Human Factors Considerations in the Selection of a Uniform Protected/Permitted Left-Turn Signal Display

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INTRODUCTION

Transportation engineering encompasses a wide array of topics related to the movement of people and goods. Given this broad diversity, very few components of transportation engineering, including the design and implementation of signalized intersections, can be fully developed without integrating an understanding of human factors. Human factors applies information about human behavior, abilities, limitations, and other characteristics to the design of environments for productive, safe, and effective human use. Specifically, human factors can be defined as the study of how drivers accomplish driving-related tasks in the context of driver-vehicle system operation, and how behavioral variables affect this accomplishment. Further, in the control of vehicular movements at signalized intersections, human factors provides insight and understanding into drivers' processing of and reaction to traffic signal display information.

The interaction of the driver and the traffic signal display, along with the interpretation of the visual message the traffic signal is intended to portray, is significant in determining the effectiveness and inherent safety aspects of a signalized intersection. If the driver/traffic signal interaction is poor, not only does the traffic signal system fail to fulfill its purpose, but potential safety issues arise. Driver/traffic signal interaction is further complicated when one considers that the single visual message that the traffic signal can portray must be acceptable and understandable to drivers of all ages, driving experience, ethnic backgrounds, and psychological states. An in-depth understanding of the human factors aspects of traffic signal operations is necessary as traffic engineers look to improve the driver/traffic signal interface. Unfortunately, a comprehensive evaluation of the human factors aspects of traffic signal systems is rarely included in design and analysis processes.

This paper provides an in-depth review of the current understanding in the human factors aspects of traffic signal operations, focused primarily on protected/permitted left-turn (PPLT) control and the corresponding PPLT signal display. Recall that PPLT signal phasing provides an exclusive phase for left-turns as well as a permissive phase during which left-turns can be made if gaps in opposing through traffic allow, all within the same signal cycle (*1*). The first section of this paper provides an overview of general concepts related to human factors aspects of traffic signal displays including the visual search process, driver perception and reaction, driver recognition and comprehension, driver expectancy, and signal display complexity. The next section provides a detailed overview of color vision and how humans observe the red, yellow, and green traffic signal indications. The third section discusses older driver issues by briefly looking at visual and cognitive changes associated with the human aging process. Finally, several comments related specifically to the selection of a uniform PPLT signal display are presented.

HUMAN FACTORS

A traffic signal display can be defined as an object placed along the roadway in an attempt to aid or control the driver. The objective of the signal display is to transmit an unambiguous message to the driver, quickly and clearly, to minimize disturbance with the primary vehicle guidance and control task, and to allow sufficient time after message recognition for decision making and control action (*2*). In the context of a signalized intersection, traffic control is provided by a group of individual traffic signal displays placed at selected locations. Within each traffic signal display, colored indications (red, yellow, green) in either a circular (ball) or arrow shape are used to provide information to the driver relevant to the function and movement that he or she is attempting to fulfill. A typical series of traffic signal displays at a signalized intersection, including a PPLT signal display, is shown in Figure 1.

Human senses provide the source of interaction between a traffic signal display and the driver, the most significant of which is vision (*3*). Information provided by a traffic signal display is aided if the signal display, associated signs, and pavement markings are consistent with the human visual capabilities of most drivers. Information transfer involves not only visual acuity, sensitivity to light, and color discrimination, but also time related effects of perception and reaction. Figure 2 presents a generalized diagram describing traffic signal display and driver interaction.

Visual Search

When a driver is looking for a traffic signal display indication (target) in an approaching intersection environment, the visual scan pattern tends to be far less structured and organized than in other control tasks (*4*). The drivers' task relative to traffic signal displays involves detection of the signal display, which is inhibited by ambiguous signal meanings and conflicting and inconspicuous displays (*5*). Consequently, modeling the drivers' target search process is difficult.

Figure 1 Typical Traffic Signal Displays.

