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APPLYING VISUAL ATTENTION THEORY TO TRANSPORTATION SAFETY RESEARCH AND DESIGN: EVALUATION OF ALTERNATIVE AUTOMOBILE REAR LIGHTING SYSTEMS

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APPLYING VISUAL ATTENTION THEORY TO TRANSPORTATION SAFETY RESEARCH AND DESIGN: EVALUATION OF ALTERNATIVE AUTOMOBILE REAR LIGHTING SYSTEMS

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ABSTRACT

This experiment applies methodologies and theories of visual search and attention to the subject of conspicuity in automobile rear lighting. Based on these theories, this experiment has four goals. First, it is proposed that current research methods used to investigate rear lighting are inadequate and a proposed methodology based on the visual search paradigm is introduced. Second, demonstrate that current rear lighting on automobiles does not effectively meet the stated purpose of regulators. Third, propose a more effective system for increasing the conspicuity of brake lamps. A fourth goal is to validate and extend previous simulator research on this same topic. This experiment demonstrates that detection of red automobile brake lamps will be improved if tail lamps are another color (amber) rather than red, as currently mandated. The experiment is an extension and validation of previous simulation studies. Results indicate that RT and error are reduced in detecting the presence and absence of red brake lamps with multiple lead vehicles when tail lamps are not red compared to current rear lighting which mandates red tail lamps. This performance improvement is attributed to parallel visual processing that automatically segregates tail (amber) and brake (red) lamp colors into distractors and targets respectively.

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CHAPTER ONE

INTRODUCTION

Within the context of visual search, this dissertation study will compare performance in detecting the presence and absence of brake lamps in three rear lighting systems using FMVSS compliant tail and brake lamp lenses and light bulbs. This study has four goals. First, evaluate current research methods used to investigate automotive rear lighting and evaluate the effectiveness of a methodology based on the visual search paradigm. Second, test whether current rear lighting on automobiles that uses red brake lamps and red tail lamps relies on serial search processes and effectively meets the stated purpose of regulators in making brake lamps conspicuous, perceived and understood in all environmental conditions. Third, propose and evaluate a system that is designed to engage efficient parallel search processes by changing tail lamp color to amber in order to increase the conspicuity of red brake lamps. Fourth, validate and extend previous simulator research on this same topic (McIntyre 2008, 2009 & 2012). Although many studies have examined the issue of brake conspicuity, only a few have proposed a color coded system. However, few, if any rear lighting studies have examined brake conspicuity within the context of the visual search paradigm.

CHAPTER TWO

BASIC RESEARCH: VISUAL ATTENTION

Psychological theories pertaining to how human visual attention is allocated in the environment are essential to understanding performance in tasks like driving. Visual attention research has discovered how humans direct their attention endogenously, what stimuli or events guide or capture attention exogenously and when visual attention fails. In this chapter, theories advanced using paradigms from visual search will be discussed to examine the boundaries of visual attention. These theories can inform not only what exogenous and endogenous factors will and will not enable efficient visual attention guidance but how to design research to assess performance in tasks like driving.

Visual Search: Exogenous Factors

Visual search theories contend that properties of stimuli and their context interact with human visual attention processing to make searching the environment more or less efficient. Triesman and Gelade (1980) found that when humans search for targets that do not share features like color, shape, size and orientation with their surrounding distractors, visual search is very fast and accurate such that targets appear to "pop-out" of the surrounding stimuli. These types of targets were called feature singletons. Searching for a red dot amongst yellow dots of the same size is an example of how a unique color feature can have this effect. The number (set size) of distractor yellow dots does not affect the speed with which people detect the target red dot despite the fact that target and distractor share the dimensions of size and shape. Another relevant finding of this

research is that operators know a red dot is not present amongst yellow dots just as quickly regardless of set size. The efficiency of searches for feature singletons despite numerous distractors has been taken as evidence for parallel and pre-attentive processes, since it appears that the visual system processes many distractors simultaneously without conscious attention.

In contrast, if targets and distractors share salient features (e.g., searching for a red dot among red squares and yellow dots and squares) or differ on less salient features (e.g. searching for a bright red dot amongst less bright red dots) a different pattern of results is found. As the number of distractors increases so does search time to locate targets. These searches are called conjunctive because targets and distractors share features that are incorporated in operator goals. The increase in search time with number of distractors is often taken as evidence for serial processing, under the assumption that focused (foveal) visual attention must move sequentially and fixate on one object before moving to the next. Both feature and conjunctive searches have similar RT and error performance when number of distractors is very small. However, unlike feature searches, as the number of distractors increases so does search time to locate targets in conjunctive searches. Another important finding with conjunctive searches is that when targets are absent, it takes operators nearly twice as long to respond as when targets are present in conjunctive searches. The rationale is that operators must on average search serially through half of the distractors for a target in target present trials but must search through all distractors on target absent trials.

More recent research has challenged whether searches can be unequivocally designated as serial or parallel based on behavioral evidence. Guided Search theory argues that features of targets and their surround can direct visual attention to shift between the very fast parallel or pre-attentive nature of feature searches and the slower serial or focused attention processes of conjunctive searches (Wolfe, Cave & Franzel, 1989). According to this theory, there is a continuum from completely parallel search which in effect preempts serial search to completely serial types of visual search that require moving focused attention from one object to the next.

Studies (Wolfe, et al. 1989) have found some searches where targets are conjunctions of color and form, color and orientation or color and size and do not match the Treisman model. Rather than divide searches into parallel or serial, Wolfe contends there are greater and lesser degrees of guidance provided by an interaction of operator strategies and environmental stimuli. Wolfe found that with larger set sizes (> 10 items), some search slopes were too shallow to be explained as strictly serial searches. For example, when searching for red X's amongst green X's and red O's the Treisman model would predict search would be conducted serially and the slope ratio of trials with a target absent compared to a target present would be 2:1. Wolfe found shallower slopes for target present searches with larger set sizes. Wolfe argued that these results suggest salient features (like color) are processed in parallel to reduce the serially searchable set. So, in the previous example the visual system could automatically segregate green and red items and eliminate green items as searchable area resulting in a serial search for the goal shape (X) amongst a reduced set of only red items. As set sizes get larger, larger

areas of color defined distractors can be eliminated automatically. It is thought that in conjunction searches there is an initial parallel stage to eliminate areas for search followed by serial search amongst distractors that are more similar to the target rather than an all or nothing parallel or serial process.

Data from millions of trials of visual search tasks has led to several predictable phenomena. Wolfe (2007) has identified a number of these that he claims a comprehensive theory of visual search should be able to explain. Of these, there are a number of phenomena that affect RTs and accuracy and are directly related to the concern of this research project. Four of these have already been discussed. Larger set sizes, trials where the target is absent, target-distractor similarity (conjunctions) and lack of guidance tend to increase RT and error. Three other findings relevant to this paper also affect visual search performance. The first is the finding that the more heterogeneity there is amongst distractors, the worse performance becomes (Duncan & Humphreys, 1989). It is easier to find X's amongst T's alone than amongst both T's and Y's. Another principle, perhaps also related to target-distractor similarity is the finding that categorical differences between target and distractor make searches easier than deviations within kind (e.g. It is easier to find a red dot amongst yellow dots than amongst crimson dots). Another finding shows that the proximity of distractors to the target affects search (Eriksen & Eriksen, 1974). Distractors closer to the target have more effect on search than those farther away. While studies have examined many stimulus properties that might engage parallel search, data indicates that there are relatively few properties that

reliably do so. When targets and distractors differ on color, shape, size or orientation, searches are most efficient (Wolfe & Horowitz, 2004).

In summary, theories of visual search indicate that important signals that need to be found efficiently should be feature singletons that are as dissimilar as possible from their surround. Importantly, target salience is largely determined by the nature (homogeneity, proximity, number, dissimilarity to the target) of the surrounding distractors rather than the features of the target itself. Thus, as Duncan and Humphreys' (1989) Similarity Theory asserts, efficiency in search is dependent on both distractor-distractor similarity and distractor-target dissimilarity. Stated from a signal-detection perspective, it is not just the signal but the nature of the noise that determines search efficiency.

Important also is the information gained from RT and error when a target is not present. The RT measures used in visual search are viewed as a proxy for amount of cognitive processing. If this is accurate, rapidly and accurately identifying when targets are absent could be of roughly equal significance as knowing when they are present when viewed from a cognitive load standpoint. The typically longer RTs in target absent trials for conjunctive search are directly related to more cognitive processing time and demand of attentional resources.

Figure 2.1 Graphically shows simulation results from an activation model of visual search taken from Chun and Wolfe (1996) and has been modified to highlight predictions of three exogenous factors (parallel vs. serial search, set size, and presence vs. absence of the target in the search display as they relate to this study. The model predicts

serial and parallel searches will be similar in RT and error with very small set sizes and are differentiated in both target present and absent responses as set size increases with serial searches taking longer. For serial search, target present RT increases with set size but target absent RT increases more. For parallel searches, target present RT has a flat slope but target absent RT tends to increase with set size due to subjective "costs" perceived by operators (Chun & Wolfe, 1996). Errors are low for both parallel and serial search. However, the model predicts more misses for serial searches with large set sizes. The predictions of this study only match the *trends* of this model but do not claim to match the values on the axis.

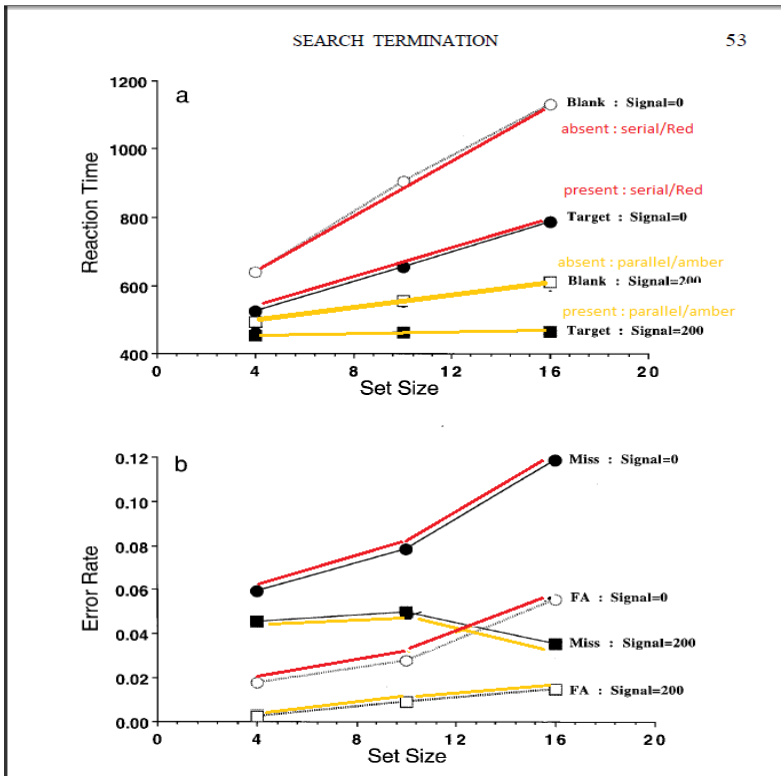

Figure 2.1. Predictions of a visual search model overlaid with predictions for this study.

Visual Search: Endogenous Factors

Much of the previous visual search research focuses on the exogenous characteristics of the environment as the determining factor for efficient search. However endogenous factors such as operator search goals, attentional load, physiological and psychological states also have to be considered. Research in attention capture, dual task paradigms, sleep deprivation and human error provide valuable information about the interaction of bottom-up exogenous and top-down endogenous factors of visual attention.

Attention capture research studies whether exogenous qualities of stimuli in the environment can orient attention despite possibly incompatible endogenous search strategies. Studies have shown that when operators search for color targets, luminance onsets do not capture attention but unique colors do and when searching for luminance onsets, unique colors do not capture attention but luminance onsets do (Folk, Remington & Johnston, 1992). Folk et al. termed this finding contingent orienting of attention because attention to stimuli was dependent on the match between operator goals and stimulus properties. For example, when operators are instructed to search for a green X amongst yellow X's, but are then shown a display with many yellow X's and a single red X, the red X will initially capture their attention despite seeming contradictory search goals. However, the red X may capture attention not because of its exogenous properties but because the operator's goal is not strictly to search for a green X but instead to search for any non-yellow object. The finding that attention capture seems to be modulated by operator goals has led researchers to question the ability of stimuli to exogenously,

reflexively and automatically orient or capture attention (Pashler, Johnston & Ruthruff, 2001).

