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Brake lamp detection in complex and dynamic environments: Recognizing limitations of visual attention and perception

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ABSTRACT

Worldwide, both brake lamps and tail lamps on motor vehicles are required to be red. Previous studies have not examined the effect of this confound in a complex, high-traffic scenario in a driving simulator or on visuomotor behavior. In the first experiment, drivers detected brake lamps on nine lead vehicles and lane changes on two rear vehicles in a 15 min simulated night time highway drive. A second experiment was used to examine the findings in the context of pre-attentive visual processing research. A third experiment analyzed visuomotor behavior and subjective workload during a vigilance task to further evaluate this hypothesis. For all studies, tail lamp color was manipulated, resulting in two conditions: the currently mandated red tail lamps and red brake lamps vs. yellow tail lamps and red brake lamps. Compared to current rear lighting, employing yellow tail lamps with red brake lamps reduced RT, error, subjective workload, improved performance in detecting lane changes and also changed visuomotor behavior. It is suggested that the mechanism allowing better performance is pre-attentive, parallel visual processing.

These studies are an extension of research previously published in this journal which examined automobile rear lighting (McIntyre, 2008). In this paper we will provide further evidence that the current international automobile rear lighting standard, which requires both tail and brake lamps to emit a red hue, is suboptimal given the cognitive and perceptual demands of driving. While there are a number of psychological phenomena that bear on this topic, we will focus on how limitations in underlying processes of visual attention and perception affect brake lamp detection behavior. Our claim is that when brake and tail lamps are both the same color, it increases subjective driver workload, requires more effortful eye scanning, and increases brake lamp detection time and missed braking signals relative to a system where the tail lamp color is changed while brake lamps remain red. In addition, we suggest that the superior performance attained when tail and brake lamps do not share the same color is due to automatic (or pre-attentive) processes guiding visual attention. We present three studies to investigate these claims.

Both brake (stop) lamps and tail (rear position) lamps on motor vehicles are required to be red (NHTSA, 2010; UNECE, 2006, 2008). Brake lamps are activated only when drivers depress the brake pedal, which typically indicates vehicle slowing or stopping. Tail lamps are activated whenever the vehicle lighting system is turned on and indicate the presence of a vehicle. Moore and Rumar (1999) present a history of the international evolution that led to this confound whereby two lamps with separate functions are coded with the same color. The key step in this process occurred when the color red was chosen for rear position lamps prior to the introduction of brake lamps. Attempts to disentangle this misstep have focused on attempts to make the red of the brake lamp more conspicuous than the red of the tail lamp by adding greater luminance to the brake lamp and later an additional lamp with a unique location, the center high-mounted stop lamp (CHMSL). However, these changes to the brake lamp have met with limited success (Lee et al., 2002). One example of the difficulties caused by these color similarities is that daytime running lights do not allow the daytime illumination of tail lamps due to the attenuating effects of daytime ambient light on luminance differences between red tail and red brake lamps. Recent proposals being studied by NHTSA once again involve adding features to the brake lamp, e.g., flashing, in hopes of attracting driver attention to braking (Wierwille et al., 2003, 2006).

Efforts to improve brake lamp detection have received consideration from researchers and policymakers because of the importance of the brake lamp signal to safe driving, as failure to detect a brake lamp may lead to a rear-end collision. Approximately two million rear-end collisions occur in the United States each year resulting in billions of dollars in loss, nearly one million personal injuries and around 2000 fatalities, constituting roughly 25% of all collisions and approximately 5% of fatalities (NTSB, 2001; Sullivan and Flannagan, 2003). The traffic conditions faced by drivers vary widely, from simple, low-traffic situations to complex, high-traffic ones. While many

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rear-end collisions occur in less complex environments, given the large number of drivers that face complex driving situations everyday and the importance of the braking signal, we focus in these studies on more complex situations.

Thus, our main research questions are as follows. Are the perceptual cues used to differentiate brake lamps from tail lamps under the current lighting system (greater luminance and unique location—CHMSL) sufficient to overcome the attention demands of more complex driving environments? Will a system where brake and tail lamps are different colors improve brake lamp detection in complex environments? The current specifications for brake and tail lamps require that they produce a red hue while allowing a range of luminance output, area (number of bulbs) and shape (aspect ratio). Research has shown that humans make inconsistent judgments of brightness of vehicle rear lighting when factors such as luminance, area and shape are not held constant on automobile rear lighting (Flannagan et al., 1998). Other factors that can affect judgments of brightness are ambient lighting differences due to time of day, visual angle due to varying distance and luminance transience due to motion and occlusion. These considerations suggest that the current reliance on luminance differences to signal brake lamp activation may lead to poor driver detection of brake signals. Perceiving the color red is also unreliable because a red luminous area on the rear of a car can have multiple meanings (stop, turn, and presence) and there may be a lack of extravehicular cues (e.g. stop signs and traffic lights) indicating which red lamp meaning applies. Additionally, not all vehicles have the unique location cue of the CHMSL and those that do vary the location, size, luminance and shape of the CHMSL.

It may seem that with the current system, noticing the onset (luminance transient), greater luminance (luminance contrast) and unique location (for CHMSL) of red brake lamps relative to tail lamps should be sufficient to overcome this color confound, capture attention and unambiguously indicate what a vehicle ahead is doing. Indeed this is often the case when visual attention demand is low, visual sensitivity for luminance changes and contrasts are maximized and extravehicular cues of braking are present. An example might be driving undistracted behind a single lead car that does not have its tail lamps activated and where looming information and traffic signals may confirm judgments of brake lamp activation. However, drivers are often distracted and, even when not distracted, are shifting attention across the road ahead, mirrors, and in-vehicle displays. In addition, there are often multiple vehicles ahead of a driver at varying distances moving to and fro as well as laterally relative to the following driver, producing differences in visual angle and occlusion and un-occlusion of rear lamps. There may also be an absence of extravehicular cues of braking. For example, when there are multiple lead vehicles in multiple lanes of traffic at various distances on a road without traffic controls during dusk, dawn or night time drive when drivers have their red tail lamps activated.

Given these complex attentional demands during driving, failure to detect a brake lamp may be caused by a failure of attention, and many reports cite failures of attention as a major contributor in collisions (Lee et al., 2002; Sullivan and Flannagan, 2003). Because limited capacity visual attention is at a premium in a task like driving, drivers may miss the onset of a brake lamp when their visual attention is focused on another location, or when an onset is occluded by vehicles ahead of the driver. In this situation, in order to determine the meaning of a red lamp, drivers are then faced with making judgments of relative brightness and location differences in a sea of moving red lamps of variable sizes and shapes at multiple locations and distances, appearing and disappearing due to occlusion. We propose that, given these complex attentional demands, having brake and tail lamps emit the same color makes detection of brake lamps suboptimal because of the demands it places upon limited capacity, focused attention. In this paper, we investigate an alternative rear light system where brake and tail lamps are differentiated by color. In this alternative system, only the tail lamp color is changed, from red in the current system to yellow in the new system. We are not proposing to change the color of the critical braking signal, which is red in both the current and the alternative system. Our claim is that this new system would reduce red brake lamp detection response time (RT), error and workload by relying more on low-effort pre-attentive processes and less on effortful focused-attention processes. The basis for these predictions is derived from studies in both basic and applied research, as described below.

Research in visual attention has demonstrated that detection of targets in some visual searches is easier than others and engages apparently separate cognitive processes. When targets do not share features like color with other objects, they are termed feature singletons because only a single feature is needed to recognize a target. The visual system processes these unique singletons in parallel or pre-attentively. Feature singleton targets “popout” or capture attention based on spatial or temporal cues. When targets share features like color with surrounding objects, recognizing a target requires the conjunction of at least two features. In this conjunctive-search situation, detection is less efficient because it engages serial, focused attention processes that are slow and effortful (Treisman and Gelade, 1980; Yantis and Jonides, 1990). In the current rear lighting system, brake lamps may not be perceived as feature singletons because tail and brake lamps share the color red. Thus, conjunctive search may be required to recognize brake signals; for example, searching for target brake lamps that are both red and bright amongst tail lamp distracters that are red and less bright, or searching for target CHMSLs that are both red and located in a high, central vehicle location amongst distracters that are red and located on the side of a vehicle. This conjunctive search could require that inefficient serial processes be used to detect the important braking signal and potentially lead to slower detection times and more detection errors.

