Luminous Intensity for Traffic Signals:
A Scientific Basis for Performance Specifications

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Final Report To:

LumiLeds Lighting, U.S., LLC
(A Joint Venture of Agilent Technologies and Philips Lighting)

Pacific Gas and Electric Company

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Executive Summary

This project evaluates light emitting diode (LED) traffic signals of different luminances relative to an incandescent traffic signal of the same nominal color and with the luminance implied by the Institute of Transportation Engineers (ITE) luminous intensity recommendations for 200 mm traffic signals (ITE, 1985).

The method used to evaluate the traffic signals is to simulate the task of steering a vehicle while approaching an intersection controlled by traffic signals. To do this, subjects viewed a large vertical wall from a distance of 2.0 m. The wall was divided horizontally into two parts, a lower portion simulating the ground and an upper portion simulating the sky. At the "horizon" was placed a small tracking task consisting of a small electric meter with a needle that continuously drifted in position. The subject made continuous adjustments of the voltage applied to the meter to keep the needle within a specified zone. Two and one-half degrees horizontally to left and right and two and one-half degrees vertically above the level of the meter were two circular apertures simulating signal lights. The luminance of the wall in the region of the tracking task and the signal lights was 5000 cd/m^2. The luminance of the signal lights could be provided by LEDs or by incandescent light sources. The luminance of the signal lights could be varied by changing the current through the LEDs and by using neutral density filters for the incandescent lamps. The chromaticity of the LED signals could be varied by choosing different LEDs. The chromaticity of the signals for the incandescent light sources could be varied by using filters.

Three experiments were conducted using this apparatus. In the first experiment, measurements were made of the reaction times to onset and the number of missed signals for red, yellow and green incandescent signals with a luminance corresponding to the ITE luminous intensity recommendations for 200 mm signals (ITE, 1985) and for red, yellow and green LED signals for luminances ranging from 1,018 cd/m^2 to 22,567 cd/m^2. The chromaticity of the signals for both LED and incandescent light sources were within the ITE chromaticity boundaries. Both signal lights were always presented using the same light source and at the same luminance and color. The presentation time for both signals was 1000 ms. The presentation of the signal and the measurement of the response were both computer-controlled. Ten subjects within the ages 25 to 35 years made the measurements, each subject seeing 50 presentations for 21 combinations of light source, signal luminance and signal color.

In the second experiment, 30 subjects in the age range 22 years to 54 years were shown all the combinations of light source, signal luminance and signal color used in the first experiment, for a single signal. After each presentation, the subject was asked to say what color the signal was from the available red, green or yellow, and to rate the brightness of the signal, its conspicuity against the background and how uncomfortable it was. The ratings were made on ten-point scales, with the ends labeled "very dark / very bright," "invisible / very conspicuous," and "not at all uncomfortable / very uncomfortable."

The third experiment was undertaken as a supplement to the first experiment, a supplement being necessary to determine the detailed relationship between signal luminance and the number of missed signals. Six subjects from the ten who took part in the first experiment (all who were available) took part in the third experiment. The procedure used was identical with that of the first experiment. However, the range of signal luminances examined was limited to 1000 to 5000 cd/m^2 and only the LED signals were used.

From the analysis of the extensive data collected, it is concluded that:

- There is no difference in mean reaction time, mean number of missed signals, percentage correct color identification and rated brightness and conspicuity for a simulated incandescent and LED traffic signal of the same luminance and the same nominal color.

- At the luminances corresponding to the ITE luminous intensity recommendations for a 200 mm signal there is a difference in the ability to detect the red, yellow and green signals, regardless of light source. The reaction times are shortest for the yellow signal and longest for the green signal.

- Higher signal luminances are needed for the yellow and green signal colors to ensure they produce the same reaction time, the same percentage of missed signals and the same rated brightness and conspicuity as a red signal at a given luminance.

- There is a hint that the greater saturation of the green LED signal relative to the green incandescent signal produces a greater perception of brightness and conspicuity.