The findings supporting contingent orienting or capture of attention may also help explain other visual attention phenomena. Research shows that when operators have highly focused goals, they can be inattentive to what otherwise would be thought of as highly salient stimuli. Numerous studies have replicated early studies by Neisser and Becklen (1975) where many of the observers given the specific goal of counting passes of a basketball between players failed to report seeing a woman with an umbrella passing across the screen; despite the fact that the out of context image passes across the fovea. This type of failure of attention was termed Inattention Blindness. The performance decrements when attending to multiple events impinging on the same sensory modality (e.g. dichotic listening) have long been known. However, performance decrements have been observed even when operators engage in dual tasks that engage different sensory modalities (auditory and visual). When drivers are focused on a non-visual but attention demanding task, visual attention suffers. Drivers engaged in a cell phone conversation in a driving simulator have delayed responses to braking vehicles and decrements in recognition memory of text on billboards that eye tracking equipment verified was fixated upon (Strayer, Drews & Johnston, 2003).

Data also indicate that as endogenous psychological and physiological states are taxed, attention is withdrawn from the environment and exogenous attentional cues, causing operators to rely on more automatic endogenous processes (Trick, Enns, Mills, & Vavrik, 2004). There are several ways in which this could happen. Circadian rhythms

and sleep deprivation can adversely affect RT and accuracy in visual search tasks but distractor characteristics that provide guidance are still effective (Horowitz, Cade, Wolfe & Czeisler, 2003). So feature searches where operators have endogenous goals that allow parallel processing such as color differences between target and distractor are still efficient while those with more complex goals suffer from more error and longer response times as time awake increases. The nature of the task can also affect attention. Monotonous vigilance tasks that require sustained attention often induce failures of attention (Warm, Mathews & Finomore, 2008). Just thinking off-task can cause operators to be inattentive to visual cues in the environment. People often engage in mind wandering or task-unrelated thought (Smallwood & Schooler, 2006). This could manifest itself in a reader realizing they have no recollection of what they have read even while their eyes have scanned the pages in the same automatic fashion as if they were attending to the content of the text or when someone drives home being guided by automatic cues when they intend to go to the store (Reason & Mycielska, 1982).

Much has been learned about visual attention but debates are ongoing about the interactions of exogenous and endogenous factors producing efficient search. Traditional models posit specific attentional filters and capacity issues (Treisman, 1980; Wolfe, 2007). A more recent approach with signal detection theory (SDT) bypasses the need to explain performances decrements with the limited-capacity attention stage that is traditionally used to explain serial search (Verghese, 2001). However, a few key ideas stand out in relation to exogenous and endogenous factors affecting search efficiency that

apply to the concern of this study and which will be repeated throughout this paper in relation to experimental design.

1. Efficient visual search as indicated by faster RT and less error is reliably differentiated from inefficient only by using larger set sizes with multiple distractors.
2. Visual search efficiency increases as bottom-up environmental factors such as target-distractor similarity decreases and distractor-distractor homogeneity increases.
3. Search efficiency allowing parallel search is dependably engaged by relatively few categorical perceptual properties that create target-distractor contrast (color being one).
4. Because target absent responses are slower and more vulnerable to set size manipulation, they provide useful information about attention allocation and signal detection independent of target present data.
5. Endogenous factors such as top-down operator search strategies, attentional demands, physiological and psychological states and the workload of the task also determine the effectiveness of environmental stimuli to orient attention thereby affecting RT and error.

CHAPTER THREE

APPLIED RESEARCH: AUTOMOTIVE REAR LIGHTING

The purpose of current automotive rear lighting mandated in much of the world by the United States Department of Transportation's (USDOT) Federal Motor Vehicle Safety Standards (FMVSS) and the United Nations Economic Commission for Europe (UNECE) as summarized by FMVSS 108 is to enhance the "conspicuity of motor vehicles on the public roads so that their presence is perceived and their signals understood, both in daylight and in darkness or other conditions of reduced visibility" (USDOT, 2011, §571.108, S2. *Purpose*). Requirements vary in regard to the function, number, location, size, shape, luminance and color of automobile rear signal lamps. The main concern of this dissertation is the mandate of the USDOT and UNECE regarding brake and tail lamps (UNECE, 2006; USDOT 2011). Brake (stop) lamps are activated when a driver depresses the brake pedal. The tail (presence) lamps are activated whenever the vehicle's parking or driving head light system is activated but not in conjunction with Daytime Running Lights (DRL). Both brake lamps and tail lamps are required to emit a red hue with the only distinguishing feature being that the brake lamp has a higher intensity that can range from 80 to 420 cd (Flannagan, Sivak, Traube, 1998). Additionally, since 1995 in the U.S. a unique spatial location of the Center High Mounted Stop Light (CHMSL) was required as an additional brake signal on most vehicles. The CHMSL is in use in other countries as well. The turn signal is allowed to be either red or amber in color in the U.S. but research indicating that having amber turn signals improves their identification has led other countries to use amber rather than red for turn

signals. In the U.S. all three signals (brake, tail, turn) are allowed to be in the same spatial location and represented by a single light source (that must be red) but manufacturers legally produce many different combinations of the signals that vary in size, shape, color (only turn signals can be either amber or red), luminance, location and number of compartments and bulb type (incandescent, neon or LED).

Presently, a red luminous area on the rear corner of a vehicle may indicate any one of four conditions: 1-presence of a vehicle with its lights on, 2-braking, 3-turning or 4-hazard. In order to differentiate which meaning the red luminous area is signaling, the driver must determine if the brightness of the red area indicates that it is a tail lamp, turn lamp or a brake lamp. Under conditions that maximize attentional and perceptual abilities for luminance contrast of lighted objects (e.g., no distractions, very low ambient light leading to high contrast, small search set), this task is not difficult. However, this signaling system is supposed to meet the goal of being perceived and understood in the largest range of conditions, which would include conditions where human perception and attention are compromised. The reason that the braking signal needs to be conspicuous across a wide range of environmental conditions and driver states is that a vehicle braking ahead of a driver is safety-critical information that could lead to crashes if not noticed and understood quickly.

In the U.S., the agency under the USDOT tasked with improving rear lighting on automobiles is the National Highway Transportation and Safety Administration (NHTSA). In an effort to meet the stated goals of FMVSS 108, NHTSA supported the introduction of the CHMSL and continues to research ways to increase safety and the

conspicuity of rear lighting. Many thousands of research hours have been devoted to improving detection of brake lamps with the majority focusing on increasing the discriminability of red brake and red tail lamps (and red turn signals in the U.S.) either by altering luminous output, temporal activation (flashing) or spatial separation. This focus is likely due to the requirements that both tail and brake lamps must be the same color. However, the origins of this requirement are not based on scientific research, but on a sequence of historical events in which tail lamps were in use and required to be red prior to the invention of the brake lamp (Moore & Rumar, 1999).

Recognizing the need to make brake lamps more conspicuous has led some researchers to conduct experiments using color to code the function of automotive lighting signals rather than only luminance. Data indicate that changing the color of the tail lamp without changing the brake lamp differentiates brake and tail lamps sufficiently to reduce RT and error in detecting brake lamps and other signals in comparison to the current system (Allen, 1964; Case 1969; Mortimer, 1968, 1969; Cameron, 1992, 1995; Lee et. al., 2002; McIntyre, 2008; 2009). Governmental agencies responsible for investigating automobile rear lighting remain unconvinced by these studies and continue to pursue other concepts involving luminance contrast to make brake lamps more effective signals (Wierwille et. al., 2003, 2006; Llaneras et. al. 2010).

Perception of Rear Lighting

Detecting and understanding vehicular rear lighting are affected by a number of visual-perception factors. The only difference between a corner brake lamp and tail lamp

is luminance contrast. It is imperative to know what factors affect perception of luminance contrast in the driving environment to know if this feature adequately distinguishes target brake lamps and distractor tail lamps sufficiently to produce the behavior characteristics observed in efficient visual search. Luminance contrast is moderated by subjective judgments of brightness and these are moderated by a host of factors that affect the contrast between the brake lamp and its surround, including ambient lighting, distance from the luminous object, method of illumination, shape, area and comparison with other luminous sources.

Currently, brake and tail lamps must be red but are allowed to vary in candela output, location, size and shape. Data has shown that perception of brightness is affected by these variables. In making recommendations regarding intensity, shape, luminance and lamp area standards for vehicle rear lighting, Flannagan et al. (1998) surveyed a number of studies that examined response times and subjective judgments of intensity to various vehicle lamp combinations of intensity and area. The various studies revealed a seeming conflict between subjective judgments of lamp conspicuity and RT to detecting lamp onsets. Lamp intensity, shape and area affect subjective judgments of brightness more than RT. Currently the FMVSS specifies using higher intensity lamps as the lighted area (number of lamp compartments) increases. However RT data from prior studies cited by Flannagan indicated that intensity (measured in cd) strongly reduced RT while changes in area had little effect on RT. In order to further test whether area has an effect on RT, Flannagan conducted an experiment where RT was measured in response to the onset of lamps with two areas (50 cm^2 and 500 cm^2) at three intensities (65, 92 & 130

cd) 15 m directly in front of participants. His results showed lamp area significantly reduced RT to the smaller area lamp given equal intensity. In addition to these effects of intensity and area on RT, the shape (aspect ratio) and area (1 to 3 compartments and from 50 cm^2 to 450 cm^2) of illuminated red lens sections affected observer judgments of brightness such that lamps with larger area appeared less bright than smaller area lamps when lamp intensity was held constant. Based on previous studies and his experiment, Flanagan argued that new standards need to be constructed for automobile rear lighting due to the large variability in intensity, area, shape and type of light source (LED, neon, incandescent) that currently exist in the fleet.

More recently, a report to NHTSA found that lamps with intensities of 840 and 1420 cd produced the same RTs as 420 cd (the current maximum intensity permitted by the FMVSS) when area was held constant (Llaneras et. al., 2010). Based on findings like this, the report stated, "increases in brake signal luminance (brightness levels) do not necessarily translate into increased signal detection or faster response times . . . This suggests that increasing the luminance of conventional steady-burn brake lamps does not appear to be an effective means of drawing attention to the brake signal" (Llaneras et. al., 2010, p. 30).

Flannagan and Llaneras focused on how the characteristics of vehicle lighting systems affect their conspicuity. However, the characteristics of lighting systems are only part of the problem of perceiving lamp brightness and thus distinguishing between tail and brake lamps. These findings do not address how brightness judgments are made in the context of varying ambient light or with multiple moving vehicles at various distances

that can also partly occlude each other's rear lamps. Adding all of these factors compounds the problem of making perceptual judgments of automotive rear lighting.

Regarding ambient lighting, of particular interest is how brightness judgments are affected in a particular, yet commonplace context when brighter ambient light (< 7,000; > 1,000 lux) reduces luminance contrast between rear signals. During morning and evening commuting hours, ambient light is changing rapidly (35 lux to 30,000 lux) due to sunrise or sunset; and drivers may have their head lamps and tail lamps activated in response to or in anticipation of these changes. In these conditions 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, making discriminating between the relative brightness of tail lamps and brake lamps of different shapes and sizes even more difficult. Similar conditions also exist during overcast days either with or without rain when some drivers activate their full lighting system including rear lighting and others do not, either because they have DRLs which do not activate rear lighting or they do not recognize the need to activate their lighting.

Another factor that increases the difficulty of detecting brake lamps are the effects of moving traffic and distance. The presence of multiple lead vehicles that move laterally in relation to a following driver produce luminance transients because rear lamps are appearing and disappearing due to occlusion by intervening vehicles. Brightness of an object also decreases with increased distance according to the inverse square law. Multiple vehicles at different distances from a following driver produce images of

varying areas on the retina due to changes in visual angle. So brake lamps farther away may appear only as bright as tail lamps that are closer.