An argument could possibly be made that in the current system, the luminance contrast between tail and brake lamps allows attention capture to occur, thus engaging more efficient pre-attentive processes. However as mentioned above, because brightness judgments are unreliable due to both environmental and cognitive limitations, the luminance transients in the current system may not capture attention reliably.

In contrast, if tail lamps were not the same color as brake lamps (e.g. yellow tail lamps), viewing red lamps on the rear of a vehicle would always and only mean braking. Thus, the brake lamp signal would be a color singleton that should reliably allow the use of efficient pre-attentive processes. With yellow tail lamps, even if drivers are looking elsewhere and miss viewing the onset of a red brake lamp (thus disallowing attention capture from a luminance transient), when they look back towards the activated brake lamp, it should pop-out by virtue of its spatial salience as a color singleton regardless of location and regardless of variations in subjective brightness caused by differences in target distance, size or ambient lighting.

In early applied research on this topic, Mortimer (1968) demonstrated that the current system of red tail and brake lamps produced worse performance than seven other designs, some of which involved changing the color of the tail lamp. We know from other applied studies that changing the color of the tail lamp differentiates brake and tail lamps sufficiently to reduce RT and error in detecting brake lamps (Allen, 1964; Cameron, 1992, 1995; Case et al., 1969; McIntyre, 2008, 2009; Lee et al., 2002). Both Mortimer and Cameron conducted their studies with real automobiles allowing for an ecologically valid perceptual experience regarding ambient light and lamp luminance which are difficult to reproduce in simulated environments. Though Cameron used complex

RT tasks both he and Mortimer used only a single lead car. These studies using a single moving or stationary lead car allow detection of brake onsets but do not produce occlusion of lamps or require search for and detection of brake lamps in the context of an array of distracter tail lamps produced by more complex traffic environments.

To rectify some of the problems of searching with only a single lead car, McIntyre (2008, 2009) used static displays of traffic with multiple lead vehicles to allow occlusion of vehicle lamps. These studies also disallowed brake lamp onset cues in order to simulate driver inattention to brake lamp onset. McIntyre's (2008) study allowed participants to terminate search of the driving scene by keyboard response after determining if a target was present or absent. That study found that drivers had less error and were faster at detecting red brake lamps when tail lamps were yellow than when tail lamps were red. McIntyre (2009) also used these same stimuli in a preliminary attempt to test the claim that advantages in brake detection with yellow tail lamps occur because yellow tail lamps allow parallel, pre-attentive search for brake lamps. Participants were not given time to move their initial gaze and search the driving scene before the trial terminated (200 ms); thus only parallel search processes could be used. As would be predicted for a parallel vs. serial search, participants had much less error detecting red brake lamps when tail lamps were yellow and were at chance accuracy when tail lamps were red (requiring serial search).

To the best of our knowledge, Experiment 1 of this paper is the first study to test the effect changing tail lamp color has on brake lamp detection that employs multiple lead vehicles moving in normal traffic flow (using a moderate fidelity driving simulator). To add workload and simulate normal demands to attend ahead and behind the vehicle, participants also had to detect driving events (lane changes) to their rear.

In Experiment 1, our hypothesis was that a system with yellow tail lamps will result in less error and faster RT than the current lighting system (i.e., red tail lamps), because the former system allows use of the efficient pre-attentive system while the latter requires use of the less efficient focused attention system. We also hypothesized that yellow tail lamps will result in better detection of driving events not signaled by lighting (i.e., lane changes), because using the pre-attentive system for detecting braking will free up focused attention that can be used for other driving events. To test these hypotheses, we analyzed whether the tail lamp manipulation led to main effects on error (miss) rates and RT in detecting brake signals and lane changes. In addition, although we had no hypotheses regarding how the traffic row in which a brake signal occurred would affect its detection, we analyzed whether any effects of the tail lamp manipulation differed across row.

Experiment 2 was designed to test the hypotheses that yellow tail lamps allow brake lamps to capture attention using pre-attentive processes, while red tail lamps require focused attention. We used the visual search standard paradigm where performance with single-feature vs. conjunctive stimuli is compared for conditions with low vs. high attentional demand (e.g., few vs. many distracters). To this end, in Experiment 2, we reduced the number of traffic vehicles from nine (as in Experiment 1) to two, and eliminated the Experiment 1 task of detecting rear lane changes.

In Experiment 3, we measured eye movements and mental workload while participants searched static scenes for brake lamps that appeared occasionally over a 10 min period, while again comparing yellow tail lamp vs. red tail lamp conditions. We hypothesized that the use of pre-attentive processes would lead participants in the yellow tail lamp condition to have fewer and longer fixations that were more centrally located on the image; whereas the use of serial search processes in the red tail lamp condition would lead to more frequent and more dispersed fixations. Also, we predicted lower subjective workload in the yellow condition compared to the red condition. The purpose of all three experiments was to provide converging evidence of our hypotheses that yellow tail lamps would improve detection of braking signals in complex traffic situations, and that different attentional systems are engaged by the use of yellow vs. red tail lamps.

1. Experiment 1

Participants followed nine vehicles in a simulated night time three lane highway drive. Participants responded to brake lamp onsets by the lead vehicles and lane changes of two following cars observed in the rear or side view mirrors. This dual-task scenario was designed to represent the multitasking involved in attending to nearby traffic, since participants had to attend to multiple vehicles both ahead and behind. Also, a driving simulator was used that simulated the visual demands of driving, since participants had to use eye and head movements similar to on-road driving to perform the task.

1.1. Method

1.1.1. Participants

Forty volunteers from the Clemson University research pool participated. There were 20 participants in the red (red tail and brake lamps) condition (12 female, 8 male; $M = 18.7$ yrs, $M = 25{,}000$ miles driven), and 20 in the yellow (yellow tail lamp, red brake lamp) condition (12 female, 8 male; $M = 18.9$ yrs, $M = 29{,}900$ miles driven). Participants were screened using the Ishihara Test for color blindness and were excluded from the study if they misidentified any slides. All participants had subjectively reported normal or corrected to normal visual acuity. Total number of miles driven, history of motion sickness and migraines were also obtained by subjective report. No participants were excluded based on these reports.

1.1.2. Design

The experiment used a between-subjects design with two conditions (red vs. yellow tail lamps). Participants were randomly assigned to either the red or yellow tail lamp condition with the constraint that the gender ratio be approximately the same for both conditions.

1.1.3. Apparatus

The DriveSafety DS-600c Research Simulator at Clemson University was used for this study. This is a fully integrated, immersive, full-cab, high-fidelity driving simulator with eight visual display channels (see Drive Safety, 2010). Five projectors display an image of $182\,W \times 139\,H$ cm on five panels to the front and side of the cab to provide a 300° wraparound display with resolution of 800×600 pixels per projector. Three rear view displays are mounted on side and rear view mirror locations.

1.2. Procedure

Participant subjective report data were collected and the Ishihara color blindness test was administered. Participants entered the vehicle and were shown a static image of the scenario while the researcher explained the tasks. Participants were instructed that the brake and accelerator pedals were disabled and the vehicle would maintain its speed automatically. They were instructed to steer the vehicle to stay in the center lane and press a button on the steering wheel as quickly as possible upon seeing brake lamp activation on any of the cars. This response was chosen because we were investigating drivers' detection of brake lamps, not their subsequent driving response. During actual driving, detecting brake lamp activation could lead to multiple responses (deceleration, changing lanes, and braking) or no response by a following driver.

Fig. 1. Brake activation in left lane middle row with CHMSL visible red tail lamp/red brake lamp condition. Yellow tail lamp/red brake lamp condition.