Further, equations have been fitted to the reaction time data, the missed signal data, and to the ratings of brightness and conspicuity for the LED signals. These equations can be used to make quantitative predictions of the consequences of any proposed changes in signal luminance for reaction time, missed signals, brightness and conspicuity. For the simulation used in this project, any reduction in signal luminance will lead to an increase in reaction time, and a decrease in signal brightness and conspicuity. The reverse is true for any increase in signal luminance. As for missed signals, the effect of a change in signal luminance depends on the starting point. At high luminances, a reduction in luminance will initially make no difference to missed signals but as the luminance continues to decline, the number of missed signals will start to increase. The equations allow the magnitude of these changes to be quantified for any proposed alteration in signal luminance. These equations should be useful for determining the consequences of any proposed change in traffic signal luminous intensity standards.

It is important to note that these results are based on exposure to a high luminance background simulating the daytime sky for a group of young subjects. Other conditions, such as night-time viewing, with and without other lighting present, and other subject groups, such as the elderly, deserve to be examined to ensure that the conclusions reached are robust for all situations in which signal lights have to be seen. Further, the rise times of the LED and incandescent signals used in these experiments were identical. A future study will determine whether the more rapid rise time of LEDs makes a difference to the detection of the traffic signals viewed off-axis.

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1. Objective

This project has been undertaken with the objective of evaluating light emitting diode (LED) traffic signals of different luminous intensities, relative to an incandescent traffic signal of the same nominal color and with the Institute of Transportation Engineers (ITE) recommended luminous intensity for 200 mm signals (ITE, 1985).

The fundamental assumption behind this project is that traffic signals using incandescent lamps and producing the ITE recommended luminous intensities (ITE, 1985) are widely used and are acceptable in practice. This project examines

- Reaction time to onset,
- Percentage of missed signals,
- Number of signal colors correctly identified, and
- Perceptions of brightness, conspicuity and comfort,

for LED signals at difference signal luminances relative to incandescent signals of the same nominal color and with a luminance corresponding to the ITE Standard: Vehicle Control Signal Heads (ITE, 1985). All these measurements have been made for signals seen against a high luminance background, simulating daytime conditions. It is hoped that the data produced by this project will be used to inform any revisions of the ITE interim specification for LED traffic signals: Vehicle Control Signal Heads - Part 2: Light Emitting Diode Traffic Control Signal Modules (ITE, 1998).

2. Method

The method used to evaluate the traffic signals is to simulate the task of steering a vehicle while approaching an intersection controlled by traffic signals. This approach is the same as that used by Cole and Brown (1966) in their study of the optimum luminous intensity for red traffic signals for normal and protanopic observers.

2.1 Apparatus

To make the simulation, a subject sits at a distance of 2.0 m away from a large vertical wall (2.44 m x 2.44 m, subtending 50° both vertically and horizontally at the subject's position), (Figure 1). The vertical wall is divided horizontally into two parts (Figure 2). The boundary between the two halves of the vertical wall is set at 1.10 m above the floor. The upper part of the wall is painted matte white (reflectance = 0.87) and the lower half, matte gray (reflectance = 0.17). This large vertical wall simulates a driver's view along a straight road in flat country, the upper part being the sky, the lower the ground.

At the center of the vertical wall, touching the horizontal division but entirely in the upper part, is a small meter (4.75 cm vertically and 1.9 cm horizontally, subtending 1.4° vertically and 33 min arc horizontally at the subject's position) with a horizontal pointer that can be moved by changing the voltage applied (Figure 2). This meter forms a tracking task for the subject. The system controlling the voltage applied to the meter provides a target voltage randomly selected from the range 0 to 10 V. The existing voltage is changed at a fixed rate until the target voltage is reached. At this point a new target voltage is randomly selected and the process repeated. If the subject were to do nothing the needle's position would vary continuously. The subject's task is to offset the voltage driving the needle to keep the needle within a vertical linear range of 1.25 cm which corresponds to an angular dimension of 21 min arc at the subject's position. The range within which the needle has to be kept is painted green while the areas outside this range are painted red. This tracking task requires continuous adjustment and keeps the observer's attention focused on the needle.