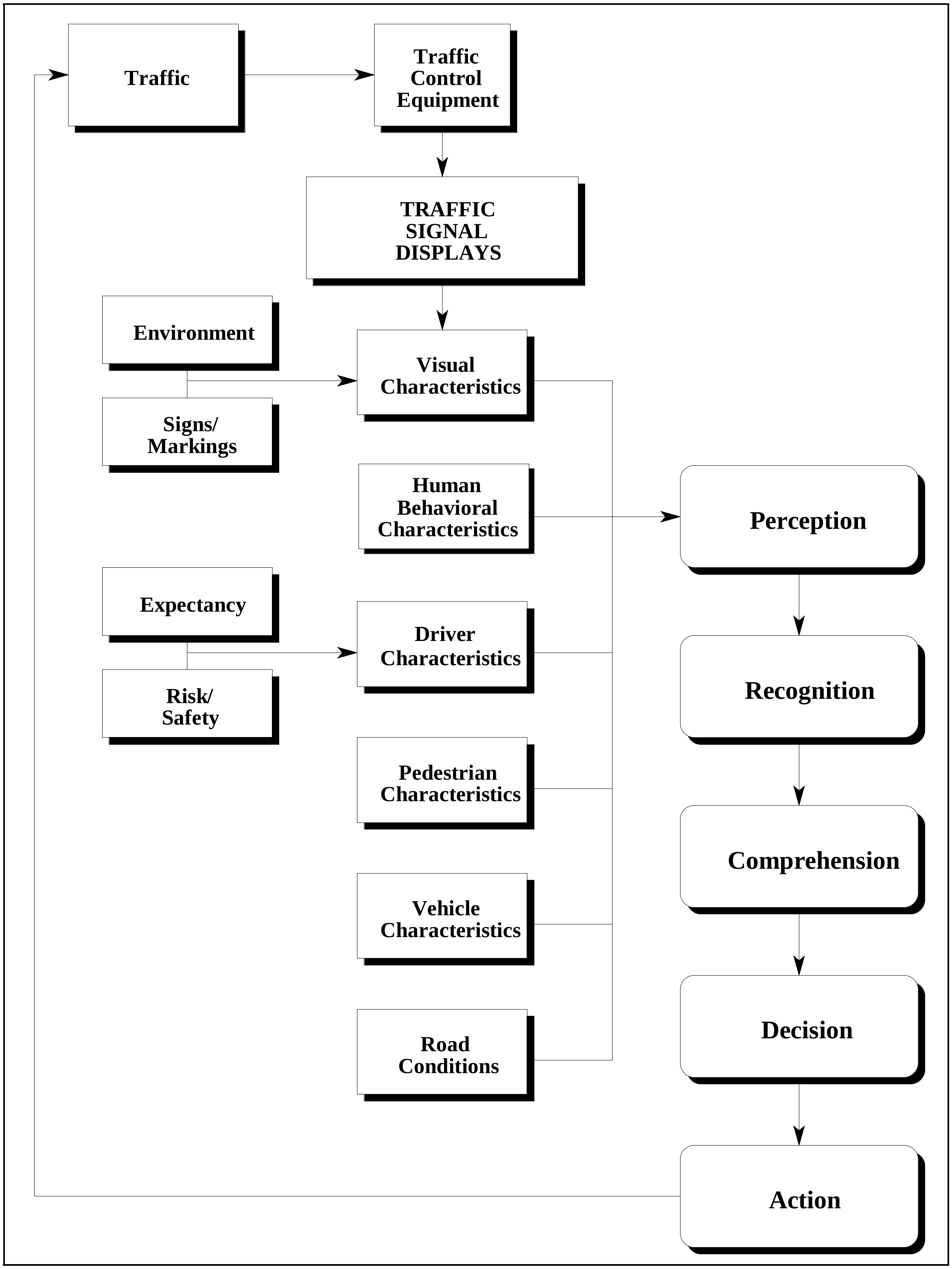

Figure 2 Basic Elements in the Traffic Signal Display and Driver Interaction.

Understanding drivers' target search process is compounded when age is included, as age negatively influences memory scanning and visual search, particularly in terms of accessing information needed for left-turn decision making (*6*). Nevertheless, target search can be described as driven in part by cognitive factors related to the expectancy of where in the visual field a target or the most useful information is likely to be found. One would expect that these areas would not only be fixated on first, but also most frequently.

In a 1972 study on the target search process, Mourant and Rockwell studied differences in target search and scan patterns between novice and experienced drivers (*7*). The researchers concluded that experienced drivers had a wider visual scan pattern and obtained additional information from cues located further down the roadway. The novice driver was found to act in quite the opposite manner with a very limited visual scan pattern. One can conclude that the experienced drivers' ability to attend to more sources of information would allow for earlier recognition and response to traffic signal displays.

The fact that much of the visual search behavior is internally driven by cognitive factors means that there are no highly consistent *physical* patterns of display scanning and no optimal scan pattern, beyond the fact that a search should be guided by the expectancy of the target location (*4*). There is little doubt that the nature of traffic signal indications with large, bright colored indications draws visual attention, yet there may be more subtle factors related to the physical locations on the display.

Megew and Richardson determined that subjects who conducted systematic scan patterns when searching for visual targets often start in the upper left part of the display (*8*). Others have found that search patterns may in fact begin in the center of the display, avoiding the outer edges (*9*). The problem lies in the fact that search tendencies are neither consistent nor strongly dominated by internally driven scan strategies. Further, driver response time and errors also increase with the number of action and display choices within the associated search patterns.

Perception and Reaction

Human factors issues related to drivers' perception and reaction is important in understanding the effectiveness of a traffic signal display. Woodson has identified the following principles that enhance perception and reaction to traffic signal displays (*10*):

Conspicuity - The traffic signal display should attract attention and be located where drivers are looking. The three major factors that determine the level of attention drivers devote to a traffic signal display are prominence, novelty, and relevance.

Emphasis - The most important information-carrying aspects of the traffic signal display should be emphasized or highlighted in some way. For example, the size of display or the intensity of the display can be increased.

Visibility - The traffic signal display should be visible under all expected viewing conditions.

Maintainability - The traffic signal display structural design, material composition, and the associated placement should be chosen to minimize damage resulting from aging, environmental wear, or vandalism.

Legibility - The contrast between the traffic signal display indications and their background should be maximized.

Intelligibility - The traffic signal display should tell the driver what to do and when to do it.

Standardization - Standard and consistent traffic signal displays and associated indications within each display should be used.

Conspicuity, emphasis, and visibility all relate to the drivers' perception of the signal display. Conspicuity, like visibility and legibility, is not an observable characteristic of a display, but a construct which relates measures of perceptual performance with measures of background, motivation, and driver uncertainty (*11*). Changes in the luminance of the display can offset the performance decrements associated with uncertainty and complexity. For the display to be effective, the driver must be able to discern the traffic signal display from irrelevant sources of light and clutter, then associate the traffic signal display to the geometrically defined placement and intended traffic movement.

Proper maintenance of a traffic signal display influences perception. A defective or degraded traffic signal display may be missed or dismissed as inoperative. Understanding perception enables one to design traffic signal displays that ensure optimal perceptual performance. Perception is also important in that the driver confronted with a specific type of signal display designed for a specific movement (such as PPLT signal displays) identifies the display, and can determine which vehicle movements the signal display controls.

