognize the color of the person's clothing in peripheral view (study 2). A perceiver's abilities to detect a person from afar and to detect the color of the target garment in their peripheral view were strongly correlated, consistent with a posited reliance on the underlying sensory system that predominantly uses cones for focal view and color detection. In contrast, differences in luminance did not affect observers' abilities to detect the presence of a person in their rod-dominated peripheral view (study 2), and peripheral person detection was not associated with distance detection or peripheral color identification.

Overall, our findings suggest that the relation of %Y luminance to the conspicuity of firefighter turnout gear, and to commonly observed object conspicuity performance in general (e.g., in road sign conspicuity performance) is not a simple one. Depending on the context, either person detection or color identification may be the more relevant task. If person detection in an incident or accident road scene is of primary importance, our results suggest that differences in %Y beyond a minimum threshold may be less important for daytime conspicuity. However, if it were of primary importance in an accident road scene to differentiate between persons wearing different colors of trims, differences in luminance may be more relevant.

The second objective of the current studies was to compare the conspicuity of newly developed segmented trim designs to existing equipment configurations. We found that differences in luminance between fluorescent lime yellow solid and segmented trims were inconsequential when detecting a firefighter from afar (study 1) and in one's peripheral view (study 2). Observers' abilities to identify a trim's color were impacted by design differences for fluorescent yellow trims, but not for fluorescent orange-red trims (study 2). Overall, this suggests that traditional solid and newer segmented trim designs show little conspicuity performance difference, with the only observed difference being in peripheral color identification.

An additional result of the studies was that—within the subject range we examined—we did not find significant age effects on daytime distance detection, peripheral person detection, or peripheral color identification. Prior research has found that older drivers performed worse in nighttime conditions, e.g., (Luoma et al. 1996; Tyrrell et al. 2009; Wood et al. 2014; Wood et al. 2012; Sayer and Mefford 2004). Similarly, a study on day and nighttime visibility found that older drivers detected road signs later than younger drivers (Jenssen and Brekke 1998). The effect has been attributed to differences in contrast sensitivity between younger and older drivers (Wood et al. 2014). One paper included a comparison of conspicuity performance during daytime and nighttime in a naturalistic setting (Tuttle et al. 2009) but did not have sufficient statistical power to detect any age differences. In line with previous research on daytime conspicuity (Sayer and Buonarosa 2008), our study suggests that age-related performance differences in conspicuity frequently evident in nighttime studies may not be as relevant in daytime conditions.

A limitation of the studies was that the ecological validity of the experiments was reduced because subjects were confined as passengers on a closed road track, and they were not experiencing the distracting demands of driving, being present in actual traffic, or experiencing the genuine disruptions of emergency scene conditions. This set-up allowed us to maintain a high level of experimental control, however, in a driving context. Disadvantages of this paradigm is that the overall workload on participants may be reduced compared to an open road scenario (Sayer and Buonarosa 2008), and exposure to multiple pedestrians may sensitize observers to their presence, inflating recognition distances. As a result, absolute detection and recognition values may be proportionally different than in real driving contexts. Indeed, average detection distances in experiment 1 of 281 m were larger than average detection distances of 231 meters in a study on daytime conspicuity of safety vests and jackets on an open course road in which participants drove cars themselves (Sayer and Buonarosa 2008). It can be and has been assumed in the current experiments and in similar studies, however, that changes in absolute detection distances due to workload and other factors would not disproportionally impact the pattern of relative performance differences between types of stimuli.

Future research should examine how differences in trim characteristics interact with other significant factors that have been shown to impact conspicuity, such as background colors, scene illumination, pedestrian orientation, and movement. Studies of nighttime conspicuity (Luoma et al. 1996; Wood et al. 2011, 2012, 2014; Sayer and Mefford 2004) commonly find a conspicuity advantage for trim placements that convey movement patterns that are visually associated with human activity [a factor referred to as biological motion or 'biomotion' (Johansson 1973)]. At least one study, however, found no differences between biomotion clothing and regular safety vests, e.g., (Moberly and Langham 2002). Similarly, studies on daytime conspicuity have not found that motion increases visibility for individuals wearing fluorescent high visibility jackets (Sayer and Buonarosa 2008). The pattern of high visibility materials required by the NFPA 1971 standard could be considered a good example of a biomotion design, but further research is needed to examine the relation between high visibility clothing and motion for firefighter turnout gear in daytime or nighttime scenes.

The findings of the current studies have two major implications. First, similarity in performance of traditional solid and newer segmented trims may have implications for high-visibility safety clothing beyond firefighter turnout gear. First responders on roadways (firefighters, law enforcement officers, and emergency medical workers) and road construction workers all rely on high visibility clothing for multiple purposes, predominantly safety related. Indeed, visibility is attributed a role in an estimated 41.5% of highway worker fatalities (Turner et al. 1997). Relatedly, the importance of using high visibility materials for clothing and accessories for the general population is increasingly recognized. Trim designs that offer benefits such as lighter weight, increased breathability, and flexibility may be attractive to users other than firefighters, if demonstrated to enhance conspicuity effectively. Although there may be important differences between firefighter turnout gear and other safety clothing, the current study suggests that segmented trim designs which meet standardized photometric requirements are a reliable alternative to traditional solid materials to achieve high conspicuity. Furthermore, with an increasing number of user types, access to variety in trim design, if implemented with awareness of performance potential, may become an important feature to combine the needs of enhanced conspicuity with the desire to differentiate on-scene user groups visually (e.g., pedestrian bystanders, road workers, law enforcement, firefighters, etc.).

Second, our results underscore the need to assess conspicuity of a target object (clothing, road sign, accessory) in the context for which it is designed. Regarding selection of color, the research reviewed in this paper and our study suggests that multiple significant scene characteristics (i.e., context) play a major role in conspicuity performance. For firefighter turnout gear deployed among common road side scenes dominated by orange-red stimuli, the current study suggests that a fluorescent yellow-green trim shows the highest conspicuity when considering distance detection and peripheral color identification. While it is important to keep in mind that a performance bias of one color over the other seems to be determined largely by the presence of similar or contrasting distractors in the scene, yellow-green's use in the context of firefighter turnout gear is recommended over fluorescent orange-red given the current standard for road scenes as used in this study, unless a compelling reason for the alternative color is present.

Authors' contributions
JTK designed and led the experimental approach and drafted the first manuscript. NJA and GC were the primary experimentalists conducting data gathering in the field and prepared figures and tables. VS did data analysis and led intermediate revisions and reformatting of the paper. TJG was the principal investigator, did final revisions and reformatting, and serves as the corresponding author. All authors read and approved the final manuscript.

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Competing interests
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Informed consent
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