The combination of all the previously discussed factors—ambient light levels, varying distances to lamps, motion of traffic vehicles, occlusion of lamps, varying lamp shapes, sizes and luminance outputs and context dependent inconsistent activations of rear lighting—compounds the perceptual difficulties of using luminance contrast as a cue to differentiating brake and tail lamp signals. This problem seems to violate a few principles of efficient visual search as applied to the task of detecting brake lamp activation. First, distractor-distractor homogeneity and distractor-target heterogeneity are both compromised when the only feature upon which they differ, luminance, is affected by vagaries in lamp size, shape, luminance and ambient light levels. Second, luminance contrast does not have unequivocal support in visual search research as an exogenous feature that produces efficient visual search (Wolfe & Horowitz, 2004). Others have recognized these limitations and have tested alternative approaches to increasing the conspicuity of brake lamps.

Research with Rear Lighting

Mortimer (1969) was one of the first to test the idea of coding rear lighting on vehicles by color and location rather than luminance alone. His study was conducted between 9 PM and midnight with 66 participants with 34 driving "city" and 32 driving "country" roadways while following a single test vehicle. Each participant experienced eight configurations of rear lighting. On some configurations Mortimer separated the tail and brake lamp spatially and used color to code lamp function. The current rear lighting

with tail and brake lamp only differing in luminance, performed worse than all other configurations. He measured RT to brake onset, error and subjective overall ratings of each system. Responses were measured to four separate signal states, the turn signal only, brake signal only, turn signal when brake signal was already on and brake signal when turn signal was flashing. The experiment also included a concurrent task of responding to small white lights mounted on either side of the front of the participant's vehicle hood.

While the statistical analysis showed significant differences in error and subjective ratings to three of the signal states, there was no significant difference in RT for detecting the brake signal only state between the eight conditions. In the city driving, current lighting had significantly more error than any of the other configurations and accounted for 40% of the errors and was rated as having the least effectiveness by participants. No differences in configurations were found in country driving errors. While color-coding reduced RT to other signal states (and error and was rated higher by participants, separation of lamps spatially by function also produced significant effects in reducing error.

However, Mortimer's investigation has a number of limitations when visual search principles are considered. First, there was only one lead vehicle and thus no requirement that participants search for targets. This is not only a set size issue. When only a single lead vehicle is present, it disallows other perceptual confounds that can make detecting brake lamps difficult. Other vehicles cause occlusion and allow relative lamp brightness comparison. These brightness differences may be the result of having

vehicles at different distances and with different size and shape lamps which can cause distractor-distractor heterogeneity problems. Second, target absent data were not able to be recorded due to the nature of the task. Other limitations are also relevant to dual task performance. He did not report how his concurrent task was affected by performance on the rear lighting task. This is problematic because there could have been improvement in the primary task while the secondary task suffered in performance. Also, he only tested the systems under conditions that only mildly inhibited operator endogenous states. In other words, the concurrent task did not create distracting conditions where drivers might miss brake onsets due to removing their visual attention from the roadway because participants were not required to move their visual gaze by more than a few degrees.

Cameron (1995) tested the current automobile lighting against a system he called Red Light Means Stop (RLMS) where the tail lamps were amber and red lamps were illuminated only during braking. Forty-three participants sat in a vehicle 15 meters behind a stationary test vehicle and used four triggers to indicate identification of turn, tail and brake signals on the test vehicle while also responding to a bank of lights at a second location 80 degrees left of the line of sight to the test vehicle. He tested 2/3 of his participants on clear sunny days and identified the remaining trials as night but did not disclose the specific lighting conditions. He did not report a significant difference in RTs between the two conditions and although he reported less error in identifying lamps in the RLMS condition he did not have any statistical analysis. Without statistical analysis it is understandable why NHTSA would discount this study. While the study did well in employing a dual task to increase operator attentional demand and calculating error,

target absent responses and set size manipulations were not used. These factors additionally limit its ability to assess visual search efficiency.

One common finding between Mortimer (1969) and Cameron (1995) was that color coding lamps by function tended to improve detection to other signals as well. Participants were faster responding to turn signals when lamp function was coded by color. Multiple studies for over 40 years have supported this finding (among others, Allen, 1964). More recently, crash data have indicated that using color to differentiate signals (e.g. turn signal) reduces crash risk (Sullivan & Flannagan, 2012).

Other studies sponsored by NHTSA examining rear lighting have not experimentally examined changing tail lamp color for at least two reasons (Lee et. al., 2002; Wierwille et. al., 2003; Llaneras et. al., 2010). First, the federal code mandates that tail and brake lamps emit the same hue and overturning this legal requirement is rightfully not taken lightly. Second, previous research like that of Mortimer and Cameron are not convincing because they lack statistical analysis, large effects and were not tested with set size manipulations or present absent trials that can discriminate visual search processes and efficiency. These studies have attempted to differentiate the brake lamp from the tail lamps by adding additional locations or luminance to the brake signal rather than attempting to change the distractor tail lamps. However, many of these studies in rear lighting have similar limitations as those conducted by Mortimer and Cameron when viewed from visual search principles. Most importantly, no set size manipulations were performed. Only a single lead vehicle (usually with a secondary task) was employed in all of these studies. The testing that led to the adoption of the

CHMSL and more recent studies looking into adding a flashing halogen lamp to indicate hard braking have the same methodological limitation (Wierwille et. al., 2006). While using a single target vehicle with a secondary task may seem to access attention capture ability of a stimulus it in no way predicts search efficiency amongst distractors. Intuition may suppose that an intense luminance onset captures attention but what if there are many bright objects surrounding the target? The lack of set size manipulation, target absent data, and possibly weak endogenous attentional demand make the methods employed by these studies unable to adequately assess efficiency of search and conspicuity of targets.

Simulation Studies Testing Alternative Lighting

In order to address some of the methodological limitations of previous research, McIntyre (2008) conducted an experiment where participants were given the task of detecting brake lamps in pictures of traffic. The task was designed to implement visual search design principles by using larger set sizes, analyzing both target present and target absent data and simulating endogenous attention demand. This was a within-subjects task where participants responded present or absent on a keypad to static traffic scenes projected onto a screen. The traffic scenes had multiple cars in multiple lanes of traffic. Either all vehicles in a scene had no brake lamps activated or at least one vehicle had a brake lamp activated. The study compared current red tail and red brake lamps to proposed lighting where tail lamps had a subjectively yellow hue and brake lamps remained red. Order of exposure to the current lighting block of trials and the proposed

lighting was counter balanced between participants. Participants fixated on a blank screen for 2 seconds then the traffic scene appeared. Participants responded on a keypad to indicate whether a brake lamp was present in the scene or not. After the response the traffic scene disappeared and the blank screen returned to begin the next trail. Yellow tail lamps led to significantly faster and better brake signal detection (lower RT, fewer errors and false alarms) than with red tail lamps. These differences between yellow and red tail lamps showed large effect sizes and demonstrated more efficient visual search as measured by visual search metrics.

In another study by McIntyre (2009), another method was used to test the theory that advantages in brake detection with yellow tail lamps occur because yellow tail lamps allow parallel/pre-attentive search for brake lamps. The stimuli and task was identical to McIntyre (2008) with the exception that subjects were not given time to move their initial gaze and search the driving scene before the trial terminated (200 ms). Thus, parallel search processes needed to be used to detect the presence or absence of brake lamps throughout the scenes. As would be predicted for a parallel versus serial search, subjects had much less error when tail lamps were yellow and were at chance accuracy when tail lamps were red.

There were advantages and limitations of the methodology for these two studies. Limitations included using static photographs of traffic rather than real cars in a moving visual field. In addition, the projected display of photos simulated luminance differences between red tail lamps and red brake lamps that were considerably less than the corresponding luminance differences on the road. Because the only available cue of

vehicle braking in the red tail lamp condition were differences in luminance and area produced by photographically simulated tail and brake lamps and the new spatial object onset of the CHMSL. This luminance replication is a serious limitation given the primary cue for the current lighting system is luminance onset and contrast. However, it was argued that this is an acceptable first test case because there are ambient lighting conditions as mentioned previously (e.g., dawn, dusk and overcast days) where the luminance contrast between brake and tail lamps is greatly reduced and may leave drivers with only location (CHMSL) and minimal luminance contrast cues. Supporting this assumption is the fact that DRL systems do not activate rear lighting for this very reason. Another disadvantage of this study was that static pictures could not capture the phenomena that occur with moving traffic of appearing and disappearing red lamps as cars move laterally in relation to each other and occlude the view of rear lighting.

Advantages of this methodology are in its ability to test specific assumptions concerning driver perception and attention while driving related to visual search principles. For example, in-vehicle media and displays often distract visual attention away from the road ahead. In order to test detection of rear lighting with this assumption that drivers may miss brake lamp onsets due to distraction, when the scenes with brake lamps present were displayed, the brake lamps were already activated. This disallowed the cue of a brake lamp onset and simulated endogenous attention load which inhibits visual search performance. While the luminance simulation problems were described above as a limitation, it was also viewed as an advantage in testing the assumption of drivers facing real limitations in detecting luminance contrast under ambient lighting

conditions that are similar to that experienced on overcast days and during commuting hours. Another advantage to this methodology was having traffic scenes that required drivers to search through multiple potential target locations compared to other studies that have used a single lead car. Additionally, obtaining RT and error when brake lamps are not present allows access to how visual attention is allocated when target brake lamps are not available which allows assessment of signal detection and attention load. Although an actual implementation of this idea would necessarily involve different spatial locations for brake and tail lamps due to having different colored lenses, using edited pictures in this study permitted testing the color hypothesis without confounding spatial location. Red brake lamps and tail lamps shared the same spatial location in the present and absent trials of the yellow condition respectively.

Recently, a series of experiments examined performance of alternative versus current rear lighting in detecting brake lamps (McIntyre, Gugerty & Duchowski, 2012). Two of the experiments were the first to test the effects of changing tail lamp color on brake lamp detection with multiple lead vehicles moving in normal traffic flow using a moderate-fidelity driving simulator. The third used eye tracking measures during a vigilance task with static stimuli similar to those used in an earlier study by McIntyre (2008).

For the first study, 40 participants followed nine vehicles on a three lane highway during simulated nighttime. 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. This driving scenario makes the visual search for target brake lamps more complex than previous studies because it allows for multiple potential target and distracter locations in a moving array that results in occlusion and un-occlusion of distracters as well as targets. Also, this more complex scenario simulates some of the high attentional loads that drivers deal with on an everyday basis, and which have been ignored in previous studies.

Participants were randomly assigned to either the current lighting or alternative lighting where tail lamps were changed to emit a yellow hue but brake lamps remained red. The scenario was a mostly straight rural three lane interstate roadway with some curves in a clear sky night time drive of approximately 18 kilometers that lasted approximately 15 minutes. The participant vehicle followed 9 other vehicles traveling in a 3 (lane) x 3 (row) array and no other ambient traffic ahead of the driver. During the drive, 45 brake signals occurred so that each vehicle displayed 5 brake onsets across the drive at pseudo-random times. 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 Two vehicles followed the participant vehicle; each starting in an outer lane. At unpredictable times, one of the two rear cars would changes lanes. Participants responded to brake lamp onsets by pressing a button on the steering wheel

with their right hand and to rear lane changes by activating the turn signal with their left hand.

In order to test hypotheses about how red vs. yellow tail lamps may engage serial vs. parallel processes, a set size manipulation was conducted in a second experiment. Twenty-two participants drove identical scenarios to the first experiment but with only two lead cars and eliminating the lane change task. Thus, the second experiment used a low set size (2 vehicles in front) and the first experiment a high set size (11 vehicles in front and rear). In the second experiment 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 first experimental scenario were collapsed onto the single car displayed in that row for a total of 30 brake events.

In using this visual search paradigm, 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, it was predicted that in the Red tail lamp condition, misses and RT to detected brake signals would increase markedly with increasing set size or 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, it was predicted that in the Yellow tail lamp condition, misses and RT to brake signals would be less strongly affected by increasing set. Since the difference between the second and first experiment involved changing between 2 vehicles and one task in the second study vs.