Legibility and intelligibility are the principles that affect the drivers' process of extracting the necessary information to make appropriate decisions. A key issue often associated with intelligibility is whether supplemental information is necessary to assist the symbolic depiction of the signal display indication. Study results considering the effectiveness of supplemental signs are inconclusive (*6*, *12*, *13*, *14*). Nevertheless, the signal display configuration and operation that provide the greatest levels of legibility and intelligibility will also result in the fastest reaction time (*15*). If, for example, two different displays are quite similar and have insignificant differences in error scores, with *A* being reliably responded to in less time than *B*, then the *A* display is superior. The effects of driver age must be considered in comparing the reaction time to signal displays as Allen found that drivers over the age of 70 required 1.5 seconds of additional time for signal display recognition (*16*).

Achieving swift and accurate perception requires that the appropriate signal display indication is illuminated, the driver pays attention in an appropriate way, and the appropriate setting of speed-accuracy criteria has been chosen. Ample time to perceive and respond to the traffic signal display is part of the speed-accuracy trade-off model. It has been shown that errors increase when drivers are asked to respond rapidly (*17*).

In addition to speed of response, the correctness of the action taken by the driver is a vital measure. Experience indicates that in both simulations and actual driving maneuvers, smooth negotiation of the intersection in response to command information provided by the traffic signal indication is indicative of good signal display design. If a driver hesitates before identifying the correct maneuver, there is a strong indication that the traffic signal display presentation may not be effective.

A recommendation for accommodating drivers at PPLT intersections is to carefully avoid the use of display elements that conflict with prior experience (*6*, *18*). The avoidance of conflicting information is even more important when considering the belief that older drivers are less able to inhibit such previously well-learned responses. Any technique that will enhance drivers' memory of signal characteristics should reduce sensitivity decrements and preserve a higher overall level of signal detection sensitivity. These techniques may include increased conspicuity, reduced uncertainty, and proper training of the signal observers (*15*). Improving the effectiveness of a traffic signal display may be as simple as applying the associated display arrangement and indications in a standard and consistent way.

Recognition and Comprehension

In the context of a simplistic sequential information processing model, the driver first recognizes the message and then comprehends its meaning. Recognition of a traffic signal display is a measure of drivers' ability to identify the contents or component parts of the traffic signal message and corresponding response. Response is a measure of driver recognition and is equated to how much time it takes for a driver to identify the traffic signal's content. Similarly, comprehension is a measure of how well the driver understands the meaning of the traffic control device's message, as intended by its designer. Comprehension of a device can be measured by the number of drivers that correctly understand its intended message within an acceptable response time.

Considerable evidence shows that drivers can only comprehend a limited amount of information at any given time (*3*). The time to respond to an event depends on the number of other activities or events currently being attended to, how far ahead the event can be predicted, whether a subsequent important event is anticipated, the number of possible alternative responses, and the complexity of the response required. Researchers have developed several conceptual models to further describe this decision making process (*4*).

The safe and efficient movement of left-turning vehicles can be assisted by limiting the informational demands placed on drivers (*3*). Reductions in informational demands can be accomplished through the minimization of competing information, ensuring that traffic signal displays are visible and legible from a sufficient distance, and most important, by ensuring consistency and uniformity in traffic signal displays. Consistency and uniformity in traffic signal displays lead the driver to single simple decisions and allow more time to be allocated to other driving tasks.

Conspicuity, recognition, and comprehension are often used to evaluate the operational performance of a traffic signal display (*19*). Conspicuity related a particular device can be difficult to measure due to the many competing information sources that exist on a roadway. Moreover, the conspicuity of a traffic signal is generally not in question, but rather, its ability to convey the correct message. Thus, recognition and comprehension may be the most important measures of signal display performance.

Driver Expectancy

The literature contains the results of many studies designed to evaluate drivers' recognition and comprehension related to various types of signal displays (*12*, *13*, *19*). Surprisingly, researchers often overlook some basic principles of drivers' interpretation of signal displays, including the important concept of driver expectancy. Driver error related to the position of a traffic signal display, intersection geometry, traffic characteristics, or operational considerations may not be the sole sources of drivers' misinterpretation of signal display indications, but may be confounded with the drivers' interpretation of the display and expectancies associated with scanning for the correct information. Australian researchers believe that the level of driver expectancy is maximized when traffic signal displays are placed in a uniform and consistent fashion at signalized intersections (*3*). Signal display visual search requirements are minimized and driver comprehension related to the signal display improved.

A common form of expectancy theory incorporates a *vigilance paradigm*, which is simply a common application of signal detection theory (*4*). Simplified, the paradigm includes a driver whose is required to detect common signals over various time periods. Over time, drivers show higher miss rates of signal detection and lower probability of making a correct response. The reasons for this extend into adjustments of individual response criteria in response to varying expectancies of target events. As detection signals are missed or misunderstood, the likelihood of further misses increases. Thus, to reduce the negative effects associated with the level of response criterion, variables that reduce the sensitivity of the display must be implemented to increase the expectancy effects of the paradigm.

Variability in signal displays can lend itself to increased signal detection error and violations of driver expectancy (*20*). First, driver expectancy can be violated when a horizontally mounted signal display and corresponding lens arrangement are observed at location *A* followed by a completely different mounting and arrangement at location *B*. Secondly, not only must drivers visually observe the signal display, they must also understand the meaning of the signal indication and make the appropriate driving decisions. Finally, drivers must know where to look to find the information that they desire and be able to interpret, select, and obtain the correct information.