2.5° vertically above the dividing line and 2.5° horizontally, left and right of the center of the meter, are two small circular apertures (4 mm diameter) (Figure 2). Each of these apertures simulates a single color traffic signal. The 2.5° deviations, horizontally and vertically, from the subject's direct view of the meter were chosen because they represent the deviation from the normal to the face of the traffic signal of the maximum luminous intensity recommended by the ITE. The size of the apertures is 4 mm diameter, a dimension scaled to subtend the same angle at the subject's position that a 200 mm diameter traffic signal does when seen at 100 m. This distance is considered to be the minimum distance at which traffic signals need to be clearly seen when driving on an urban road (Schreuder, 1981; Janoff, 1991).

Visible through each aperture is the interior of a small integrating sphere. The use of an integrating sphere ensures that the luminance of the signal is insensitive to small head movements so the subject's head does not have to be fixed using a chinrest or a bite bar. The integrating sphere can be lit internally by one of three different LEDs, corresponding to a red, green or yellow traffic signal. The integrating sphere can also be lit from outside by a beam of filtered tungsten halogen light, the filtering being designed to produce a spectrum matching the spectral power distribution of incandescent red, green or yellow traffic signals. The luminance of the integrating spheres can be varied by changing the current through the LEDs and by inserting neutral density filters in the tungsten halogen beams before they enter the integrating spheres.

Figure 3 shows a schematic of the optical system used to create one traffic signal stimulus. Inset is the arrangement used for the two traffic signals seen through the vertical wall. The LED light sources are permanently installed in the integrating sphere. The beam produced by the tungsten halogen MR16 light source is first filtered to remove the infra-red radiation and then passed through a dual-motorized filter wheel. One of the two filters in the path is a neutral density filter which produces the required signal luminance and the other is a color filter that creates the CIE chromaticity coordinates required for each signal. After leaving the filter wheel, the beam passes through a condensing lens and mirror designed to focus the light onto the input port of the integrating sphere through a reflecting cone. The exposure of the traffic signal to the observer is controlled by an electromechanical shutter mounted across the exit port of the integrating sphere. This shutter has an opening time of 3.5 ms. The selection of the light source, luminance and color of the signal to be presented to the subject is controlled by Labview (Version 5.1) software. This has been written to ensure that both light sources can be brought to full light output before being presented to the observer, at which point the shutters ensure that the rise time of luminance is the same for both LED and tungsten halogen light sources. Both signals were always presented with the same color and the same luminance, at the same time and for the same time duration. The Labview software also allowed the different combinations of signal color and luminance to be presented in random order for each subject.

The luminance of the large vertical surface, which is assumed to simulate the sky, was set to 5000 cd/m^2 in the area containing the tracking task and the signal apertures. This value is similar to the luminance used by Cole and Brown (1966) for their background. Figure 4 shows a contour plot of the luminance distribution over the “sky” part of the vertical wall visible to the subject. The illuminance that produced this luminance distribution was provided by two 1000 W sulphur lamps hung from the ceiling, both aimed at the display area of the vertical surface (Figure 1). One sulphur lamp could be dimmed while the other could not. In front of each sulphur lamp was a diffusing panel; the spectrum of one lamp was corrected with a magenta filter. The lamps produced light with a continuous spectrum. The CIE 1931 x, y chromaticity coordinates of the vertical surface in the display area were x = 0.3782, y = 0.3460. This chromaticity is slightly on the purple side of the black-body locus and corresponds to a CCT = 3846 K. The chromaticity coordinates of the color of the vertical surface varied slightly across the surface but without any obvious perception of a color difference. A white curtain was hung behind the sulphur lamps, shielding the view of the lamps from the subject. This curtain restricts the vertical angle subtended by the “sky” part of the wall at the subject’s eyes to 20°. All other lighting in the room was switched off.