Participants were instructed to activate and then cancel the turn signal upon seeing either of the two vehicles behind them change lanes. Participants were not told to give priority to one task. After participants reported understanding the two tasks, a brief practice drive was initiated where 4 brake signals and 2 lane changes occurred and the participants were asked to perform the behavioral response and give a simultaneous verbal confirmation that they had seen the event. After confirming the participant understood the tasks, the test scenario was run. After completing the scenario, the Motion Sickness Assessment Questionnaire was administered to assure participants were fit to leave the experimental session. No participants reported feeling ill due to the simulation.

1.2.1. Brake lamp detection task

The scenario was a mostly straight rural 3 lane interstate roadway with some curves in a clear sky nighttime drive of approximately 18 km that lasted approximately 15 min. Night time was simulated by darkening all objects in the parts of the scene not lighted by the simulated headlights, thus reducing luminance and visual contrast. The participant vehicle followed 9 other vehicles traveling in a 3 (lane) × 3 (row) array and no other ambient traffic ahead of the driver (see Fig. 1). The three cars nearest the participant vehicle were labeled near, the next three cars were middle and the three cars furthest from the participant vehicle were far. The participant vehicle braking was disabled and speed (70 kph) was maintained by a cruise control algorithm in order to ensure that each participant had similar visibility of all brake signals by maintaining the same following distance from the lead vehicles. The participant car followed the vehicle directly ahead in the center lane of the near row with a 1 s following time. Traffic cars in the near and middle rows followed the vehicles ahead of them by about 0.5 s. At greater simulated distances (2 s between rows) aliasing due to projector resolution limitations made the tail lamps appear to flicker in the far rows. While this was not a problem for the yellow condition because tail and brake lamps differed in color, it was deemed as a bias against the red condition where aliasing of tail lamps may be perceived as brake lamp activation. Therefore, following times between vehicles were chosen so as to minimize aliasing of pixels in far row lamps. Reducing following time between rows and 0.5 s did not make the vehicles appear unrealistically close to each other.

Fig. 2. Current lighting: tail lamp on, brake lamp on.

During the drive, 45 brake signals occurred at pseudo-random times ranging from 2 to 118 s ($M = 18.8$, $SD = 21.1$) between signals. This high standard deviation relative to the mean suggests that the inter-signal intervals were inconsistent and therefore unpredictable. The 45 brake signals also occurred for the 9 lead cars in an unpredictable order, so that all 9 cars activated their brake lamps 5 times. All brake signals appeared only on the forward center 60° field of view screen (182 $W \times 100$ H cm visible to driver). The vehicle widths for near, middle and far rows subtended angles of approximately 5°, 3° and 1.5° respectively. Brake lamps were activated for 2 s on each occurrence by reducing the chosen lead vehicle's speed by 0.6 m/s for 2 s. Brake lamps were disabled at all other times to avoid any unintended brake signals activated by the standard simulator algorithm for controlling traffic flow.

A note on the limitations of simulated driving: the driving simulator cannot match the luminous output of motor vehicle lights required by federal standards. Due to limitations of the simulated environment, the manufacturer default luminance of red tail lamps and red brake lamps in the simulator is identical when measured in cd/m^2 ($L_v = 2.34$ cd/m^2, RGB ~ 255, 15, 15). In order to simulate brake lamp onset, the simulator changed luminance on a rectangular brake-lamp area above each tail lamp rectangle and at the CHMSL location (see Figs. 2 and 3). Specifically, these three rectangles changed luminance from .08 cd/m^2 to 2.4 cd/m^2 at brake lamp onset. Additionally, a "halo" of red (RGB ~ 120, 12, 12) extended beyond the brake lamp rectangle at onset. At a brake onset, these three changes indicating braking (i.e., onset of the brake lamp

Fig. 3. Alternative lighting: tail lamp on, brake lamp on.

rectangle above each tail lamp, the CHMSL and the halo) occurred identically for the red and yellow conditions. The behavior of the tail lamp rectangle at a brake onset differed for the red and yellow conditions. In the red condition, the red tail lamp rectangle remained at the same luminance before and after a brake onset (see Fig. 2). In the yellow condition, the yellow tail lamp rectangle changed from 10.4 cd/m^2 (RGB ~ 255, 255, 0) to .08 cd/m^2 (RGB ~ 40, 2, 2) to simulate tail lamp offset (see Fig. 3). This results in the target red brake lamp in the yellow condition being nearly half the size of the brake and tail lamp in the red condition.

1.2.2. Concurrent task

Two vehicles followed the participant vehicle; each starting in an outer lane. At unpredictable times, one of two rear cars would change lanes (e.g., from outer to center lane; from center to outer lane). All lane changes were visible using the rear view and side view mirrors. There were a total of 12 lane changes in the scenario and none occurred simultaneously with a forward braking event.

1.3. Results and discussion

Accuracy in detecting brake signals was measured by missed signals and false alarms. If participants did not respond within 4 s of a brake onset (2 s from offset), it was counted as a miss. Any responses longer than 4 s after brake onset were considered false alarms. Regarding the 4 s threshold for defining misses vs. false alarms, in the red tail lamp condition, where RTs were slowest, the mean RT as measured from brake onset was 0.96 s (*SD* = 0.19) and 93% of RTs were less than 2 s. The fact that almost all responses were made while the brake signal was still present suggests that responses more than 2 s after a brake offset (4 s after onset) are likely not in response to that signal and therefore should be counted as false alarms.

In support of our hypothesis, the number of missed brake lamps was significantly lower in the yellow tail lamp condition than the red tail lamp condition, $F(1, 38) = 34.81$, $p < .001$, partial $\eta^2 = .48$. See the top two rows of Table 1 for the percentage of brake lamps missed for each row and tail lamp condition. Pairwise, simple-effects comparisons within rows showed misses for yellow were significantly fewer than red for each row: far, $F(1, 38) = 24.17$, $p < .001$, partial $\eta^2 = .39$; middle, $F(1, 38) = 10.60$, $p = .001$, partial $\eta^2 = .22$; near, $F(1, 38) = 8.64$, $p = .03$, partial $\eta^2 = .19$. Interestingly, 19 of the 20 participants in the red condition missed at least one brake signal (total = 60), while the only two misses occurring in the yellow condition were due to 1 of the 20 participants.

A *t*-test showed significantly fewer false alarms in the yellow than in red, $t(38) = 3.5$, $p = .001$, partial $\eta^2 = .24$. Because it cannot be determined what row caused any false alarm, only the mean number of false alarms per person (red = 3.35, yellow = 0.75) are reported. We feel these are largely legitimate false alarms and not due to aliasing of the computer image for two reasons. First, we compensated for aliasing by displaying the vehicles closer to the participant thereby increasing the size of the brake lamp polygon. Second, many false alarms (>30%) in the red condition occurred on curves where tail lamps appear in following vehicle rear windows as if they were a CHMSL (see Fig. 4).

Fig. 4. As the car in the middle row, middle lane moves laterally during cornering its tail lamp appears in the window of the car directly ahead of the subject in the near row, middle lane. While this seems to be a CHMSL it is not.