The need for uniformity in traffic signal displays as it relates to driver expectancy has been well documented (*21*). Expectancies will be formed by driver experience and training and will affect the drivers' readiness to respond to common situations in predictable and successful ways. Expectancy will also affect how drivers' perceive and handle information, and the time required to process and react to this information. Reinforced expectancies, through uniform presentation of traffic signal information, help the driver respond rapidly and correctly to the intended control message. The unusual, unique, uncommon, or inconsistent situations that violate expectancies lead to longer response times, inappropriate responses, and ultimately, driver error (*22*).

Signal Display Complexity

Ideally, traffic signal displays should provide the minimal level of complexity that is acceptable to all drivers. Quiet often, however, traffic signal displays are too complex for a subset of drivers. Complex signal displays are those where misinterpretation may result from simultaneously viewing multiple signal messages (*5*). From a human factors standpoint, traffic signal display complexity can be divided into basic behavioral dimensions. These include quantifying the number and distribution of information sources, the amount of perceptual processing required to integrate this information, and the decision making workload in selecting among several potential alternative actions.

Traffic signal display complexity is not only a human factors issue, but it is often considered a combination of both human factors and traffic engineering variables. The human factors variables can be broken down into basic behavioral dimensions including (*5*):

- Number and distribution of data sources;
- The visibility and conspicuity of signal displays for different approaches;
- The amount of perceptual processing required to integrate necessary information; and
- The decision making workload in selecting among several potential alternative actions.

Traffic engineering complexity problems are considered to be derived from:

- The configuration and arrangement of signal displays and combination of signal indications;
- Geometric conditions where the proper behavioral action for stopping/proceeding is unclear;
- Phasing for turn lanes where PPLT movements take place; and
- Need for supplemental signs.

Complexity of traffic signal displays can be related to the concept of driver workload, or demands placed on the attention of the driver by subsidiary influences. Left-turn maneuvers tend to increase driver workload which exacerbates the complexity of traffic signals. In an investigation of response time to traffic signs, Dewar and others found that reaction time to traffic signal messages increased with both processing workload and additional task demands (*23*).

Complexity also becomes pertinent in understanding how much of the visual field the driver can evaluate. Engel found that conspicuity of targets decrease, in terms of the probability of detection, when objects were more than five degrees off the line of sight (*24*). Similar research in Australia found that the probability of detecting objects superimposed on driving scenes decreased significantly when moved from six degrees to 12 degrees off the line of sight (*25*).

Allen and Hill looked at a wide array of factors that may lead to traffic signal complexity (*5*). Evaluating 134 drivers in California, Florida, Pennsylvania, Virginia, and Washington, Allen and Hill found that supplemental signing leads to the greatest deterioration in subject performance concerning significant misunderstanding and long response times. Signal indications that prohibit movements, such as red arrows and red and yellow balls, generally gave the best performance. Protected indications gave the poorest performance while permissive indications gave intermediate results. Traffic signal display complexity was determined to be a result of unclear and ambiguous signal indications and the added complexity of supplemental signing.

Allen and Hill identified the following as ways to decrease signal display complexity (*5*):

- Minimize supplemental signing;
- Minimize simultaneous viewing of conflicting displays between separate approaches and/or intersections;
- Establish a clear, unique, and unambiguous meaning for each part of the protected and permitted left-turn movements;
- Place signal displays is a consistent location where each movement is apparent by placement; and
- Assure that all signal displays are conspicuous.

Some intricacies of traffic signal displays may not be appreciated by a portion of the driving public which adds to the complexity problem. One cannot rely on implied meanings or meanings with perceived multiple alternatives that require significant deduction based on multiple display indications for the driver to comprehend. This point is emphasized in a study that included 300 driving educators in Texas (*26*). Signal display complexity associated with left-turn traffic signal displays was identified by the educators as the most difficult traffic control device for their students to comprehend.

SIGNAL DISPLAY COLORS

One of the most important variables related to the conspicuity of traffic signal displays is the color of each indication. The ability of most humans to see color makes detection or discrimination of different traffic signal indications possible. Objects *appear* colored because they reflect light from a particular region of the color spectrum. For an object to appear colored, light reflected from the object must be correctly processed by the human eye and nervous system (*27*). Because some people have abnormal eyes and nervous systems, their experiences of color differ radically from those that most people enjoy. It is this variable that has a direct bearing on the effectiveness of traffic signal displays.

The *color* of traffic signal indications, in terms of color perception, considers three different qualities (*27*). These qualities are referred to as hue, brightness, and saturation. Hue refers to the quality that distinguishes the red, yellow, and green. Technically speaking, traffic engineers should refer to the red, yellow, and green *hue* of traffic signal indications, not the color. Brightness is related to the amount or intensity of light. This property allows the traffic signal indications to be described and changed from bright to dim. Saturation characterizes a color as pale or vivid. A comprehensive description of the color of a traffic signal indication requires a description of hue, brightness, *and* saturation.

The earliest traffic signal displays used variations of red, yellow, and green indications, largely determined by available color medium. Over time, indication colors were modified by manufacturing process, experience, and characteristics of the traffic signal (*28*). Ultimately, detailed specifications were developed by the Institute of Transportation Engineers (ITE), Commission Internationale De L'Eclairage, i.e., the International Commission on Illumination (CIE), and the Society of Automotive Engineers (SAE). CIE further developed a chromaticity diagram that defined the color boundaries (in nanometers) for red, yellow, and green signal indications (*3*, *29*).