The subject sat 2.0 m from the vertical surface and viewed the tracking task at near-normal incidence. In front of the subject was a small table on which was stood the response panel (Figure 1). The response panel had a simple flip switch on the sloping front and a rotating knob on the right-hand side. The rotating knob was used to offset the voltage on the tracking task so that the subject could keep the needle in the green area. The flip switch was used in the measurement of the simple reaction time to the onset of the light in the apertures. The subject held the switch down and as soon as he/she detected the onset of the light, released the switch. While doing the simple reaction time measurements, the subject wore headphones through which white noise was played. This was necessary to prevent the subject from hearing the movement of the shutters that control the presentation time of the signal lights through the apertures. The white noise also provided feedback to the subjects about their performance on the tracking task. If the needle of the tracking task moved outside the green zone into the red zone, the sound pressure level of the white noise was increased noticeably and was only reduced to its original level when the needle moved back into the green zone. The white noise was also used to acknowledge receipt of the reaction time response. On releasing the flip switch to indicate detection of the onset of the signal light, the sound pressure level of the white noise was noticeably reduced and only restored to its original level when the flip switch was held down ready for the next signal presentation.

2.2 Photometric measurements

The ITE recommendations for traffic signals are given in terms of luminous intensity in specified directions, for signals of a specified size (ITE, 1985, ITE, 1998). Given that both luminous intensity and signal size are specified, the standard could equally well have been given in terms of the average luminance of the signal face but this would have made photometric measurements more difficult and expensive to undertake. However, it is luminance that describes the stimulus a signal presents to the visual system, so when simulating a traffic signal with a smaller size than that used in practice it is the luminance of the signal that has to be preserved. Table 1 summarizes the minimum luminous intensity on the reference axis specified by the ITE for 200 mm diameter, round, incandescent signals (ITE, 1985) and 200 mm diameter, round, LED signals (ITE, 1998) and the equivalent luminances.

Table 1. ITE recommendations for 200 mm diameter, round traffic signals and the associated luminances (ITE, 1985; ITE, 1998)

Signal color	Luminous intensity for incandescent signals (cd)	Average luminance for incandescent signals (cd/m^2)	Luminous intensity for LED signals (cd)	Average luminance for LED signals (cd/m^2)
Red	157	5,000	133	4,250
Yellow	726	23,121	617	19,652
Green	314	10,000	267	8,500

To ensure that the apparatus, as constructed, did provide the average signal luminances defined by the ITE recommendations and to define the other luminances used, photometric measurements of signal luminance were made. Luminance measurements of the signals are complicated for the following reasons:

1. The signal presentations were presented with periods of 1000 ms or less. Continuous operation of the LEDs was not possible because self-heating affects the light output and emission spectra.

2. The narrow-band spectra of the LED sources and the filtered incandescent sources make the photopic spectral response of the measurement instruments very critical.

3. The small size of the signals (4 mm diameter) requires a narrow angular response (small spot size) luminance photometer and provides a low overall signal strength despite the relatively high signal luminance.

Luminance measurements of the signals were performed on three occasions; immediately prior to the first experiment in order to set the desired conditions, and twice at the completion of the second experiment using two methods employing different measurement methods and equipment. A PhotoResearch Model 705 spectroradiometer was used to measure luminance and chromaticity at the start and end of the experiments. The 705 has a single grating for wavelength dispersion, a temperature controlled photodiode array detector element and Prichard-style viewing/measurement optics. The spectral bandwidth is approximately 2.5 nm over the wavelength range of 380 to 780 nm with a measurement area corresponding to a 7.5 min arc viewing angle.

Precise triggering of the spectroradiometer measurement exposure to synchronize with the onset of the signal was not possible. Therefore, a measurement technique was used that did not rely on precise triggering, but only on the accuracy of the flash duration and exposure duration times. Spectroradiometric measurements of the signal were taken for an exposure duration of 5000 ms. Within the 5000 ms period, the signal would flash for a period of time between 50 ms and 1500 seconds. The flash period varied depending on the radiance of the signal necessary to attain a large signal-to-noise ratio without saturating the detector. The luminance of the signal was calculated as the product of the average luminance measured over the exposure time and the exposure time divided by the flash duration.

The flash duration was measured on a separate occasion using a digital storage oscilloscope monitoring the signal from a PIN photodiode in direct view of the signal. Flash duration was measured over the range of those encountered during the luminance measurements and the data were fit with a linear function relating flash duration (measured optically) to loop cycles of the microprocessor used for controlling the flash duration. For the luminance measurements flash duration was then calculated from the microprocessor loop cycles. The measurement resolution is better than 1 ms.