RT was calculated for correct responses only. In support of our hypothesis, drivers were significantly faster in detecting brake lamps when tail lamps differed from brake lamps in color than when brake and tail lamps were both red, $F(1, 38) = 24.11$, $p < .001$, partial $\eta^2 = .39$. Interestingly, this speed advantage increased as targets increased in distance from the driver (see top two rows of Table 1). As the third row of the table indicates, the RT advantage for yellow vs. red tail lamps increased by approximately 0.10 s for each row increase in distance from the driver. Pairwise, simple-effects tests compared the RT for yellow and red tail lamps within each row. RT for yellow was significantly faster than red for each row: far, $F(1, 38) = 22.87$, $p < .001$, partial $\eta^2 = .38$; middle, $F(1, 38) = 13.58$, $p = .001$, partial $\eta^2 = .26$; near, $F(1, 38) = 5.45$, $p < .03$, partial $\eta^2 = .13$. With yellow tail lamps, RT to brake lamps at the farthest distances (0.84 s) was about as fast as RT to brake lamps at the closest distances with red tail lamps (0.80 s), $t(38) = 1.04$, $p = .31$. The foregoing demonstrates there is no speed accuracy trade off with yellow tail lamps; both error (misses and false alarms) and RT are reduced in the yellow condition. The effect size of the performance advantage with yellow tail lamps is large; the tail lamp color manipulation accounted for 48% of the variance in misses, 24% in false alarms and 39% in RT. Also, the performance advantage with yellow tail lamps is amplified with increased distance between the braking signal and driver. Others have found effects of distance on braking detection in tasks similar to our red condition (DeLucia and Tharanathan, 2009). DeLucia and Tharanathan (2009) showed that drivers' use vehicle motion (e.g., looming) for near vehicles with fast decelerations but rely on other cues (e.g., brake lamps) when vehicles are far and have slower decelerations. While vehicle motion may partly explain the increase in RT from near to far rows when using red tail lamps, it cannot account for differences between tail lamp conditions (see Table 1). Because the vehicle motion and brake onsets were identical between conditions, the differences in RT between conditions can only be accounted for by the tail lamp color change.

Not only does changing tail lamp color improve performance in detecting brake lamps, it also facilitated performance on the concurrent task. Participants missed few of the 12 lane changes in both the red (*M* = 2.1, *SE* = 0.35) and yellow (*M* = 2.2, *SE* = 0.33) conditions; and there was not a significant difference between conditions, $t(38) = .21$, $p = .84$, However, yellow tail lamps allowed significantly faster RT in detecting lane changes observed in the rear view mirrors, $t(38) = 1.95$, $p = .03$, partial $\eta^2 = 0.10$ (red: *M* = 23.8 s, *SE* = 9.7; yellow: *M* = 4.5 s, *SE* = 1.5).

To summarize, in Experiment 1, yellow tail lamps greatly improved detection of brake lamps in moving traffic and also improved detection of lane-change events not related to rear lighting. The large decrease in misses in the yellow tail lamp condition seems particularly important, since brake signals that are missed altogether could have greater safety consequences than brake signals that are responded to slowly. Our theoretical explanation for this effect is that yellow tail lamps allowed the use of efficient preattentive processes (like popout) by making the red brake lamps a color singleton; whereas red tail lamps required use of slower focused attention processes because they involved conjunctive search using multiple features.

Table 1
Mean RT in seconds, with SE in parentheses and percentage of brake signals missed by row for brake detection.

Tail lamp color	Near row		Middle row		Far row	
	RT	%Misses	RT	%Misses	RT	%Misses
Red	0.80 (0.03)	3.3	0.98 (0.05)	4.7	1.12 (0.05)	12.0
Yellow (Exp 1, offset)	0.71 (0.01)	0.0	0.79 (0.02)	0.3	0.84 (0.03)	0.3
Red–yellow RT	0.09		0.18		0.28	
Yellow (Exp 1control, dim)	0.78 (0.03)	0.3	0.81 (0.03)	0.0	0.85 (0.03)	1.0

2. Experiment 2

Experiment 1 presents limited evidence for use of pre-attentive vs. focused processes with yellow tail lamps, because we did not use the technique commonly used in visual search studies to provide evidence for these processes. The common method of doing this in visual search studies is to increase the attentional demands of the search task (e.g., by increasing the number of distracter objects in the search set) and show that this increase degrades search performance for conjunctive stimuli much more than for feature-singletons (e.g., Treisman and Gelade, 1980). The attentional demands in Experiment 1 were rather high, in that drivers had to attend to locations ahead and behind, to 11 vehicles, and to two types of events (braking, lane changes). Therefore, we created a situation with simpler attentional demands in Experiment 2 by eliminating the lane-change detection task and having drivers detect brake lamp activation in only 2 vehicles ahead of them. As in Experiment 1, both red and yellow tail lamp conditions were compared. This allowed us to investigate whether shifting from the low attentional demands of Experiment 2 to the higher demands of Experiment 1 degraded braking detection more strongly with red tail lamps than with yellow tail lamps.

In using this visual search paradigm, we made the assumption that searching for red brake lamps amidst tail lamps requires using multiple (conjunctive) features in addition to color, which has been shown to require serial shifting of focused attention across small groups of potential targets. The expected consequences of using serial search is that as the number of distracter objects increases, participants are more likely to miss brief targets altogether and to detect targets slowly. Thus, we predicted that in the red tail lamp condition, misses and RT to detected brake signals would increase markedly with increasing attentional demands. The other assumption from the visual search paradigm is that searching for red brake lamps amidst yellow tail lamps allows the brake lamps to act as color singletons, which engages parallel pre-attentive processes that are not affected much by the increasing attentional demands. Thus, we predicted that in the yellow tail lamp condition, misses and RT to brake signals would be less strongly affected by increasing attentional demands. We tested these hypotheses statistically by testing for an interaction between attentional demand (low vs. high) and tail lamp condition; and by simple effects tests of whether attentional demand affected each of the tail lamp conditions in the manner described above.

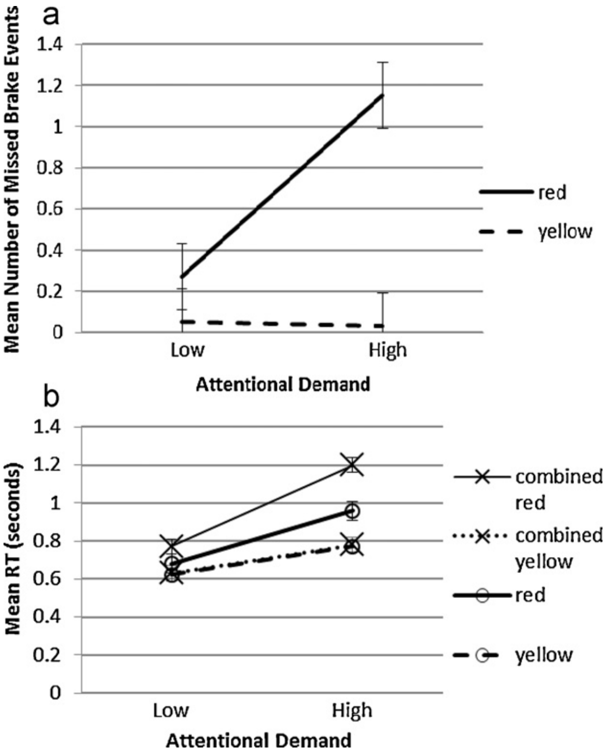

Fig. 5. RT and miss data with standard error bars comparing Experiment 2 (low attentional demand) to Experiment 1 (high attentional demand).

Note that the nature of pre-attentive vs. serial attentional processes as just described is to make the search process itself more or less efficient, leading to the predictions just made regarding misses and RT. However, these attentional processes do not make clear predictions regarding false alarms; since it is not clear how making search more or less efficient would affect false alarms. For this reason, we did not use false alarms in testing these hypotheses about attentional and search processes.

2.1. Method

2.1.1. Participants

Twenty-two participants (18 females, 4 males; 11 in each tail lamp color condition) obtained from the same subject pool as Experiment 1.

2.2. Procedure

Participants drove identical scenarios to Experiment 1 with the exception that there were only two lead cars and no following cars or concurrent task. The lead cars were in the center lane of the near row and the left lane of the far row. The 15 brake events from the respective near and far rows of the Experiment 1 scenario were collapsed onto the single car displayed in that row for a total of 30 brake events. Five participants in Experiment 2 had potentially extraneous factors affecting their performance: one reported post-test, not understanding the instructions; two had minor interruptions during testing; and two may have had the rear view mirror (not needed for this task) incorrectly oriented. However, the data for these participants were similar to other participants; and the results shown in Fig. 5 are the same when these five participants are excluded. Therefore, they were included in the analyses.