Today, the color of a traffic signal display is most often developed by placing a filter material over a white light source. The intensity and chromaticity of the light emitted from a signal indication are dependent on the choice of filter material and are therefore interdependent. Changes in technology have led to the gradual replacement of filtered light sources with light emitting diodes (LED). Even with LED technology and the development of rigid color specifications, there remains no *optimum* green, yellow, and red indication color for traffic signal displays (*28, 29*).

The Human Eye

Three attributes of the human eye are important in the context of drivers' ability to perceive and respond to traffic signal displays (*3*). These attributes are visual sensitivity, visual acuity, and perception of color. Visual sensitivity refers to the ability of the eye to respond to luminance differences and contrast. The threshold for the detection of contrast rises with increased age. At 40 years of age, contrast requirements are 18 percent higher and at 65 years of age 80 percent higher than in young, ocularly fit persons (*3, 30*). Older drivers therefore require a higher target light intensity to arouse the same contrast response as younger drivers. One technique often used to increase the contrast between background luminance and the traffic signal display is the installation of backplates.

Visual acuity describes the ability of the eye to clearly distinguish fine detail. Visual acuity is quantitatively expressed by the ability of the individual to resolve one minute of arc in relation to a standard viewing distance of 20 feet (*27*). Normal visual acuity of drivers without refractive vision errors is 20/20, meaning that the individual can read at 20 feet what the average healthy person can read at 20 feet. Specifically, normal 20/20 vision is assumed to be the ability to resolve a target detail of one minute of arc at 20 feet, referred to as Snellen acuity (*15*).

Color perception is the result of the interaction of the visual sensitivity of the observer when the object is viewed. The spectral reflectance distribution of the object being viewed also effects the perception of color. Illumination under which the object is observed is significant since objects appear to be different in color in bright light (day) and low light (night) conditions.

Color vision research has confirmed that there are two types of photoreceptors in the human eye: rods, responsible for reception of low levels of light, and cones, responsible for reception of higher levels of light and color perception (*31*). The rods contain one type of photopigment, maximally sensitive at a wavelength of about 505 nanometers (nm). Short wavelength sensitive cones (S cones) are sensitive to wavelengths of approximately 420nm, medium wavelength cones (M cones) to wavelengths of approximately 530nm, and long wavelength cones (L cones) to wavelengths of approximately 560nm (*10*, *27*). In general, the eye is sensitive to a band of wavelengths from approximately 400nm to 700nm.

The three types of color receptors in the eye are linked into a system with two separate color channels; one red and green and the other blue and yellow, along with an achromatic channel (*31*). The yellow response is actually created by the interaction of red and green photopigments. Related aspects of the visibility of a traffic signal display, and the function of the eye, have been described by Adrian (*32*).

A small percentage of drivers, mostly male, have some form of deficiency in the eye that prevents them from seeing the colors associated with traffic signal displays as most others see colors, termed color deficient or color anomalous vision. Color anomalies are related to the alteration of a photopigment, whereas color deficiencies or dichromatism involves the genetic omission or loss of one photopigment (*31*). Color abnormalities range from a total lack of color vision (monochromat) to blue-green-yellow confusion (tritanopic dichromats; tritanomalous trichromats) and red-green confusion (protanopic and deuteranopic dicromats; protanomalous and deuteranomalous trichromats).

Monochromats have only one photopigment type which, according to the Univariance Principle, does not allow them to see color (*27*). An eye with only one photopigment is unable to distinguish one wavelength of light from another and thus all items appear as shades of gray. Incidentally, all drivers are monochromatic under conditions of dim light. Dichromats contain only two photopigments which allow for normal vision of color at some wavelengths, but confused or undistinguishable colors at other wavelengths. The normal eye contains three photopigments which provide the color perception properties which exist in most human beings. Abnormalities in color perception and vision are commonly, and in most cases, wrongly described as *color blindness*. Only drivers with monochromic vision, often associated with albinism, are truly color blind.

In most forms of color anomalous vision, the eye has the normal number of cones, but it behaves as though it had fewer than three types of cone photopigments. The predominate type of color vision abnormality in this case is the red-green deficiency associated with deuteranomalous trichromatism or deuteranope dichromatism and the genetic elimination of either the M or L cone (*27*, *31*). Protan-type drivers (protanopes) tend to have reduced sensitivity to reds (red appears very dark) and tend to use lightness differences as cues for distinguishing color. Protanopes have been found to have a reaction time to a red indication four times greater than drivers with normal color vision (*33*). Tables 1 and 2 provide a summary of the color deficiencies and anomalies associated with dichromatism and trichromatism (*27*, *34*).

Table 1 Colors Perceived with Dichromatism

Type	Missing Cone	Normal Vision Colors				
		Blue	**Green**	**Yellow**	**Orange**	**Red**
Protanope	L	Blue	None	Yellow	None	Black
Deuteranope	M	Blue	None	Yellow	Gray	Gray
Tritanope	S	None	Green	None	Orange	Red
Tetartanope	--	Red	None	Green	None	Red

Table 2 Color Anomalies with Trichromatism

Type	Cause	Color Anomaly
Protanomalous	Abnormal L-Type Pigment	Red Weak; Green O.K.
Deuteranomalous	Abnormal M-Type Pigment	Green Weak; Red O.K.
Tritanomalous	Abnormal S-Type Pigment	Blue weak; Yellow O.K.

Sekuler identified the many genetic and acquired abnormalities that lead to some form of color deficient or anomalous vision (*27*). Genetic causes are related to deficiencies in the inherited X-chromosome at birth; whereas, acquired abnormalities are related to ocular disorders such as glaucoma and the effects of diabetes. Another common cause is simply old age as drivers over 50 years of age begin to experience a yellowing of the eye's crystalline lens due to yellow pigment accumulation in the lens. Estimates of the number of drivers who have some form of color deficient and anomalous vision vary, but recent estimates state that approximately 10 percent of all men (eight percent of Caucasian; five percent of Asiatic; three percent of African/Native Americans) and one percent of women have some form of color deficiency (*27*).