11vehicles and two tasks in the first study, this change can be viewed as more than a set size manipulation. Therefore, in the following, changes in set size are referred to as attentional demand. Also, better performance on the lane change task was predicted for the Yellow condition. These hypotheses were statistically evaluated 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.

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 this study, the brake target was displayed for only 2 seconds, 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 RT's in the visual search paradigm) and RT must be analyzed to test for effects of parallel vs. serial search.

All hypotheses were supported. Increasing attentional demand (set size and concurrent task) had little effect on RT and accuracy with yellow tail lamps (flat slope) and a large effect with red tail lamps. Both the yellow and the red systems were similar in RT and accuracy with the reduced set size. However, in the larger set size with a concurrent task, the number of missed brake lamps and false alarms was significantly lower in the Yellow tail lamp condition than the Red tail lamp condition. 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. Interestingly, RT increased as targets increased in distance from the driver for the Red condition but not for the Yellow. 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 did changing tail lamp color improve performance in detecting brake lamps, it also facilitated RT performance on the concurrent lane change task. All of these findings had very large effect sizes. The larger number of misses with red tail lamps relative to yellow tail lamps seems particularly important, since brake signals that are missed altogether could have greater safety consequences than brake signals that are responded to slowly. More false alarms in the Red condition indicate problems with distractor-target similarity between red tail lamps and red brake lamps. The effect of manipulating attentional demand on RT and accuracy for these systems provides preliminary evidence that yellow tail lamps facilitate efficient visual search that allows guidance or parallel processes, while red tail lamps are more likely to require focused attention that moves serially in search of red brake lamps.

Performance was equal for both conditions with only two lead vehicles so the poor performance in the larger set size with red tail lamps could not have occurred because red brake lamps and red tail lamps were not distinguishable in the simulator. In the simulator the yellow tail lamps had greater luminance than the red brake lamps. Thus, it could be argued that luminance differences between the yellow tail lamps and the red brake lamps in the Yellow condition were facilitating the use of pre-attentive processes rather than color alone. However, in the field 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 luminance from the red brake lamp than did his amber colored tail lamp.

The findings of these two experiments extend findings from earlier studies (Cameron, 1995; McIntyre, 2008, 2009) that yellow tail lamps strongly improve detection of brake lamps. Furthermore, compared to previous research, they have done so in a more dynamic and complex traffic environment and with a concurrent task. A novel contribution of these experiments is using a set size manipulation to assess search efficiency and possible underlying cognitive processing driving the behavior. Performance benefits for yellow tail lamps occur 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 the first experiment is that yellow tail lamps facilitate improved detection of important driving events (lane changes) that were not signaled by lighting.

The third experiment 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, the *absence* of a target terminates search as quickly and effortlessly as when a target is present (Treisman & Gelade, 1980). However, search for conjunctive targets 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, Matthews & Finomore, 2008). This difference in workload may be caused by the different types of visual scanning behavior needed for pre-attentive versus 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 & 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, it was 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, fewer and longer fixations that are less dispersed was expected. In addition, as in previous studies, it was hypothesized that red brake lamp detection would be much better when tail lamps are yellow. These predictions were tested by examining how tail lamp condition affected eye movement variables (number and duration of fixations; fixation dispersal) and workload.

Twenty participants were exposed to both conditions (red tail lamps and yellow tail lamps) in a counterbalanced order. A single driving scene was displayed for 10 minutes. 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 minute 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 seconds 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 seconds 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 minute condition. After completing the first condition, the NASA TLX was administered. The same procedure was repeated for the second condition.

The main interests in this study were workload perceptions and oculomotor behavior. Participants reported significantly higher subjective workload in Mental Demand and Effort as measured by the NASA TLX in the Red condition than the Yellow. When in the Yellow condition, participants spent over 70% of their time fixated in a centrally located 5 degrees of visual angle compared to 46% in the Red. 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.

These data suggest that less focused visual attention and effort is required to detect brake lamps when they differ from tail lamps in color. The stimuli used in this experiment suffer from the same limitations as McIntyre (2008). This limits the generalizability of the results to a specific range of ambient lighting conditions, such as during overcast, rainy or near dusk and dawn (commuting) hours. Acknowledging these limitations, these data are still 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.

One argument against the results found in these simulator experiments is that the luminance contrast between the red tail lamp and red brake lamp was not representative

of what drivers experience on the road. In other words, the only reason the color manipulation had significant performance benefits was because the one cue used to differentiate red brake lamps and red tail lamps was faulty. The following field experiment using actual automotive lighting that meets the FMVSS guidelines for brake and tail lamps has been designed to validate these simulation studies and test the proposed alternative rear lighting (amber tail lamps) in the context of the visual search paradigm.

CHAPTER FOUR

DISSERTATION STUDY INTRODUCTION

This study will use visual search principles to examine the conspicuity of brake signals with current mandated automobile rear lighting compare current rear lighting to two alternative rear lighting systems where the red tail lamp lens has been replaced with an amber lens. One of these conditions will simply use an amber lens in place of the red tail lamp lens. This condition was included for external validity reasons to examine the effects of simply replacing the red tail lamp lens with a DOT approved amber lens without any other changes. However, this single mechanical change not only alters the color of the light but increases its brightness relative to the red tail lamp. This means the distractor set in this condition is not only a different color but brighter relative to the red tail lamp condition. So, a second amber condition was included for internal validity to control for this color and brightness change confound. In this condition neutral density filters were placed over the amber lenses so the amber lamp perceptually matches the red tail lamp in brightness. The result is a tail lamp condition where the distractor set only differs in color from the current lighting. Despite the luminance difference in the two amber tail lamp conditions, it was predicted that there would be no significant performance differences between them if the color change was driving behavior rather than luminance.

Considering the safety implications of detecting brake signals, test circumstances should examine as many exogenous and endogenous factors affecting driver identification of brake lamps as possible. In order to assess the effect of these variables,

the five principles learned from visual search research mentioned in chapter 2 should be applied to research design. For the current study these principles will be applied in the following manner:

1. Set size manipulation—Employing single vs. multiple lead vehicles to be searched
2. Distractor-distractor and target-distractor similarity—Allow occlusion of vehicle lamps and perceptual differences in brightness due to the effects of distance on brightness, visual angle and ambient light.
3. Manipulation of target-distractor contrast—Use color to differentiate distractor tail lamps from target brake lamps and compare this to the current system which uses only luminance contrast to differentiate tail and brake lamps.
4. Analyzing target absent responses—Use discrete trials that allow participants to indicate both presence and absence of target.
5. Simulating challenging endogenous states—Employ a distraction task that disallows viewing brake onset.

The primary hypotheses for this study should mirror those of visual search for serial and parallel searches. Because distractors (tail lamps) and targets (brake lamps) in the currently mandated lighting share the same color and are only differentiated by brightness which is attenuated by the various factors discussed earlier, the hypotheses for the current lighting (red tail lamps with red brake lamps) are the same as for a serial conjunctive search. If changing the tail lamp color sufficiently homogenizes the distractor set and categorically differentiates it from the target brake lamp, both alternative rear lighting systems (two kinds of amber tail lamps with red brake lamps) can

be categorized as parallel searches. If these assumptions are accurate, set size manipulation will have differential effects on performance both between and within conditions as illustrated in Figure 2.1 and the following hypotheses should hold.

Hypotheses

Tests of set size effects (i.e., changing from one to multiple vehicles) for Red vs. Amber tail lamps

1. The increase in RT and error with set size for Red tail lamps will be greater than the set size increase for Amber tail lamps.
2. For Red tail lamps, RT and error will increase with set size.
3. For Amber tail lamps, the change in RT and error with set size will be negligible.
4. With a single vehicle, RT and error for Red tail lamps will not differ much from RT for Amber tail lamps for both brake present and absent trials.
5. With multiple vehicles, RT and error for red tail lamps will be greater than RT for amber tail lamps for both brake present and absent trials.

Tests of effects of brake present vs. absent:

1. For Red tail lamps, the increase in RT and error with set size will be greater for absent trials than for present trials.
2. For a single vehicle with Red tail lamps, RT and error for absent trials will not differ much from RT and error for present trials.
3. For multiple vehicles with Red tail lamps, RT for absent trials will be greater than present trials.

4. The activation hypotheses presented by Chun and Wolfe (1996) argues that observers calculate the "cost" of target absent response errors and may therefore adjust their RT. As the "cost" of an error increases so does RT due to more exhaustive search. Thus brake absent responses may be slower than present responses with amber tail lamps in this applied visual search due to the cost of missing a safety related signal.

CHAPTER FIVE

RESEARCH DESIGN AND METHODS

Participants

Forty-eight Clemson University undergraduates (18 male; mean age = 20) who were licensed drivers were recruited from a Psychology participant pool. Participants were screened using a version of the Ishihara Test for Color Blindness and were excluded from the study if they misidentified more than two plates. All participants met the criterion for the Ishihara test. One participant was dropped from the Red condition (see below) as an outlier being more than 3 standardized residual deviations slower than the mean, leaving 47 participants for the data analysis.

Design

The task was to indicate by keypad response whether brake lamps were present or absent on mock vehicles in two lanes of traffic. Groups of participants were randomly assigned to one of three tail lamp conditions:

1. Red (n = 16, 6 male, mean age = 19) - current lighting; all vehicles had red tail lamps and red brake lamps with a standard luminance difference as the sole distinction between the lamps.
2. Amber DOT (n = 15, 6 male, mean age = 21) - all vehicles have DOT/SAE amber lenses in place of the red tail lamp lens and retain red brake lamps. This new lens produces a color difference between brake and tail lamps but also increases the luminance of the tail lamp (relative to red tail lamps),

thereby reducing the luminance difference between the brake and tail lamp within this condition.

3. Amber Matched (n = 16, 6 male, mean age = 21) - the same amber lamps as condition Amber DOT except with brightness reduced by a neutral density filter to match the current tail lamps. The only difference between this condition and the Red tail lamp condition is the color of the tail lamp. Red brake lamps are used as with the other conditions.

All three conditions retain red brake lamps and only tail lamp color or brightness is manipulated. All participants in each condition performed the brake identification task in two set sizes; single vehicle and eight vehicles. There were 20 randomly ordered trials in the single vehicle block and 40 in the eight vehicle block balanced for brake present and absent trials within every 10 trials. The lamp activations were not controlled by computer so a computerized randomization could not be practically carried out between each trial. Thus, both blocks had two predetermined randomly ordered sequences that were counterbalanced between participants. The order of blocks, i.e., single or eight vehicle task as the first block, was counterbalanced across participants.

Materials and Tasks

The rear lighting of eight stationary mock vehicles arranged to represent two lanes of same direction traffic with four cars in each lane were visible to the participant (see Figures 5.1 and 5.2). Figures 5.1 and 5.2 were taken in brighter ambient light than testing conditions in order to provide the reader a clear image of the display. For the single vehicle task, the participant vehicle was 35 m directly behind the first vehicle in the left

lane. For the eight vehicle task, the participant was 20 m behind the vehicle in the first row of the right lane. For the eight vehicle task, the four rows of rear lamps were 20, 30, 40 and 50 m from the participant vehicle respectively (see Figure 5.3). The lateral distance between the two outside lamps of the vehicles in the first row was 5 m. The entire display subtended a horizontal angle of 20 degrees. The mock vehicles were fabric covered 1.5 m wide x 1.5 m high frames with FMVSS approved combination tail and brake lamps. The first row vehicles had two lamps on each side whereas the remaining six had lamps had one on the only side visible due to occlusion. Thus, there were two brake lamps and two tail lamps (one set on each side) visible on the first row vehicles and only one brake lamp and one tail lamp on each of the six remaining vehicles. Lamps were mounted horizontally or vertically adjacent to one another. None of the mock vehicles had a center high mounted stop lamp (CHMSL). This was done to avoid a confound between visible lamps in the first row which could have a visible CHMSL (with the exception of vehicles not required to have a CHMSL or an equipment malfunction) compared to the vehicles in the other rows on which a CHMSL likely would not be visible because of occlusion.

Figure 5.1. Eight vehicle display in Amber DOT condition with brake lamp activated in left lane third row.