2.3. Results and discussion

2.3.1. Interactions with attentional demand

Before analyzing the findings from Experiment 1 and Experiment 2 to test for interactions between attentional demand and tail lamp condition, we point out an important difference between our experimental paradigm and the standard visual search study. In most visual search studies, the stimuli remain on until the participant responds; so accuracy is very high and RT is the only variable affected by experimental manipulations. However, brake signals often do not remain on until following drivers respond to them. In our study, the brake target was displayed for only 2 s, so misses occurred. Also, both missed brake signals and signals that are responded to slowly can have important safety consequences. Therefore, in a driving study, both misses (which would be very long RTs in the visual search paradigm) and RT must be analyzed to test for effects of pre-attentive processes vs. focused attention.

As mentioned previously, the use of pre-attentive vs. focused attention processes does not make clear predictions regarding false alarms. Before presenting the miss and RT data, we point out that in Experiment 2, there were 0 false alarms per person in the yellow and 0.64 per person in the red condition. This difference was significant, $t(10) = 2.28$, $p = .05$ (using a one sample t-test due to the 0 variability in the yellow false alarm data).

Fig. 5 (panel a) shows the effect of attentional demand and tail lamp color on misses. The figure suggests that increasing attentional demand had little effect with yellow tail lamps (flat slope) and a large effect with red tail lamps. This assessment was confirmed by a between-subjects attentional demand (low vs. high) by tail lamp color (red vs. yellow) ANOVA, in which the interaction between attentional demand and tail lamp color was significant, $F(1, 58) = 7.65$, $p = .01$ (partial $\eta^2 = .12$). As would be expected from a visual search paradigm, the yellow condition was not affected much by increasing attentional demand, $F(1, 29) = .18$, $p = .67$ (partial $\eta^2 = 01$); but for the red condition, misses increased markedly with attentional demand, $F(1, 29) = 7.46$, $p = .01$ (partial $\eta^2 = .21$). This attentional-demand by tail-lamp-color interaction is the classic pattern indicative of pre-attentive processing with yellow tail lamps and focused attention with red tail lamps.

Fig. 5 (panel b) shows the corresponding data for correct response RT (see the lines labeled red and yellow) The figure suggests that increasing attentional demand increased RT for both tail lamp colors, but more strongly for red than yellow tail lamps. The interaction for RT between attentional demand and tail lamp color approached significance, $F(1, 58) = 3.56$, $p = .06$ (partial $\eta^2 = .06$). However, RT increased significantly with attentional demand for both yellow, $F(1, 29) = 21.04$, $p < .001$ (partial $\eta^2 = 42$), and red, $F(1, 29) = 25.96$, $p < .001$ (partial $\eta^2 = 47$), tail lamp conditions. This finding presents only weak evidence for pre-attentive processing.

Because the miss and RT data led to different conclusions regarding pre-attentive processing, we created a combined variable that allows an overall conclusion about the evidence for pre-attentive processing. To do this we set all missed brake events to have an RT of 4 s and then calculated the mean for each participant and condition using both the missed (4 s) RTs and the RTs for hits. The reasoning behind the 4 s assumption was that, since misses were cases where participants did not respond within 4 s, their RT given unlimited time to respond would be at least 4 s. Thus, the combined RT variable gives a conservative (possibly too low) estimate of what our participants' RTs would look like if they had unlimited time to respond as in the standard visual search task. The combined RT data are shown in Fig. 5 (panel b; see the lines labeled combined red and combined yellow). For these data, the interaction between attentional demand and tail lamp color was significant, $F(1, 58) = 8.23$, $p < .01$ (partial $\eta^2 = .12$). Combined RT increased significantly with number of distracters for both yellow, $F(1, 29) = 13.72$, $p = .001$ (partial $\eta^2 = 32$), and red, $F(1, 29) = 25.64$, $p < .001$ (partial $\eta^2 = 47$), tail lamp condition. The combined RT variable gives a conservative estimate of RT because given unlimited time, some of our miss data might actually translate to RTs much longer than 4 s. Since most of the miss data were in the red-tail-lamp, high-attentional-demand condition, this means that the attentional-demand interaction for the combined RT variable may underestimate the true size of this interaction.

The RT increase with attentional demand for yellow tail lamps (for both regular and combined RT) does not fit the ideal pre-attentive vs. focused attention pattern as well as the miss data. A potential explanation for the lack of a flat RT slope for yellow tail lamps could be the much larger field of view required for visual search in the high-attentional-demand condition, i.e., Experiment 1 (about 133° horizontal by 7° vertical due to scanning the three mirrors and the road ahead) than in the low-attentional-demand condition, i.e., Experiment 2 (about 12° horizontal by 2° vertical for the two cars ahead). The larger field of view in Experiment 1 probably necessitated large saccades and some head movements that were not needed with few distracters. Thus, the increase in RT with attentional demand for yellow tail lamps could be due to the times when participants were focusing on a mirror during brake lamp onset and had to make a large saccade or a head movement to focus on the brake lamp detected in the periphery. Other studies of pre-attentive vs. focal attention processes have found RT increasing with attentional demand (e.g., set size) for the hypothesized pre-attentive condition, sometimes significantly so (Yantis and Hillstrom, 1994; Jonides and Yantis, 1988; Yantis and Jonides, 1984). Yantis explains these positive slopes by suggesting that pre-attentive processes may not operate on every trial, due to eye movements or focused attention strategies. Our explanation of the positive yellow tail lamp slope follows Yantis.

Taken together, the analyses of how attentional demand and tail lamp color affected misses, regular RT and combined RT provides preliminary evidence that yellow tail lamps facilitate use of pre-attentive processing, while red tail lamps are more likely to require focused attention. However, the comparison of low vs. high attentional demand should be made within a single experiment in further research. Also, further research is needed to identify which aspects of the increased attentional demand of Experiment 1 were driving the effects found here. Was it the increased number of distracters, the increase in spatial search area, or the addition of a second event (lane change) to search for? Experiment 3 of this article offers additional evidence regarding the use of pre-attentive vs. focused attention processes with yellow and red tail lamps.

2.3.2. *Alternative explanations*

An alternative account of our findings in Experiment 1 is that the poor brake lamp detection with red tail lamps could have occurred because red brake lamps and red tail lamps were not distinguishable in our simulator; and therefore red brake lamps were not noticeable. The Experiment 2 data for red tail lamps does not fit this account, since in this condition participants detected 98% of the brake lamps at an average RT (0.68 s) that was close to the yellow tail lamp, low-attentional-demand RT (0.62 s) and potentially faster than the yellow tail lamp, high-attentional-demand RT (0.77 s).

Although comparing the Experiment 2 condition with the Experiment 1 data provides some evidence that the better signal detection with yellow tail lamps is driven by the use of parallel, pre-attentive processes, we cannot say unequivocally that changing the color of the tail lamps is the sole reason for any pre-attentive processing. The yellow condition differed from the red tail lamp condition in tail lamp color, luminance and deactivation at brake lamp onset. In the simulator, yellow tail lamps were more luminant ($L_v = 10.4\,\mathrm{cd/m^2}$) than red tail lamps ($L_v = 2.34\,\mathrm{cd/m^2}$). Research has shown that, in addition to chromaticity, luminance differences in targets and distracters can affect search such that salient onsets defined only by luminance can capture attention. For example, Nagy and Sanchez (1992) demonstrated that luminance and chromaticity differences between target and distracters can independently and equally speed search. Thus, it could be that luminance differences between the yellow tail lamps and red brake lamps in the yellow condition were facilitating the use of pre-attentive processes rather than color alone.

We feel that empirical findings from applied vehicle lighting research as well as theory regarding visual search and attention capture suggests that in this case the color change is the primary factor. First of all, the current automotive lighting system relies on luminance differences between lamps that share the color red. However, in research by Mortimer (1968), Cameron (1995) and others cited by Lee et al. (2002), the current luminance-based system resulted in poorer performance than differentiating lamps by color (green or amber tail lamps with red brake lamps). According to Cameron (1995), this was true even though the red tail lamps in his study differed more in illuminance from the red brake lamp than did his amber colored tail lamp. Additionally, some visual search research indicates that abrupt onsets, but not offsets, engage pre-attentive processes that result in attention capture (Yantis and Jonides, 1990). Thus, we tentatively attribute the performance gains to the onset of the red hue exclusively emitted by brake lamps in the yellow condition, and not to the offset of the higher luminance yellow lamp, but note that further empirical research is required to distinguish between the chromaticity and luminance explanations.