A panel of experts, reviewing the federal vision standard for commercial motor vehicle carriers, recently changed the color vision requirements from "ability of distinguish red, green, and yellow/amber" to "a safe and effective response to traffic signals and devices" (*35*). This change was based on the opinion that drivers with color deficiencies present little risk to the traveling public since traffic signalization has been *standardized* and drivers have many other cues for safe and effective vehicle operation. Further, there is no evidence to suggest that drivers with red-green deficiencies have worse driving records than those without color deficiencies.

No research has been identified that finds a correlation between poor color visual performance and driver safety (*36*). This lack of research evidence may suggest that drivers with color vision abnormalities somehow compensate in their driving behavior to overcome their deficiencies, or simply reflects the difficulty in quantifying this relationship. Nevertheless, providing traffic signal displays and indications that drivers with color vision deficiencies can effectively comprehend stresses the importance of uniformity and consistency in application.

OLDER DRIVERS

The rapidly increasing number of drivers in the United States over the age of 65 requires special consideration of this segment of the driving population when analyzing improvements to traffic signal displays. It has been estimated that 20 percent of the United States population will be 65 years old or older by the year 2030 (*37*). This percentage is compared to approximately 12 percent of the population over the age of 65 today.

In addition to color vision abnormalities previously described, the human aging process leads to losses in other visual functions (*37, 38, 39*). The largest single factor contributing to declining visual performance in the aging eye is increased light absorption and scattering in the crystalline lens (*6*). Other age related decrements in vision include:

- Useful field of vision - degradation in ability to perform visual information processing, loss of peripheral vision, inability to ignore distractors and to prioritize divided attention tasks.
- Visual search - decrements lead to longer response times, exacerbated by visual clutter.
- Visual spatial skills - deficits can affect interpretation and response to roadway milieu.
- A decrease in dynamic acuity - difficulty tracking objects moving slowly across the visual field at angular velocities greater than 10 degrees per second.

Further, the lens of the eye yellows with aging, reducing the amount of light reaching the retina and impacting color vision. Presbyopia diminishes the lens's ability to accommodate, contributing to the inability to focus on nearby objects. The ability to discriminate fine, stationary, high-contrast details declines. Cataracts and glaucoma are roughly eight times more common in drivers over the age of 65 than in younger drivers (*27*, *39*).

Visual abilities related to contrast sensitivity and glare recovery also experience age-related reductions. A 60 year old driver requires roughly three times the contrast as a 23 year old driver for the same level of target visibility (*6*). Glare from ocular media scatter can pose a serious problem at night, in rain, or in bright sunlight, but results in little difficulty on mildly overcast days. Nevertheless, a very high proportion of drivers over the age of 60 will show serious limitation in visual performance under at least *some* typical driving conditions.

Along with changes in visual abilities, the human aging process also leads to diverse changes in cognitive capabilities. The cognitive components involved in driving have been modeled by Wickens', as shown in Figure 3 (*4*). The driver first samples several information sources either simultaneously or sequentially. The driver then develops a hypothesis which is a prediction or forecast of a future event. Hypothesizing requires interplay between long-term and working memory. After processing, a choice of actions is developed and a response action selected.

The outcome of the decision, whether successful or not, can influence future decisions. Feedback provides this learning mechanism and opportunities to modify memory. Wickens' model emphasizes the parallel nature of drivers' processing of roadway information while identifying specific cognitive components that may define the location of age-related differences in driving performance capabilities.

Studies of working memory show an age effect favoring younger over older drivers. This age effect is probably due to a decline in storage capacity, reduced processing efficiency, or impaired coordination in these functions. As shown in Figure 3, working memory interacts with the decision and response selection cognitive functions and is continually updated as new information replaces previous inputs. This function is critical to the left-turn driving task as signal displays and roadway features must be sampled and stored temporarily as the basis for instant-to-instant vehicle control and the planning of downstream maneuvers. Thus, older drivers will be most at risk in situations that require rapid mental operations for vehicle control, such as the left-turn maneuver, especially when they are required to perform such operations and retain information for future use.