Figure 5.2. Eight vehicle display in Red condition with brake lamp activated in left lane third row.

Although the dual filament bulbs permit a single lamp activating as both a tail lamp and brake lamp, the brake lamp could not be displayed in the same location as the tail lamp in the two amber conditions due to color differences. Because of this, in order to allow the possibility for brake lamps to be displayed on each of the eight vehicles, each vehicle could only have one tail lamp and one brake lamp. This design would have created a situation in which anytime a single lamp was activated, it would indicate a tail lamp; and if two lamps were activated one of them had to be a brake lamp. Thus, this design would have provided an additional cue that a brake lamp was activated (i.e., activation of two lamps) separate from the cue of increased brightness. It is important to note that this additional spatial cue to braking is not present in on-road driving, because many vehicles do not have separate brake and tail lamps.

In order to avoid this spatial confound, only one vehicle in each row was permitted to exhibit a brake lamp and the other four vehicles displayed two tail lamps instead of one (see Figure 5.3). This meant that when participants saw two lamps activated on a vehicle, it could be two tail lamps or one brake and one tail lamp, which is more similar to real on-road conditions. While this reduced the number of locations at which a brake could appear, participants could not easily notice this was the case (unless they remembered the sequence of brake lamp locations) and thus they would still have to search all vehicles for brake lamps. This is important to note as the set size is a critical manipulation in the design.

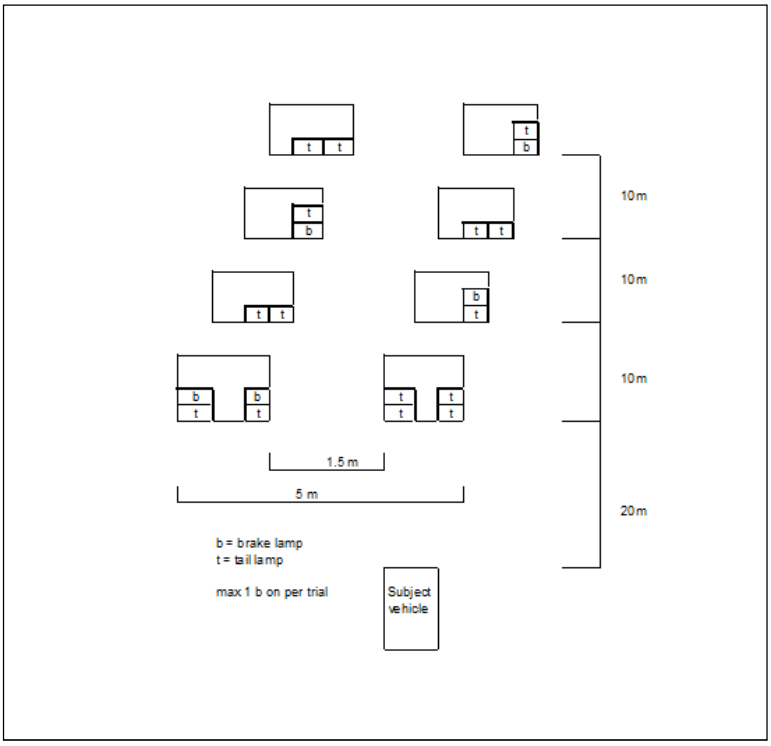

Figure 5.3. Schematic overhead view of mock vehicle display.

The lamps were a pedestal mounted, round, 80 cm^2, double faced (amber lens on one side and red on the other), with a single original equipment equivalent 1157 dual filament incandescent bulb that permitted a single lamp to activate as either a brake lamp or tail lamp. The distance from the ground to the midline of each lamp assembly was 0.84 m. All lamps were powered by a single fully charged 12 volt battery. The minimum amperage draw on the system was 8 amps. A maximum of 12 amps occurred only when all 8 mock vehicles had all tail lamps and both brake lamps on the first row vehicle activated. The longest session on one charge was 2 hours with the lamps activated for about half of the total time. From the participant's location, an individual lamp in the

first row subtended a horizontal and vertical angle of 0.3 degrees and 0.11 degrees in the last row. Under a variety of ambient lighting conditions, the red brake lamp was consistently10x the luminance of the red tail lamp and 5x the luminance of the amber tail lamp of the Amber DOT condition when measured at 6 meters by a Minolta LS-100 spot luminance meter with a 1 degree acceptance area encompassing the entire lens.

The method of adjustment was used to match the brightness of the amber lamp for the Amber Matched condition. Four additional participants were used in this procedure. The researcher adjusted voltage to the amber lamp to reduce its brightness until the participant standing three meters distance in 3.0 lux ambient lighting reported that it matched the subjective brightness of the red tail lamp. Resistance in Ohms was then measured. This procedure was repeated three times for each of the four participants to obtain an average resistance. Once the matched brightness level was determined through the method of adjustment, the luminance of the dimmed amber lamp was measured with a Minolta LS-100 spot luminance meter with a 1 degree acceptance area. The amber lamp that was matched in brightness to the red tail lamp in brightness was now 0.5x the luminance of the red tail lamp. However, in order to implement this amber lamp in the mock vehicle display for condition 3, a 0.6 neutral density filter that reduced the luminance of the amber lamp identically to the voltage reduced lamp was placed over the amber tail lamps.

The experiment was conducted after sunset when ambient light levels were less than 100 Lux as measured from the third row of the display by a Minolta T-1 illuminance meter oriented to capture light from the direction of the participant. The participant

vehicle did not have the head lamps activated. A street lamp located 35 meters behind the participant vehicle kept the testing area at a constant illumination. The average Lux at the first, third and fourth rows was 7.4, 3.6 and 2.4 respectively. These illumination levels are consistent with the range of illuminance produced by automotive head lamps at night and ambient light levels at civil twilight (Owens, Francis & Leibowitz, 1989).

Procedure

Participants were given a consent form and a version of the Ishihara Test for Color Blindness. Participants sat in the passenger seat of a vehicle (eye height 1.2 m) with a laptop computer in their lap for recording responses and presenting the secondary task. Exposure to the single or multiple vehicle configuration as the first block of trials was counterbalanced between participants. The participant was instructed that they would be indicating by keypad response whether brake lamps were present or not on the mock vehicles. Because both brake present and absent responses were being compared, the brake present and absent response keys were reversed for half the participants to avoid possible bias of handedness.

Before beginning the trial, the participant was shown the tail lamps activated and then the brake lamps. For the multiple vehicle display, tail lamps were activated on all eight vehicles. Leaving the tail lamps on, a brake lamp was then activated on the last row right lane vehicle to familiarize the participant with identifying a brake lamp. No plausible search strategy was given verbally to the participant such as “any red light is a brake light” for the amber conditions or “look for the brighter light” for the Red condition. They were simply shown the target brake lamp and distractor tail lamps.

All lamps were extinguished between trials. The researcher then demonstrated the sequence of screens on the laptop that would be seen by the participant and directed the participant to respond as quickly and accurately as possible on each trial. In order to simulate distraction, the participant was instructed to look at the laptop at all times except when cued to make their response. The participant's focal gaze on the laptop was equivalent to looking just below the centerline of the steering wheel. Each trial began by the researcher prompting the participant to press a key. Then a screen displayed a string of twenty individual numbers (Bold, 16 pt font and different on each trial) which the participant read aloud to confirm their focal vision was not on the vehicle display. The experimenter in the vehicle with the participant monitored whether the participant's gaze was on the screen and that they were correctly reading the numbers on the screen. Trials where participants did not keep their gaze fixed on the screen or read most of the numbers correctly were dropped, as discussed below. While the participants were reading the numbers aloud, the research assistant out of sight and located near the vehicle display activated the lamps for the trial. After three seconds the numbers disappeared and the words "brake" and "no brake" appeared on the screen above their corresponding keys. The participant then looked up at the already activated lamps and pressed either the corresponding "brake" or "no brake" key. When the participant responded or if the participant did not respond within 4 seconds, the laptop screen recycled to the initial screen directing the participant to press a key when prompted to begin the next trial. The lamps were again extinguished until the next trial.

Five practice trials with two brake present trials were performed. Participants were given feedback for incorrect responses during the practice to ensure they understood the task. After the practice, the 20 trials for the single vehicle or 40 trials with multiple vehicles were performed and the opposite block followed. The five practice trials were always repeated prior to the multiple vehicle block. A single session with a participant took approximately 20 minutes.

Correct (hits and correct rejections) and incorrect (misses and false-alarms) responses and RT were recorded for each trial. The response time started with the disappearance of the number string display and ended with the keypad response. Only trials with correct responses were included in the RT data. RT's in this experiment examine lamp conspicuity and denote search, detection, and decision time and are not meant to be indicative of RTs for a braking response. Trials with error in the light display or where a participant looked at the display rather than reading the numbers on the laptop screen were not included in the data analysis (total dropped = 1% of trials).

CHAPTER SIX

RESULTS AND DISCUSSION

In order to assess the findings in the context of visual search, two techniques were employed to simplify the data. First, because visual search is measured by two variables—speed and accuracy—that that both provide important information about behavior on the same task, a composite variable (corrected RT) was created. Corrected RT adjusts RT for accuracy. This is often necessary because participants could favor speed over accuracy or vice-versa so analyzing RT or accuracy independently could be misleading. For example, a participant could decide to rapidly respond without any regard for accuracy such that they miss every target. Assuming their RT is representative of how the search is performed would be erroneous. One way this is dealt with is to mathematically divide the mean (or median) RT by the proportion of correct responses (Horowitz et al. 2003). For this experiment, the corrected RT on present trials was the mean RT on present trials where the participant responded correctly divided by the proportion correct on present trials. The corrected RT on absent trials was the mean RT on absent trials where the participant responded correctly divided by the proportion correct on absent trials. This corrected RT variable can be interpreted as the RT to produce each correct response. The corrected RT data were screened for violations of skew and homogeneity of variance. A log-normal transformation was used on the corrected RT data in all statistical analysis to correct violations of skew and homogeneity of variance.

Secondly, the two amber conditions were included in this experiment to address the different internal and external validity concerns mentioned in the introduction and design sections of this paper but no difference between the two conditions was predicted. Therefore, before addressing the main hypotheses, the two amber conditions were compared alone (ignoring the red condition) for any statistically significant differences. Figure 6.1 shows how corrected RT in the amber-DOT and amber-matched conditions was affected by set size and target presence vs. absence. A 2 x 2 x 2 (type of amber tail-lamp x set size x presence) mixed model ANOVA for corrected RT did not have a main effect of type of amber tail-lamp, $F(1, 29) = 1.97$, $p = .17$, partial $\eta^2 = 0.06$, and type of amber tail-lamp did not interact with set size, $F(1, 29) = 0.2$, $p = .66$, partial $\eta^2 = .007$, or presence $F(1, 29) = 1.37$, $p = .25$, partial $\eta^2 = 0.05$. There were only main effects of set size, $F(1, 29) = 22.03$, $p < .001$, partial $\eta^2 = 0.43$, and target presence, $F(1, 29) = 20.67$, $p < .001$, partial $\eta^2 = 0.42$. Based on the lack of significant effects of the type of amber lamp and the low effect sizes for the type of amber lamp, in the following analyses the amber-DOT and amber-matched conditions were combined to form a single condition called Amber (n = 31). The means for the combined Amber condition are also shown in Figure 6.1.