However, contrary to the findings of Yantis and Jonides (1990), research by Theeuwes (1991) suggests that sometimes abrupt offsets can capture attention. Given Theeuwes' finding, the fact that tail lamps offsets upon brake lamp onset in the yellow but not the red condition is a difference between our two conditions that could potentially be driving the yellow tail lamp performance advantages in Experiment 1. For example, perhaps the abrupt offset of the yellow tail lamp and the simultaneous abrupt onset of the red brake lamp above it created a perception of apparent motion that was not present in the red tail lamp condition. This apparent motion could have captured attention. In Experiment 1 and 2, we had the yellow tail lamp offset upon brake lamp onset because this is one way that yellow tail lamps might be implemented. However, another reasonable way to implement this lighting change is to have the yellow tail lamp dim (but remain on) upon brake lamp onset. In this situation, there would be no offset of the yellow tail lamp and any apparent motion would be reduced or eliminated.

To test this variation, we ran an additional condition that was identical to the yellow-tail lamp condition in Experiment 1 except that the yellow tail lamps dimmed instead of offset upon brake lamp activation. In the new condition, tail lamps changed from RGB ∼ 255, 255, 0 before brake lamp activation to RGB ∼ 150, 100, 20 while brake lamps were activated. The subjective impression of this RGB change was that after brake lamp onset, the tail lamp was dimmed but still present. Twenty participants were tested in this dimmed yellow tail lamp condition. Their results are shown in the bottom line of Table 1. Brake lamp detection, as measured by misses and RT to correct detections, was very similar in the original, offset yellow tail lamp condition and the dimmed yellow tail lamp condition. When compared to the red tail lamp condition in Experiment 1, the dimmed yellow tail lamp condition led to significantly fewer misses, $F(1, 38) = 30.7$, $p < .001$, partial $\eta^2 = .45$ and shorter RT, $F(1, 38) = 13.2$, $p = .001$, partial $\eta^2 = .26$. Thus, the dimmed yellow tail lamps led to the same large performance advantages over red tail lamps as did the original deactivating yellow tail lamps in Experiment 1. These findings replicated the performance advantages with deactivating yellow tail lamps in Experiment 1 and suggest that these performance advantages were not driven by the offset of the yellow tail lamps or by related apparent motion.

3. Experiment 3

Experiment 3 was designed to further investigate the claim that yellow vs. red tail lamps engage different attentional processes by using eye tracking and workload measures. The participants' task was to view static scenes with multiple traffic cars and report whether any brake lamps were illuminated or not. Experiment 3 was primarily concerned with how the salience of the brake signal affects visuomotor behavior and attention during the ongoing process of monitoring and searching the driving environment for relevant signals such as brake lamp activation, including the relatively long periods when brake lamps are not activated. Importantly, visual search research indicates that when targets are feature singletons (e.g. red brake lamp targets with yellow tail lamp distracters), the absence of a target terminates search as quickly and effortlessly as when a target is present (Treisman and Gelade, 1980). However, when search targets are defined by multiple features that are also shared by distracters (conjunctive search), the search is not terminated until a target is located or all potential targets have been searched. Thus when targets are not present in conjunctive searches, effortful search using focused attention must be sustained for longer periods than when targets are present. This demands more cognitive resources than when a target is present. Research indicates that subjectively rated workload increases as target salience decreases in vigilance tasks such as hazard detection during driving (Warm et al., 2008). This difference in workload may be caused by the different types of visual scanning behavior needed for pre-attentive vs. focused attention searches. When targets are feature singletons the parafoveal pre-attentive system is sufficient to orient attention when targets appear, so less visual scanning is needed when targets are not present (Kramer and McCarley, 2003). In conjunctive searches, frequent shifting of focused attention is needed iteratively across all distracters to confirm they are not targets.

Based on this research, we hypothesized for Experiment 3 that with red tail lamps, ongoing visuomotor search behavior would indicate more use of focused-attention scanning and workload would be higher; while with yellow tail lamps, there would be less focused-attention scanning and lower workload. The serial scanning used in shifting focused attention was expected to lead to a large number of brief fixations that are dispersed widely as participants scan for the unpredictable target location. In contrast, since pre-attentive processes use less shifting of focused attention, we expected fewer and longer fixations that are less dispersed. In addition, as in previous studies, we hypothesized that red brake lamp detection would be much better when tail lamps are yellow. We tested these predictions by testing how tail lamp condition affected eye movement variables (number and duration of fixations; fixation dispersal) and workload. We also were interested to see if in this relatively short task, the change in eye scanning behavior over time would be different in the red and yellow tail lamp conditions. Therefore, we tested how some of the eye movement variables changed over time, and whether this change differed for the red and yellow conditions.

Because we did not have eye tracking equipment suitable for use in the driving simulator, Experiment 3 measured eye movement and subjective workload in static scenes with multiple traffic vehicles similar to Experiment 1. However, the stimuli in Experiment 3 attempt to simulate particular daytime ambient lighting conditions, namely overcast, dusk, or dawn (∼1000–7000 lux) when some drivers may activate their tail lamps. In these conditions, the ambient lighting reduces contrast and make luminance of activated red brake lamps and activated red tail lamps is very difficult to distinguish relative to night time hours. In these difficult lighting conditions, the unique luminance onset at the location of the CHMSL may be the only reliable indication of braking. Thus, Experiment 3 examines how the tail lamp manipulation affects visuomotor behavior by simulating a difficult situation for brake signal detection but nevertheless a situation similar to one experienced by millions of drivers every day.

3.1. Method

3.1.1. Participants

Twenty Clemson University undergraduates (11 females, 9 males; *M* = 19; years driving: *M* = 3.3) were recruited from an Introductory Psychology subject pool for a within-participants experimental task. Visual acuity was obtained by self report and the Ishihara test for color blindness was administered to screen for color vision deficits prior to the experiment. All participants had acceptable acuity either with or without corrective lenses. All participants completed the Ishihara test without error.

3.1.2. Design

The study used a within-participants design. Two conditions (red tail lamps vs. yellow tail lamps) were presented to all participants. The order of conditions was counterbalanced across participants.

3.1.3. Apparatus

A Tobii 1750 table mounted binocular eye-tracker was used to collect the eye movement data. The display, study parameters and data collection were managed by the ClearView 2.7.1 eye tracking software on a Windows XP computer. A high-resolution camera integrated into a 43 cm FT display unit with a maximum resolution of 1280 × 1024 pixels was used to acquire images of the eyes. Near infra-red light-emitting diodes were used to capture the reflection patterns on the corneas of the participant's eyes. Participants sat approximately 50 cm away from the display screen which provides the stimulus. Eye position data were sampled at 50 Hz, with a position accuracy of ~0.5° (Tobii, 2003).

3.1.4. Stimuli

Seven digital pictures (six with at least one vehicle braking, one with no vehicles braking) taken from inside a vehicle to simulate a following driver's visual field were used as stimuli in both conditions. The entire image subtended a visual angle of 20° vertical × 32° horizontal. The only difference between pictures in the two conditions was the color of the tail lamps. All identifying markers such as road signs, license plate numbers, and personal images were obscured with computerized editing to enable privacy and eliminate extraneous cues related to vehicle behavior such as braking. Because of the lowered luminance contrast that can be presented on a current computer display, in both conditions all vehicles appear as if their tail lamps are activated. In the red condition, tail lamp color was left unedited (red tail lamps, red brake lamps), and brake lamp onset was simulated by replacing a dark (off) CHMSL rectangle with a red rectangle. Thus, only the CHMSL indicated braking in the red condition. (As mentioned previously, this simulated a dawn or dusk condition where red tail and brake lamps on the right and left of the vehicle are very difficult to discriminate.) The yellow condition pictures presented the proposed lighting (yellow tail lamps, red brake lamps) using the same pictures as the red condition but with red tail lamps replaced by yellow tail lamps edited in Adobe Photoshop^{TM} (see Fig. 6). In the yellow condition, a brake onset consisted of the yellow tail lamps being replaced by red brake lamps and the adding of a red CHMSL as in the red condition. In both the red and yellow tail lamp conditions, the changes at brake onset were reversed to simulate brake offset. Because the six braking pictures and the one picture with no braking were identical except for the brake lamps, the only noticeable feature that changed in the scene was the onset and offset of the brake lamps.