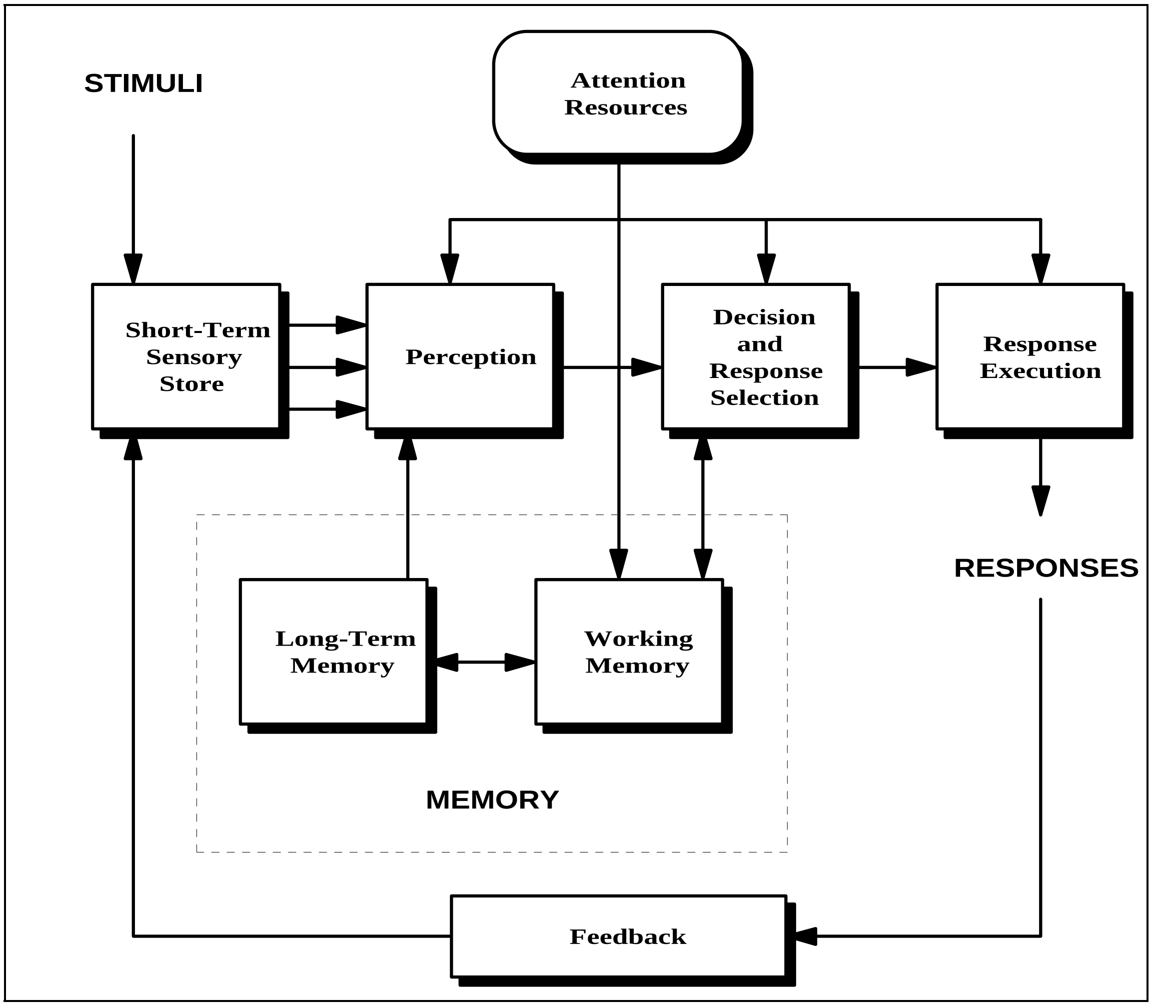

Figure 3 Theoretical Model of Cognitive Components in a Drivers' Processing of Traffic Signal Display Information (*12*).

Several related research efforts point to an overall decline in physical performance parameters in older drivers including (*38*, *40*):

- A decline in information processing ability starting at 45 years of age;
- A decline in dual task performance after age 60;
- Memory decrements resulting in slower time retrieving information from primary memory; may place older persons at risk in situations requiring rapid manipulation of information; short-term memory loss may affect appropriate responses;
- Attention-related decrements leading to deficits in visual scanning and other maneuvers that require rapid reorientation of attention; difficulties in refocusing attention quickly enough to respond to changing stimuli;

- Divided attention deficits that affect the speed at which information is processed as it affects prioritization of incoming information, often requiring more decision time-decision time can also be affected by visual clutter; and
- Additional time (estimated to be two seconds) to determine what to do when crossing an intersection and to decide on left-turn safety.

The operational significance of age-related differences in motor response capabilities regarding traffic signal displays should be negligible for a single response to a familiar display. For example, average brake reaction time following perception of a traffic signal display will be slowed by only one-tenth of a second for a 75 year old driver versus a 25 year old driver (*41*). If multiple responses in rapid succession are required, as when earlier vehicle control decisions must be overridden by a later response, then exaggerated increases in reaction time for older drivers would be likely. Demonstration of such deficits could have implications on the type and placement of traffic signal displays as well as the signal indications shown.

The safe and efficient use of traffic signal displays invariably depends on the parallel processing of information from all aspects of the roadway environment. Dynamic inputs of road surface features, other vehicles, navigational landmarks, competing signal displays and indications, and pedestrians—among all other stimuli—compete with signal display elements for drivers' limited attention resources. Since the human aging process can affect the ability of a driver to successfully process this diverse group of inputs, minimizing the number of inputs through uniform applications of traffic signal displays appears prudent.

PPLT SIGNAL DISPLAYS

The positive attributes of PPLT signal phasing cannot be realized unless this information is successfully presented to the driver. Drivers' response to a signal display, in terms of time, accuracy, and safety, depends on the conspicuity and clarity of the signal display along with the (*42*):

- Position of the signal display within the drivers' field of view;
- Ratio of signal-to-background contrast;
- Degree to which the appearance of the signal display is expected;
- Degree to which the precise location of the signal display and indication are known;
- Amount of competing information sources (i.e., visual clutter); and
- Degree to which the message conforms to the drivers' knowledge and expectations.

Guidance in the selection of signal displays, intended to maximize the elements referenced above, has been provided in the Federal Highway Administration's (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD) since its first edition in 1935 (*43*). The MUTCD has also been adopted as the national standard for traffic control devices in the United States. All traffic signal displays placed and maintained by governmental agencies or their representatives must conform (by federal statute) to MUTCD guidelines or to a state developed MUTCD supplement in substantial conformance to the national manual.

Although the intent of the MUTCD is to provide a national *standard* for traffic control devices, a lack of specific mandates in the selection and use of some traffic signal displays has led to a variety of applications. For example, when implementing PPLT signal phasing at a signalized intersection, the MUTCD indicates that a separate signal display for the left-turn maneuver is *not required* (*43*). If a left-turn signal display is provided, the MUTCD provides no specific directives and allows for variation in nearly all attributes of the display including arrangement, placement, and indication.