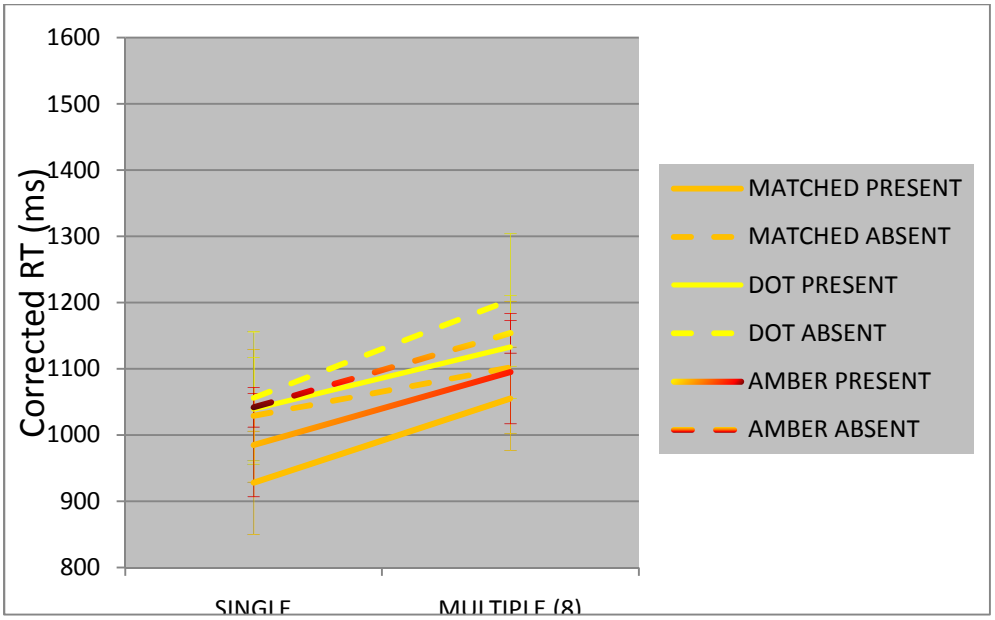

Figure 6.1. Mean corrected RT for Amber DOT, Amber Matched and Amber (combined).

The corrected RT variable will be used for the statistical tests of the hypotheses. Before presenting the corrected RT data, uncorrected RT and error (misses and false alarms) for the Red and Amber (DOT and Matched combined, n = 31) are presented in Tables 6.1, 6.2 and Figures 6.2 and 6.3. These tables and figures are presented to demonstrate that prior to combining the two variables, the uncorrected RT and error data generally supports the hypotheses. Thus, any support for the hypotheses based on the corrected RT variable does not depend on the RT correction. The uncorrected RT and error data will be discussed in more detail after the corrected RT analyses are presented.

Table 6.1. Mean uncorrected RT (SD) in ms for Red and Amber tail lamp conditions in both set sizes

	Single Vehicle RT (ms)		Multiple Vehicle RT (ms)	
Tail lamp condition	Present	Absent	Present	Absent
Red	938 (207)	964 (196)	1114 (244)	1381 (300)
Amber	976 (176)	1014 (168)	1047(159)	1112 (186)

Table 6.2. Mean proportion of misses and false alarms for Red and Amber tail lamp conditions in both set sizes

	Single Vehicle		Multiple Vehicle	
Tail lamp condition	Miss	False Alarm	Miss	False Alarm
Red	0.05	0.03	0.15	0.07
Amber	0.01	0.03	0.03	0.04

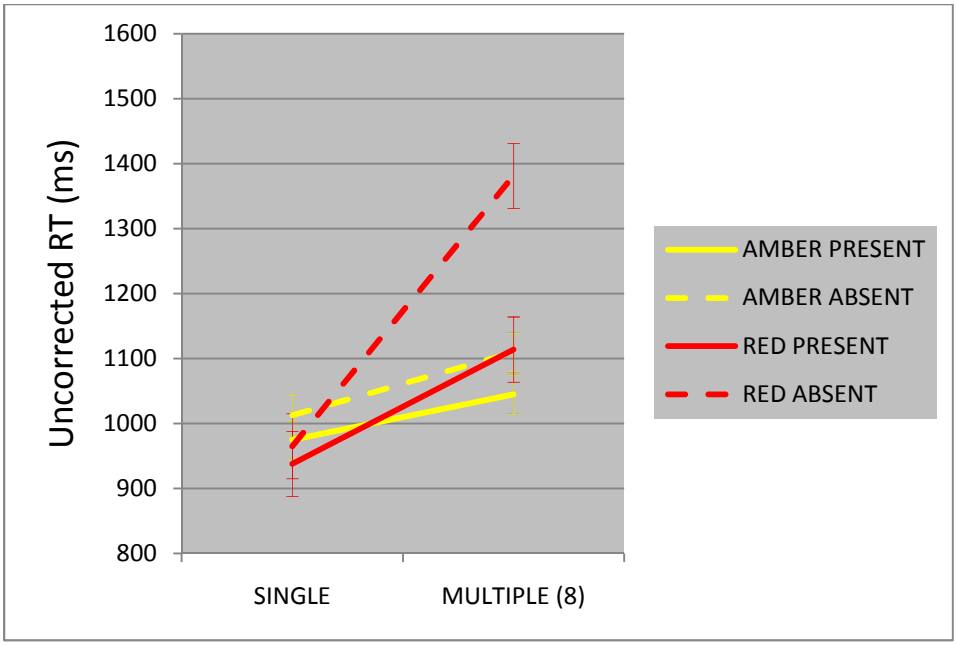

Figure 6.2. Uncorrected RT (ms) with SE bars for Red and Amber

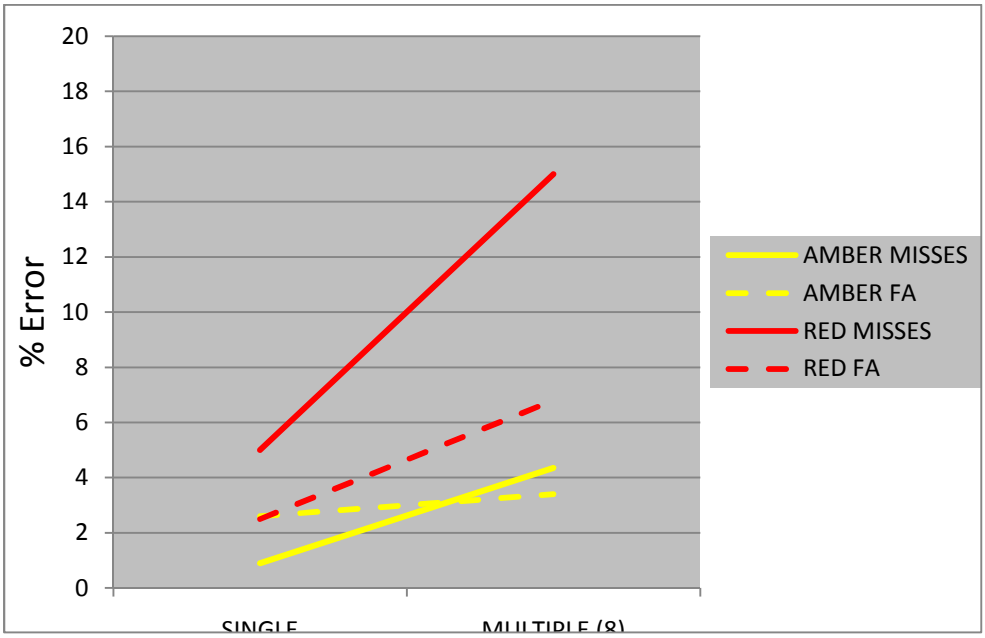

Figure 6.3. Miss and false alarm (FA) data for Red and Amber

Tests of set size effects for Red vs. Amber tail lamps

The first set of hypotheses tested whether set size affected corrected RT for Red and Amber tail lamps as would be expected if Red tail lamps engaged the serial attentional system and Amber tail lamps engaged the parallel attentional system. This predicted pattern involves: an increase in RT with set size for Red tail lamps but not for Amber tail lamps; negligible RT differences between Red and Amber tail lamps with a single vehicle; and RT for Red tail lamps greater than for Amber tail lamps with multiple vehicles. Figure 6.2 shows how tail-lamp condition, set size, and presence-absence affected corrected RT which will be called RT in the rest of this section. This figure seems to support most of the hypothesized pattern of results. Statistical tests of these hypotheses are now presented.

A key prediction from visual search theory is that the set size effect for serial searches is greater than that for parallel searches. In support of this and hypothesis one, a significant interaction of set size and tail lamp color, $F(1, 45) = 44.22$, $p < .001$, partial $\eta^2 = 0.50$, was found. In support of hypothesis two, in the Red, RT for multiple vehicle present trials was significantly greater than single vehicle present trials, $F(1, 15) = 59.18$, $p < .001$, partial $\eta^2 = 0.80$. The same strong set size effect was found for absent trials in the Red condition, $F(1, 15) = 146.3$, $p < .001$, partial $\eta^2 = 0.91$. The interaction, which showed a large effect size, along with the very large set size effects for target present and absent displays in the Red condition support the hypothesis of an increase in RT with set size for stimuli that engage the serial attentional system.

Hypothesis three, a negligible RT increase with set size for the Amber condition—w as not supported. Multiple vehicle RT present trials were significantly greater than single vehicle present trials, $F(1, 30) = 22.4$, $p < .001$, partial $\eta^2 = 0.43$. The same was true for absent trials, $F(1, 30) = 11.0$, $p < .01$, partial $\eta^2 = 0.27$. This set size effect, even though smaller than for the Red condition, does not fit a strict parallel search. While Chun and Wolfe's (1996) model predicts absent trial set size effects, no model predicts target present set size effects for parallel search.

According to visual search theory, small set sizes (< 5) are expected to have negligible RT differences for either parallel or serial searches as predicted by hypothesis four (Wolfe, 2007). This hypothesis was supported because, for the single vehicle condition, there were no significant differences between Amber present (M = 985 ms, SD = 172) and Red present (M = 994 ms, SD = 241) trials, $F(1, 45) = 0.02$, $p = .88$, partial $\eta^2 = 0.0$, or between Amber absent (M = 1042 ms, SD = 175) and Red absent (M = 992 ms, SD = 207) trials, $F(1, 45) = .79$, $p = .38$, partial $\eta^2 = 0.02$.

In contrast, visual search theory predicts that with larger set sizes (as in the multiple vehicle condition) RT for serial searches will be greater than RT for parallel searches as predicted by hypothesis five. This hypothesis was supported as Red brake present trials (M = 1318 ms, SD = 294) were significantly greater than Amber brake present trials (M = 1095 ms, SD = 168) with multiple vehicles, $F(1, 45) = 9.9$, $p < .01$, partial $\eta^2 = 0.20$. Similarly, Red brake absent trials (M = 1505 ms, SD = 407) were significantly greater than Amber brake absent trials (M = 1154 ms, SD = 215) with multiple vehicles, $F(1, 45) = 15.5$, $p < .001$, partial $\eta^2 = 0.26$. These set size effects

between tail lamp conditions demonstrate the superiority of separating brake and tail lamps by color rather than luminance as well as the importance of using multiple vehicles to test for manipulations that may affect visual search.

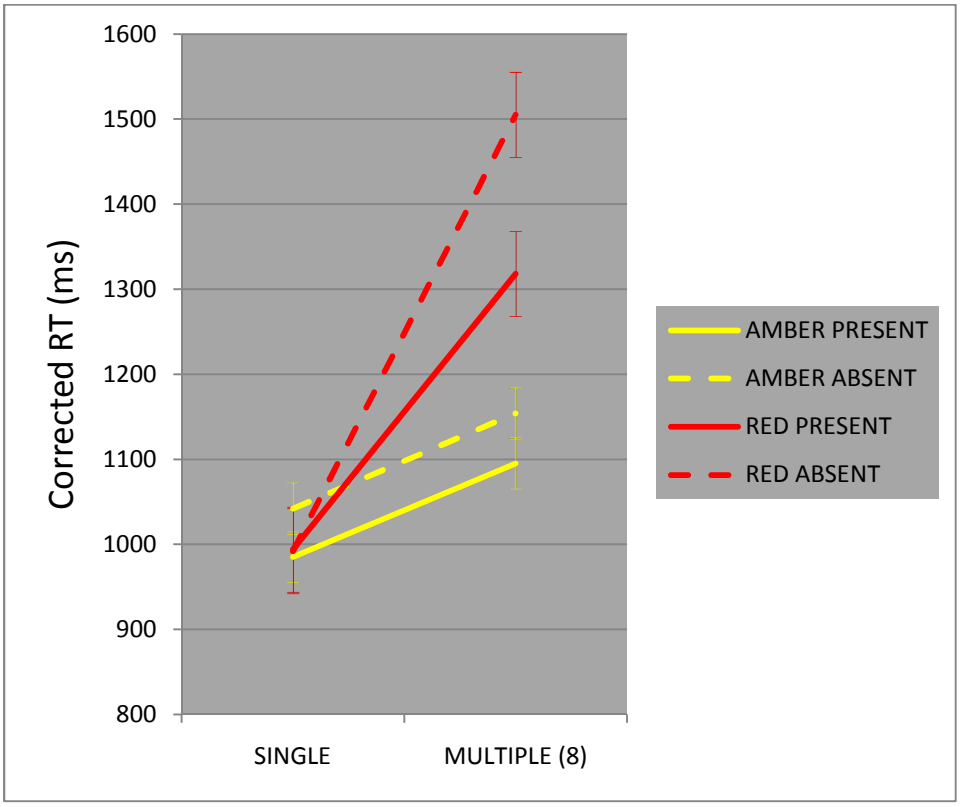

Figure 6.4. Mean corrected RT (ms) with SE bars for Red and Amber

Tests of effects of brake present vs. absent effects

The second set of hypotheses tested effects of presence vs. absence of the brake target. For serial searches, visual search theory predicts a negligible effect of presence vs. absence for small set sizes, greater RT for absent than present trials for large set sizes,

and an interaction such that the increase in RT with set size will be greater for absent than present trials. For parallel searches, the activation hypothesis of Chun and Wolfe (1996) predicts brake absent RT will increase with set size but brake present should not. Figure 6.2 seems to support these hypotheses.