3.1.5. Eye tracking

A five point binocular calibration was performed where participants fixate on a small colored disc as it appears sequentially in the four corners and center of the screen prior to each task to ensure accurate measurement of fixations and saccades.

3.1.6. Workload self report

The NASA Task Load Index (TLX) was administered after each condition as a self report measure of workload.

3.2. Procedure

Upon arrival participants were given consent forms and given oral instructions that the nature of the task was for them to identify as quickly as possible by keypad response the presence of any brake lamps. Demographic, acuity and color vision data were collected and participants were given two experimenter demonstrated trials to familiarize themselves with the task. Before beginning the experimental task, experimenters confirmed that the participants understood the instructions and felt comfortable in identifying a brake lamp. The five point binocular calibration was performed prior to beginning the task.

In each condition, a single driving scene was displayed for 10 min. The same 11 cars remained visible for the entire time, without moving. No brake lamps were present in the scene at the beginning of the 10 min condition. After an unpredictable time, the brake lamp(s) (only the CHMSL for the red condition) would activate on one or more cars in the scene. When participants detected the presence of the brake lamp, they pressed the space bar to extinguish the lamp(s). If a participant did not press the space bar within 10 s after the onset of a brake lamp, the experimenter pointed out the brake lamp and instructed the participant to extinguish the lamp by pressing the spacebar. This process was repeated by varying the time of onset of the brake lamp from 5 to 120 s after the previous onset, and varying which car(s) activated the brake lamp. There were a total of 9 instances of braking over each 10 min condition. After completing the first condition, the NASA TLX was administered. The same procedure was repeated for the second condition.

3.3. Results and discussion

3.3.1. Accuracy and RT data

Accuracy was measured by misses, i.e., instances where the participant failed to respond to a brake lamp within 10 s. The accuracy and RT data replicated Experiment 1 and previous studies in showing that changing tail lamp color improved brake detection accuracy and speed. In the red condition 12 participants had a total of 21 misses; whereas in the yellow condition, 2 participants had a total of 2 misses. A natural logarithm transformation was applied to the RT data to reduce skew to acceptable levels. The transformed RT data were used for statistical comparisons; although untransformed means are presented here for clarity. RT for the red condition (*M* = 0.89 s, *SE* = 0.2 s) was significantly slower than the yellow condition (*M* = 0.5 s, *SE* = 0.02 s), $F(19) = 20.6$, $p < .01$, partial $\eta^2 = .52$.

3.3.2. Workload data

For both the red and yellow conditions, participants rated mental demand as the highest weighted of the six workload dimensions on the NASA TLX. The weighted workload rating on mental demand for the red condition (*M* = 189, *SE* = 26) was significantly higher

Fig. 6. Yellow condition (left panel) and red condition (right panel).

than the yellow condition ($M = 134$, $SE = 27$), $t(19) = 3.31$, $p < .01$ partial $\eta^2 = .37$. Effort was the second highest weighted rating. The weighted workload rating on effort for the red condition ($M = 123$, $SE = 15$) was significantly higher than the yellow condition ($M = 60$, $SE = 14$), $t(19) = 4.1$, $p < .01$ partial $\eta^2 = .47$. No difference was found on the other TLX dimensions. These large effect sizes suggest that participants experienced much higher mental demand and required effort in the red than in the yellow condition.

3.3.3. *Eye movement data*

As mentioned previously, for Experiment 3 we were primarily interested in the eye scanning behavior of the participants during the approximately 9 min 55 s of the 10 min trial when brake lamps were not present, i.e., during the ongoing search process. Eye movement behavior during this period was characterized in terms of the number, duration and spatial dispersal of fixations. The filter parameters for fixation in ClearView were defined as dwell times of at least 100 ms in an area of 30 × 30 pixels. One Area of Interest (AOI) subtending 5° visual angle centered horizontally and vertically in the driver's direct line of sight was defined. The degree to which fixations were more widely dispersed vs. centrally focused was measured by calculating the percentage of time fixation was within the central AOI.

Eye tracking data for four participants had to be discarded due to calibration problems. The mean number of fixations was significantly less for the yellow condition ($M = 923$, $SE = 54.7$), than the red ($M = 1129$, $SE = 81.7$), $t(15) = 2.49$, $p = .02$, partial $\eta^2 = .37$. Mean fixation duration was significantly longer for the yellow (0.37 s, $SE = 0.33$) than red (0.30 s, $SE = 0.25$), $t(15) = 3.68$, $p < .01$, partial $\eta^2 = 34$. In the yellow condition, participants fixated in the centrally located AOI 71% of the time compared to only 46% for the red condition. This was a significant difference with a very large effect size, $t(15) = 6.14$, $p < .01$, partial $\eta^2 = .72$.

Thus, participants in the yellow condition tended to look straight ahead in the central AOI using fewer and longer fixations. In contrast, participants in the red condition shifted focused attention more frequently, used shorter fixations, and distributed their fixations over a wider spatial extent. This visuomotor pattern is consistent with greater use of pre-attentive processes (such as attention capture) in the yellow condition, and greater use of serial focused scanning in the red condition. Graphical pictures of this pattern are shown in Fig. 7, which are images obtained from ClearView from each condition depicting the fixation data aggregated from the 16 participants across all instances of the scene where brake lamps are not present. Red coloring on the image represent areas with at least 100 fixations.

To determine if eye movement behavior changed over the 10-min scene, the eye movement data were compared for the first and last 1-min segments of the task. A 2 × 2 (color × segment) repeated measures ANOVA was run with number of fixations as the dependent variable. The main effects of color condition, $F(1, 15) = 4.73$, $p = .05$, partial $\eta^2 = .24$ and time segment, $F(1, 15) = 14.39$, $p < .01$, partial $\eta^2 = .49$ were significant. The interaction was not, $F(1, 15) = 0.11$, $p > .05$. The mean number of fixations in the first minute of search for the red and yellow conditions was 147 and 121, respectively. The mean number of fixations in the last minute of search for the red and yellow conditions was 116 and 94, respectively. Thus, number of fixations decreased during the scene at an approximately equal rate for the two conditions.

To summarize the findings of Experiment 3, searching for red brake lamps amongst yellow tail lamps improved brake lamp detection (less error and shorter RTs), decreased workload, and changed visuomotor behavior (with fewer, less eccentric, and longer duration fixations), when compared to searching for red brake lamps amongst red tail lamps. These data suggest that less focused visual attention and effort is required to detect brake lamps when they differ from tail lamps in color.