To accommodate the various signal indications required for PPLT signal phasing, a five-section signal display is generally recommended (*44*). The MUTCD allows the use of several five-section PPLT signal display arrangements, the most common being the five-section vertical, horizontal, and cluster, shown as displays *m*, *n*, and *s* in Figure 4. Again, substantial latitude is given as a four-section horizontal or vertical signal display may be used if the yellow and green arrow indications are contained within the same lens.

Because of the variability issues described above, there is a need for the standardization of PPLT signal displays. Standardization and uniformity can improve driver understanding and expectancy, ultimately improving safety for left-turn drivers. The issue of uniform PPLT signal displays is currently being investigated as part of NCHRP 3-54, "Evaluation of Traffic Signal Displays for Protected/Permitted Left-Turn Control." Ultimately, the selection of a uniform traffic signal display(s) will significantly rely on the human factors issues described above.

SUMMARY

An understanding of the human factors components related to traffic signal displays is necessary when a traffic engineer must select between an array of possible signal display types for implementation. In today's changing environment, the traffic engineer must also be aware of how the signal display will affect all potential road users, especially older drivers.

The literature provides only general guidance when considering human factors variables in the design of PPLT signal displays. There is little consensus as to how drivers visually scan for traffic signal display information and where the optimal position is when locating display information. Further, variability in drivers' perception, reaction, recognition, and comprehension of traffic signal displays due to such dynamic factors as age, cognitive state, ocular attributes, and signal complexity limit the ability of previous research to provide definitive results.

The safe and efficient movement of left-turn vehicles can be enhanced by limiting the informational demands on the driver. Drivers can only comprehend a limited amount of information at a time, and the information handling capacity is reduced as the complexity and the associated informational demands increase. Uniform and consistent PPLT signal displays can reduce the level of informational complexity placed on drivers. Driver expectancy is also an important consideration as signal displays that conflict with prior experience can increase complexity, informational demand, and driver error.

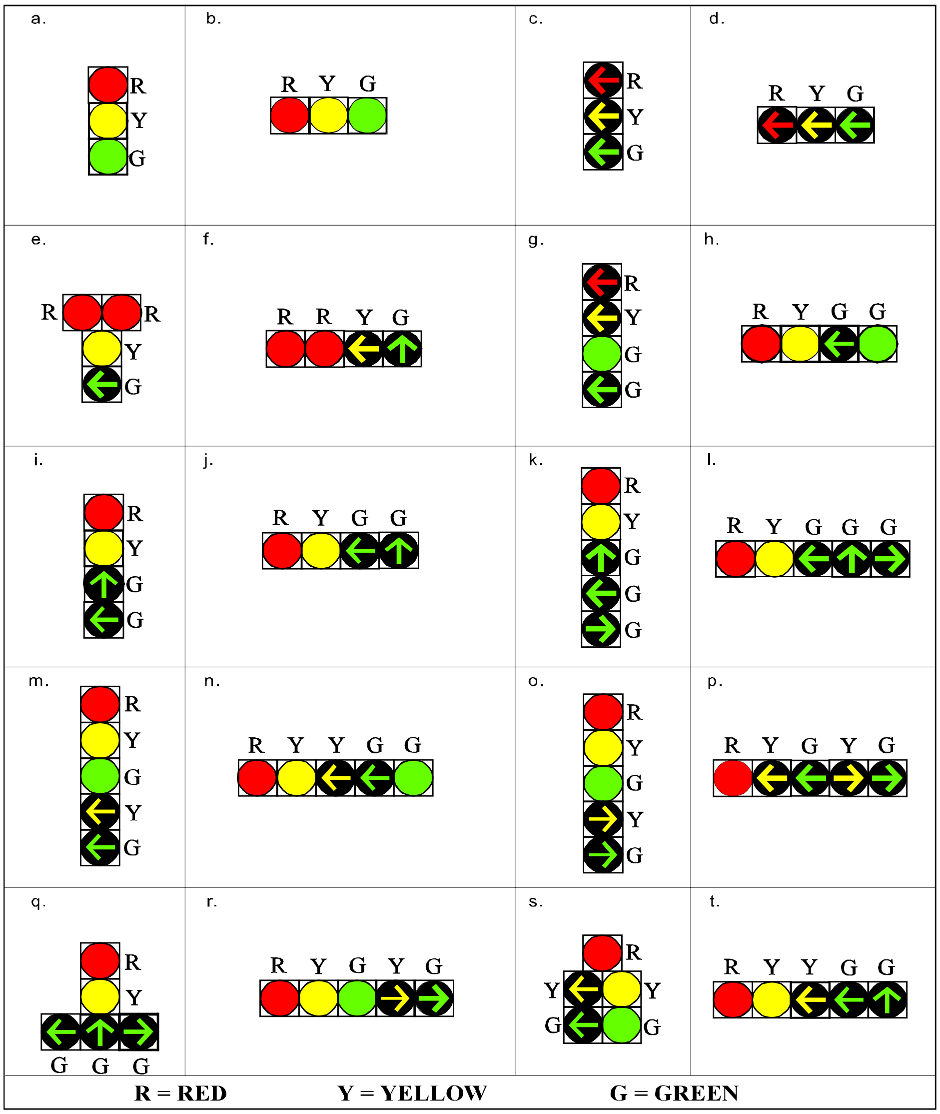

Figure 4 Typical Arrangements of Lenses in Signal Displays.

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