The first hypothesis was supported in that, for the Red condition, there was a significant interaction of set size with target presence and absence, $F(1, 15) = 7.2$, $p < .05$, partial $\eta^2 = 0.32$ as would be predicted by serial search in this condition. The second hypothesis was supported as there was no apparent difference between target present and absent RT for single vehicle $F(1, 15) = 0.01$, $p = .92$, partial $\eta^2 = 0.001$. In support of the third hypothesis, in the Red tail lamp, multiple vehicle condition, absent trial RT was significantly greater than for present, $F(1, 15) = 9.7$, $p < .01$, partial $\eta^2 = 0.39$. The interaction of set size with target presence and absence with significantly longer RTs on brake absent trials compared to brake present trials with multiple vehicles fits the serial search model, which assumes that serial searches for absent targets take longer because more distractors must be searched. Additionally, the fact that target absent responses take longer with larger search sets indicates that target absent data is important in assessing conspicuity of signals and provides information that experimental designs that only use target present data cannot provide.

In support of hypothesis four, that in a parallel search absent RT will be greater than present RT, the main effect of target presence in Amber was also significant, $F(1, 30) = 20.63$, $p < .001$, partial $\eta^2 = 0.41$. Target present RT in Amber was significantly faster than absent in both single vehicle, $F(1, 30) = 6.7$, $p = .02$, partial $\eta^2 = 0.2$, and

multiple vehicle $F(1, 30) = 8.3$, $p < .01$, partial $\eta^2 = 0.22$. There was no interaction of set size and target presence, $F(1, 30) = 0.1$, $p = .75$, partial $\eta^2 = 0.003$. The lack of an interaction fits with classifying the Amber condition as a feature search task using parallel processes. Finding both set size and target presence effects fits with the activation model of visual search (Chun & Wolfe, 1996) and again reinforces the need to use multiple vehicles and target absent trials in research design.

Uncorrected RT and error Data

Uncorrected RT data and error data are graphically displayed in figures 6.3 and 6.4, respectively, for comparison to the corrected RT data. The set size effects on uncorrected RT data are essentially the same as the corrected RT data for all but one effect. The multiple vehicle RT for brake present in the Red condition (1114 ms) is not different from the Amber (1047 ms) and so does not conform to the predictions of set size effects hypothesis five that RT for Amber brake present multiple vehicle would be faster than Red. However, the need for a corrected RT can be seen in this case as the proportion of missed brake signals (15%) and false alarms (7%) were very high for this condition.

For the error data, there were no significant differences between tail lamp conditions or set sizes for false alarms. These are typically very low in visual search tasks. The miss rate for the Amber condition is typical for a single feature or efficient conjunctive search (2-4%) particularly given the small number of trials (40) relative to typical visual search tasks (100+) where practice effects can dilute “key confusion” errors

by participants. However for miss data with multiple vehicles, the Red condition had significantly more misses than the Amber condition, supporting the claim that the Red condition engages serial processes.

Comparing the uncorrected RT and error data in Figures 6.2 and 6.3 suggests that no speed-accuracy trade-off were present, as the independent variables affected both variables in similar ways, so that when error increased, speed increased also. In addition, a bivariate correlation analysis between each condition's respective uncorrected RT and error showed no significant relationships.

In order to assess if participants learned that brake lights would only appear on four of the eight vehicles, the multiple vehicle trials were divided into four sequential blocks of ten trials and uncorrected RT (called RT in this section) was analyzed by ANOVA. If RT decreased with time on task, this might indicate either learning the reduced set of target locations or normal practice effects (e.g., learning the locations of the response keys). Although there were significant reductions in RT over time for both Amber, $F(3, 93) = 10.43$, $p < .001$, partial $\eta^2 = 0.25$, and Red, $F(3, 42) = 5.76$, $p < .01$, partial $\eta^2 = 0.29$ (see Figure 6.5), this is not conclusive evidence that participants were only searching four of the eight locations. First, visual search tasks often see decrease in RT after hundreds of trials even when target locations are randomly located in the display so that participants cannot predict target location (Wolfe et al., 1989, Duncan & Humphreys, 1989). Second, the large effect sizes due to set size effects between single and multiple vehicle displays are not likely to occur if participants reduced the searchable set to only the four brake light locations instead of the full display.

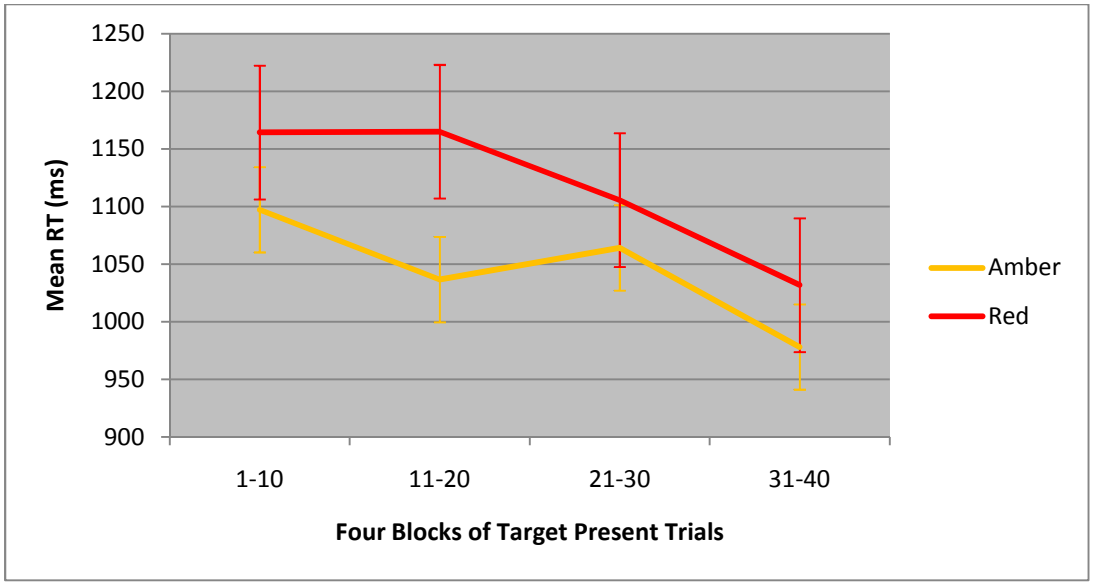

Figure 6.5. Time on task effects on RT with multiple vehicles

Row/Distance Effects

A row by row analysis of miss and uncorrected RT for brake present trials (to examine effects of miss data separately) was done to see if there were performance differences due to effects of brake lamp target distance (2 0, 30, 40, 50 m) from the participant (see Figure 6.5). For both target present RT and miss data, a 2 x 4 (tail lamp color x row) mixed model ANOVA was run with an alpha of .05. In addition to possible effects of distance on brightness perception, there was an unavoidable confound between distance and lamps for the first row vehicle compared to the other rows. The lamps of the first row vehicles were not occluded at all by another vehicle, while some lamps were occluded on all vehicles in the remaining three rows. Thus the first row vehicles had two tail lamps and two brake lamps whereas the remaining six only had a single tail or brake lamp.

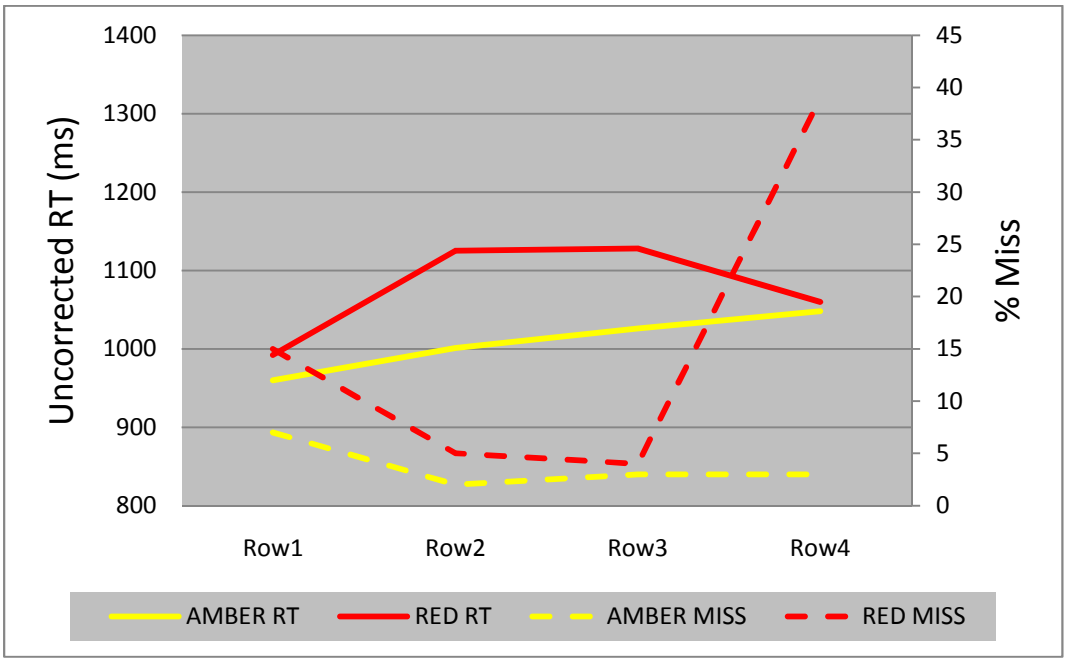

Figure 6.6. Uncorrected RT for brake present trials (ms) and misses (%) across rows.

Row significantly affected RT for the Amber condition, $F(3, 90) = 5.6$, $p = .001$, partial $\eta^2 = 0.16$. Within subjects contrasts revealed that RT for row 1 ($M = 960$ ms) was significantly faster than row 3 ($M = 1026$ ms), $F(1, 30) = 14.42$, $p < .01$, partial $\eta^2 = 0.33$ and) and row 4 ($M = 1048$ ms) $F(1, 30) = 9.27$, $p < .01$, partial $\eta^2 = 0.24$, but not row 2 ($M = 1001$ ms). The Row did not significantly affect miss rate for the Amber condition, $F(3, 90) = 1.71$, $p = .20$, partial $\eta^2 = 0.05$, (Grand Mean = 3.75%).

Data from three Red condition participants were excluded by the RT ANOVA analysis because they missed all the row 4 brake present trials and so had no RT. Row did not significantly affect RT for the Red condition, $F(3, 45) = 0.65$, $p = .59$, partial $\eta^2 = 0.04$. Row significantly affected miss rate for the Red condition, $F(3, 45) = 7.58$, $p <$

.001, partial $\eta^2 = 0.34$. Within subjects contrasts revealed significant differences ($p <$ .05) between row 4 misses ($M = 39\%$) and rows 2 ($M = 5\%$) and 3($M = 4\%$) but not row 1 ($M = 15\%$).