One limitation for the manipulation in Experiment 3 is simulating ambient lighting conditions where luminance between red tail

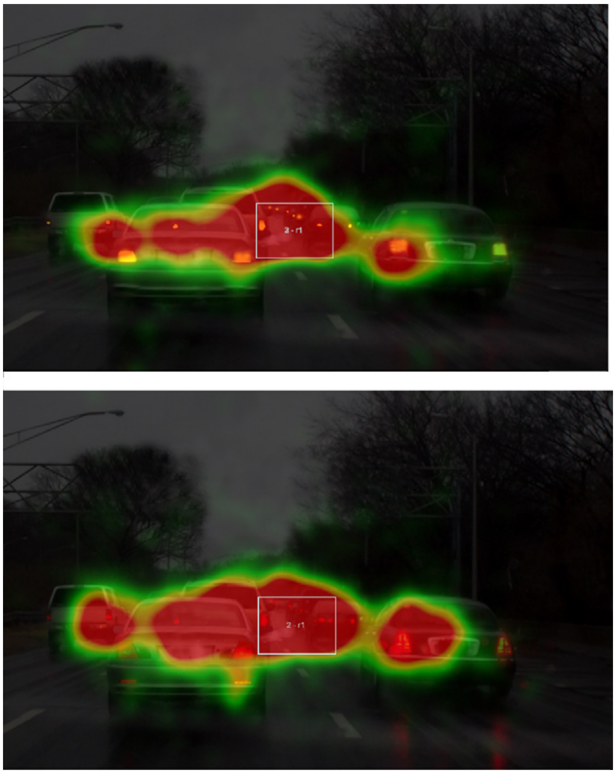

Fig. 7. Aggregate fixations, yellow condition (top panel) and red condition (bottom panel). Central rectangle is the AOI (Experiment 3).

and red brake lamps is difficult to distinguish as mentioned in Sections 3 and 3.1. This made the red condition much more difficult but does capture a circumstance drivers' face regularly during overcast, rainy or near dusk and dawn (commuting) hours when drivers may drive with their tail lamps on and where there is sufficient ambient light at low angles to diminish the luminance contrast of red tail and red brake lamps compared to darker night time hours. While this limits the results to very specific conditions, the eye movement findings from Experiment 3 are consistent with the hypothesis that, when brake lamps are color singletons because they are not the same color as tail lamps, drivers use less serial, focused scanning and instead tend to rely on pre-attentive processes such as attention capture from brake lamp onsets using parafoveal or peripheral vision.

4. General discussion

The findings of all three experiments extend findings from earlier studies (Cameron, 1995; McIntyre, 2008, 2009) that yellow tail lamps strongly improve detection of brake lamps, with the color manipulation accounting for 48% to 39% of variance in accuracy and RT, respectively, in Experiment 1. Furthermore, compared to previous research, Experiment 1 has done so in a more dynamic and complex traffic environment and with a concurrent task. A novel contribution of Experiment 1 is the demonstration of performance benefits for yellow tail lamps not just when drivers fixate on a single vehicle directly ahead of them, but also when drivers distribute attention across multiple vehicles at varying distances and locations, both ahead and behind them, and in the context of temporary occlusion of brake and tail lamps. Another novel finding of Experiment 1 is that yellow tail lamps facilitate improved detection of important driving events (lane changes) that were not signaled by lighting.

Comparing the findings of Experiment 2 and 1 showed that increasing the attentional demands of the driving situation led to large decrements in brake lamp detection with red tail lamps and small or no decrements with yellow tail lamps. This provided tentative evidence that the performance advantages of yellow over red tail lamps occurred because searching for red brake lamps amongst yellow tail lamps engaged parallel, pre-attentive processes while searching for red brake lamps amongst red tail lamps required the use of serial, focused attention processes. Experiment 3 provided further evidence for this claim by showing that changing tail lamp color has the effect of reducing driver mental effort and reducing focused scanning in searching for brake lamps in a relatively short (10 min) vigilance task while still improving brake lamp detection performance.

Reducing focused attention demands and driver workload may have benefits far beyond improving detection of brake lamps. Drivers who can detect brake lamps parafoveally and pre-attentively, as in the yellow tail lamp condition, should have more attention resources to allocate to other potentially hazardous objects in the visual field. In effect, no search for brake lamps needs to be conducted because the color change pops out to the visual system (Treisman and Gelade, 1980) or captures attention (Yantis and Jonides, 1990). This can be particularly important at busy intersections requiring attention to many parts of the visual field in addition to brake lamps. Current lighting may cause drivers to distribute their visual attention across more objects in a continual search for brake lamps. If changing tail lamp color can reduce driver fatigue or allow fatigued drivers to perform better at detecting brake lamps as is suggested by Experiment 3, the benefits could be substantial.

The studies reported here support the idea that detection of brake lamps is improved when rear-vehicle lamps use the color red to always and only mean braking. Other research that supports this idea includes research by Allen (2009) and Sullivan and Flannagan (2008) demonstrating that use of amber turn signals is associated with fewer rear-end collisions on turning vehicles than red turn signals.

4.1. Theoretical limitations of the current studies

As mentioned earlier, further research is needed to determine whether changing the color alone is sufficient or the combination of color and luminance change with yellow tail lamps is facilitating use of pre-attentive processes. Also, the use of contrasting colors to differentiate brake signals depends on good color discrimination in the periphery. However, research has demonstrated that color discrimination sometimes decreases with increased eccentricities from the fovea in certain situations, i.e., the smallest ($50\,\text{cm}^2$), dimmest (80–146 cd) and shortest duration (.33 s) vehicle lamps permitted by the FMVSS code viewed at 30 m (Sivak et al., 2000). However, practical implementation of such a color coding will necessarily include the addition of other lamp features that improve conspicuity. Nevertheless, further research is needed to determine how well brake lamps status as color singletons can be detected in the periphery.

Another limitation of our argument for pre-attentive processing is that the current studies all used environments where, in the yellow tail lamp condition, red braking signals were color singletons. The claim that red brake signals become color singletons when all cars use yellow tail lamps is only true if one ignores other red signals near the roadway, such as traffic lights and roadside reflectors. Thus, a more accurate description of the effect of switching from all red to all yellow tail lamps is that in the former situation, drivers have to detect red brake signals in the context of many red distracter lights, while in the latter, they have to detect red brake signals in the context of a smaller number of red distracter lights. Guided Search theory suggests that reducing the number of red distracters when searching for potential red targets should facilitate target detection (Wolfe et al., 1989). However, further research is needed to assess this more realistic roadway situation.

4.2. Implementation issues

One practical critique of the proposal to change tail lamps to yellow is that the benefits of this system may be driven mainly by novelty, and therefore will diminish over time as with the CHMSL (Lee et al., 2002). However, if the performance gains with yellow tail lamps occur because this system engages pre-attentive processes; then these performance gains should not diminish over time, since pre-attentive processing relies on low-level, automatic properties of the visual system. Anecdotally, post test queries of participants in the yellow condition in Experiment 1 of this study indicate that drivers were often not conscious of the novelty of yellow tail lamps, and they often could not recall what color tail lamps actually are.

These studies support the conclusion that efforts to circumvent the confound of two signals with different meaning sharing one color by relying on luminance transients has been less effective than if these signals were separated by color. Mandating that both brake and tail lamps share the same color may demand more effortful sustained focused attention from drivers that results in slower responding and missed brake signals. The current studies are not intended to articulate details needed in an implementation of the proposed lighting. As mentioned in McIntyre (2008), there are multiple pragmatic issues that must be addressed with changing tail lamp color, such as size, shape, location, hue, luminance, onset and offset of the tail lamp, as well as coordinating tail lamp parameters with other lamps. The goal of the current studies was to test the effectiveness of an alternative tail lamp scheme, to test some theoretical ideas regarding attentional systems, and to propose a direction for policymakers similar to previous field studies (Mortimer, 1968; Cameron, 1995).

Another implementation issue is the question of what happens if yellow tail lamps are introduced gradually amongst existing red tail lamps. Data from McIntyre (2005) indicate that even a gradual introduction of such a color change (e.g., with few tail lamps yellow and most tail lamps red) will improve performance in brake lamp detection. A current study in our lab is investigating the effect of gradual introduction further. This fits with predictions of guided visual search theory, which argue that search time is reduced when pre-attentive processes can operate to eliminate the need for serial search on subsets of the visual field (Wolfe et al., 1989).

5. Conclusion

Differentiating rear lamps on the feature of color (by changing the color of tail lamps) promises to reduce the visuomotor and cognitive workload required to search for brake lamps, which frees visual attention for other necessary driving tasks, while improving speed and accuracy of brake lamp detection. General vehicle conspicuity issues could be improved also, as separating the lamps by color would permit daytime running light systems to also activate tail lamps during daylight hours. Given the large improvements in detecting braking and other important driving events with yellow tail lamps, we suggest that yellow (or non red) tail lamps offer the potential for large improvements in driving safety. However, this suggestion needs further empirical testing in simulators and real world environments.

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