The large number of misses for the fourth row brake lamp in the Red condition was a cause for concern. Electrical equipment examination, luminance readings and subjective evaluation of brightness indicated that the equipment was not faulty. This brake lamp was also the exemplar demonstrated to every participant prior to beginning the task. The only explanation that accounts for the large number of misses is that the brightness difference for the red brake lamp at that distance was not sufficient to reliably distinguish it from the comparator red tail lamps activated at nearer distance. Because relative brightness is not a primary cue of braking in the Amber conditions, distance had no effect on error.

Because visual search tasks typically take place in two dimensions, the row by row analysis has no parallel in that paradigm. However, in practical application it is important to know how distance affects performance. As distance increases, brightness of a constant size and luminance stimulus decreases according to the inverse square law. Also, because head lamp illumination of forward objects decreases rapidly with distance the ambient light differentially affects luminance contrast of objects at different distances (Owens, Francis & Leibowitz, 1989). It should be noted that the distances between rows for this experiment were very short (10 m). At a speed of 60 mph the participant vehicle would only be 2 seconds from the vehicles in the last row in the display (50 m).

CHAPTER SEVEN

CONCLUSIONS

The data from this study basically follows the theoretical predictions of visual search for RT and error with parallel and serial search; particularly given the small set size manipulation. The set size manipulation in this study is very small compared to typical visual search manipulations (which are normally greater than 10 and can be greater than 50) so effects were expected to be comparable to a small set size manipulation in basic research. However, in this real world application the set size manipulation was deemed appropriately realistic and theoretically sufficient to produce the predicted outcomes.

This study has achieved its four goals. To reiterate they were:

1. Evaluate current research methods and propose a new methodology based on the visual search paradigm.
2. Demonstrate that current rear lighting on automobiles relies on serial search and does not effectively meet the stated purpose of regulators
3. Propose a more effective system relying on parallel processes for increasing the conspicuity of brake lamps.
4. Validate and extend previous simulator research on this same topic.

First, the value of a set size manipulation, which is rare in rear lighting research, was clearly demonstrated. With a search set of eight vehicles, amber tail lamps led to large reductions in RT and error relative to red tail lamps; while with a search set of one vehicle, the tail lamp manipulation led to little to no performance differences. These

findings provide strong evidence that the current practice of employing a single vehicle to assess rear lighting conspicuity is insufficient, and they demonstrate the need to test any proposed lighting systems with multiple potential distractor locations present.

In addition to the set size manipulation, this experiment has demonstrated the need to follow visual search paradigms by examining not only detection of the target brake lamp but target absent data. This unique piece of information allows analysis of signal detection performance and the response time can serve as an indicator of cognitive load. Attention devoted to searching a field of red lamps without a brake lamp, is attention that cannot be directed to other potentially hazardous road conditions and signals such as traffic signals, signage, pedestrians and cyclists.

Simulating compromised endogenous states by not allowing participants to see the brake onset is another important design factor in this study that is often not employed in rear lighting research. Other research has employed concurrent distracting tasks but this experiment goes a step further in simulating inattention rather than divided attention. While drivers often are able to make use of the lamp onset cue foveally, at least two factors make missing a brake onset a real possibility and argue for biasing against this occurrence in research design: first, the proliferation of in-vehicle devices that demand visual attention and second, research demonstrating that serious visual attention deficits can occur even with non-visual attention demands such as mind-wandering or other off-task cognitions. Additionally, incandescent bulbs can fully activate in less than 300 ms which amounts to a slow eye blink or a saccade to a touchscreen, instrument panel, roadway sign, passenger, or other potential hazard. Lighting technology appears to be

moving toward the use of light emitting diodes for vehicle lighting and these can fully activate faster than the blink of an eye (less than1ms).

Regarding the second goal, the large performance decrements with increased set size in the Red condition supports the claim that current rear lighting on automobiles relies on inefficient serial search processes and does not effectively meet the stated purpose of regulators in making brake lamps conspicuous, perceived and understood in all environmental conditions. Current lighting relies on luminance differences between brake and tail lamps; and luminance does not have much empirical support as a feature that produces efficient search. When multiple vehicles are present, the current lighting had significantly higher error and slower RT compared to a system designed to engage parallel search and differentiating brake lamps from tail lamps based on color.

One objection to the design of this experiment might be that the CHMSL, which is available on American cars since 1995 was not used in the display. As mentioned previously this was partly done to avoid another confound between first row and subsequent row vehicles. Additionally, it is a very real occurrence in everyday driving when following vehicles that either do not have a CHMSL by design (commercial trucks, buses, motorcycles, and older model cars) or equipment malfunction. Also, as was simulated in this experiment, the CHMSL is regularly obstructed by other lead vehicles.

However, in a variety of ways this experiment was a best case scenario for the current lighting. Shape, size and luminance of lamps was controlled which made the distractor set as homogenous as possible. Yet, as mentioned previously, brake and tail lamps on the road are allowed to have a range of shapes, sizes and even luminance which

have all been shown to affect judgments of brightness, which is the only perceptual difference between brake and tail lamps in the current system. Additionally, the ambient lighting conditions in this study favored a luminance contrast based system. Yet, a color coded system that had less luminance contrast between brake and tail lamp (Amber DOT) than the current lighting system performed significantly better than the current system. In brighter ambient lighting (1, 000-7,000 lux; UNECE, 2011) such as overcast days or commuting hours prior to sunrise and sunset where drivers regularly activate their driving lamps, the current system would be predicted to perform even worse because of its reliance on perceived brightness.

The third goal of this study was to propose and evaluate a more effective system for increasing the conspicuity of brake lamps that engages parallel search processes. This was accomplished by making distractor tail lamps categorically different from target brake lamps by using a feature (color) that is well established to engage parallel processes. The reduction in RT to identify a brake lamp relative to current lighting could be as much as 200ms with amber tail lamps. At 60 mph this could amount to reducing stopping distance by 5 m. With the proposed color coded system, the endogenous search goal is simplified to be a single feature search of "any red light" amongst amber lights. Many visual search studies have demonstrated that single feature searches can be performed efficiently in the face of conditions that degrade performance in conjunction searches. Thus, vagaries in brightness and all of the variable factors that affect its perception such as manufacturer lamp shapes, sizes, number, locations and luminance have no bearing on this single feature search goal. Additionally, because a system that

differentiates lamp function by color does not rely on luminance contrast, future tests under the environmental factors mentioned above (brighter ambient lighting, distractor heterogeneity) will likely have little adverse effect on that system relative to current lighting. This not only makes detection more efficient but reduces cognitive load when brake lamps are not present, allowing attention to be distributed to other potential and equally important events in the environment. For example, when approaching an intersection drivers need to monitor the traffic signal state, cross traffic and nearby pedestrians and cyclists in addition to the activation of brake lamps. With amber tail lamps, drivers will probably detect brake activations faster and more accurately while still being able to devote more cognitive resources to those other potential hazards. McIntyre's (2012) simulator study supports this as participants were faster to detect rear lane change events when monitoring forward brake events when vehicles had amber tail lights rather than red.

Search in current rear lighting with red brake lamps and red tail lamps induces a suboptimal endogenous goal directed toward a "relatively brighter red light" or "red light in center of vehicle . . . *if* on vehicle or not obstructed" (CHMSL); this conjunctive search for "red" and "brighter" amongst distractors that are "red" and "bright" has been demonstrated to induce suboptimal performance. The ambiguity in detecting red lights amongst red lights may cause drivers to discount red lights as a reliable signal and default to other strategies to confirm whether a vehicle is braking or not. Some studies have shown that under some circumstances people do rely on other cues of braking, like looming instead of brake signals (Delucia & Tharanathan, 2009). This lack of cue

reliability for brake lamps has moved regulators to prevent vehicles with DRLs from illuminating tail lamps under brighter ambient conditions so it is easier to differentiate between red tail and brake lamps that rely on perception of relative brightness. However, daytime activation of full lighting systems, including rear tail lamps, is either mandated or encouraged for tractor-trailers, buses and motorcycles, which makes identifying their brake lamps more difficult with a luminance based system.

The final goal of the current study was to validate previous simulator research on this same topic. This study is methodologically similar to the first studies published by McIntyre (2008, 2009). All three used multiple distractors, present and absent responses, and disallowed visibility of brake onset. They differ in a few respects. First, the computer simulations intended to simulate brighter ambient lighting conditions than were tested in the current study. Second, the simulator studies only used multiple vehicle displays and allowed the shape and size of vehicle lamps to vary, creating a less homogenous distractor set than the current study which controlled for shape and size of lamps. The overall RT and error results are similar in supporting the conclusion that the current lighting system produces serial search and a color coded system engages parallel search and demonstrating the usefulness of computer simulation tests of rear lighting.

The driving simulator experiments and the eye-tracking and subjective workload computer experiment conducted by McIntyre et al. (2012) also produced results similar to the current study for the effects of tail lamp condition, set size and target present vs. absent on RT and error; indicating that simulated driving behaviors related to automobile lighting conspicuity can produce ecologically valid results. However, these studies

differed in methodology. The main similarity was that the driving simulator study used a similar set size manipulation (11 vs 2 vehicles). However it differed in that the simulator study employed a concurrent task in the larger set size to simulate distraction, the simulator study vehicles had a CHMSL, participants could see brake lamp onsets and the simulator had moving vehicles that produced lateral movement that would obstruct vehicle lighting at various times, though not when a brake was activated. The row effects for error and RT was also similar between this experiment and the simulator study.

The eye tracking study was a vigilance task but the oculomotor data is consistent with the results of this study that participants take significantly longer with current lighting to determine a brake lamp is not present, indicating possibly more saccadic eye movements. The combination of the subjective workload ratings, more saccades from the computer simulation and the poorer signal detection, longer RTs and more error in the current experiment all point to greater cognitive resources and attention load needed to monitor current vehicle lighting for brake lamps. Again, both of those simulation studies were intended to assess performance with brighter ambient light than was used in the current experiment. The overall correspondence of results between the simulator studies and this experiment provide validation for the simulations and further evidence for the beneficial effects of separating tail lamps and brake lamps by color rather than luminance.

One major criticism of all the simulator studies was that simulators cannot accurately represent the luminance changes in the current lighting system and thus were biased in favor of the color differentiated system. For example, McIntyre et al. (2012)

found poorer detection of red brake lamps with red than with yellow tail lamps in the context of multiple distractor vehicles, but the poor performance with red tail lamps could have occurred because red tail and brake lamps were the same luminance in the simulator. This field study was conducted in part to address criticisms such as this. However, if the poor performance with red tail lamps in McIntyre were due mainly to the lack of luminance differences between red brake and tail lamps in the simulator, then the effect sizes between the red and yellow tail lamp systems would be smaller in the field experiment, which employed the realistic, large luminance differences between red tail and brake lamps. However, the reverse was found. The red tail lamp system performed even more poorly relative to the yellow tail-lamp system (i.e., larger effect sizes) in this field study than in the simulator study by McIntyre et al. (2012), indicating that simulated research on this topic can produce valid findings.

In summary, this experiment suggests that conducting future studies with vehicular signaling within the visual search context is appropriate and even essential. This means employing a larger set size than one, measuring target absent behavior as well as target present and simulating suboptimal endogenous states for participants (such as inattention). Also, testing participants under a broader range of common but compromised endogenous states such as with sleep deprivation or visual impairments may reveal further differences between a color coded and luminance coded system. Another principle that should be used involves manipulating distractor homogeneity. Because this study wanted to control lamp luminance, size and shape, it was lacking in assessing how these systems would perform with less homogenous distractors. This is a

major consideration since real world environments have much more heterogeneous distractors and targets. Future studies should deliberately create heterogeneous but realistic distractor and even target sets to assess performance. This can be done by using lamps that are differing sizes, shapes and luminance. Additionally, testing these systems under slightly brighter ambient lighting but when drivers would still activate their lights would be an important and realistic manipulation, as would using moving locations that replicate what was done in McIntyre's (2012) simulator study and on the road. Application of these visual search principles in research design will help ensure the conspicuity goal stated in the federal code for automobile rear lighting.

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