The filtered incandescent signals could be measured as steady signals and were measured as such prior to the first experiment, but measured using the above technique at the end of the second experiment.

To verify the accuracy of the spectroradiometric measurements an alternative luminance measurement method was performed at the end of the second experiment using an LMT model P30SC0 broadband silicon photodetector having a highly accurate mosaic photopic color correction (f1' = 0.4%). The illuminance due to the signal was measured at a precisely known distance. The luminance of the signal was calculated knowing the geometry of the set-up. For this particular measurement set-up:

$$L = E*d^2/A$$

Where

L = signal luminance (cd/m^2)

E = illuminance (lx) measured a distance, d, in front of and in the direction of the surface normal of the signal,

A is the area of the signal (m^2).

The accuracy of this measurement technique is highly dependent on the accuracy of the distance and signal area measurements. Nevertheless, the luminance ratios of the different color signals can be accurately attained for a static geometry as the case is here.

The results of the measurements show variations up to 25% for the different measurement techniques (flashed signal, steady signal or calculation from illuminance) and times, but most variations were in the range of 5 to 15% from the desired luminance settings. A small amount of this variation (about 5%) is attributable to changes in the apparatus and conditions over the course of the experiments. For example, the red and yellow LED signals all measured about 5% higher at the end of the second experiment, most likely due to a drop in room temperature.

The luminance values used for data analysis are the averages of the different measures taken at the start and end of the experiments and using different techniques. Since there are no noticeable systematic differences between the left and right side signals, the three measures for each side were combined to arrive at six separate measurements for each signal condition.

The chromaticity of the signals was calculated from the same spectroradiometric data used to determine luminance. The CIE (1931) chromaticity coordinates used to characterize the signals are averages for the four chromaticity measurements taken (measurements of the left and right sides prior to the first experiment and at the end of the second experiment). Each of the four chromaticity measures for the LED sources is the mean of at least ten measurements taken at different LED drive currents over the range of currents used in the experiments. The range of chromaticity values for the different pulsed drive currents is equal to or less than the variation of measurements taken at different times.

2.3. Performance measurements

2.3.1 Measurement of simple reaction time and missed signals

The simple reaction time to the onset of a signal and the number of missed signals was measured in the first and third experiments, as follows:

The subject viewed the tracking task and kept the needle within the green zone by adjusting the rotating knob on the response panel. At the same time the subject held down the flip switch. Holding down the flip switch was the signal to the software that the subject was ready; this started the time sequence for presentation of both signal lights as a stimulus. Both signal lights were presented at the same time and luminance at some time between two and five seconds after the flip switch was held down. The actual time delay was randomized, subject to the constraint that the needle of the tracking task was in the green zone at the moment of presentation. If the needle was in the red zone when the signal lights should have come on, the presentation was delayed until the needle returned to the green zone. On detecting the onset of the signal light, the subject released the flip switch. This turned off the signals. The reaction time was measured as the time interval between the onset of the stimulus and the release of the response switch. If the subject had not released the switch 1000 ms after the onset of the signal lights, the lights were extinguished, the reaction time was counted as 1000 ms and marked as a missed signal. If the subject's reaction time was less than 200 ms, it was assumed that the response involved some anticipation and so it was rejected and another presentation of the same stimulus was made to replace the one rejected. The response for each presentation was stored in a computer file. When the subject was ready to continue, he/she simply held down the flip switch.

This process was repeated for 10 successive presentations at the same signal luminance and color. In the first experiment, 21 combinations of light source, luminance and color were presented in sets of 10, in one session, in random order. In the third experiment, 13 combinations of signal luminance and color were presented in sets of 10, in one session, in random order. Only the LED light sources were used in the third experiment.

Table 2 shows the luminances used for each type of light source in one session in the first experiment. These luminances are averages of the measurements made in different ways at different times, as described in section 2.2. The standard deviations for the mean luminances are all less than 10% of the mean luminance. Each session took about one hour and every subject performed five sessions, giving a maximum of 50 reaction times or missed signals collected from every subject for each combination of luminance, color and light source used.

These mean luminances were aimed at target luminances chosen with a number of criteria in mind. First, the luminances of the incandescent stimuli should be what would be produced by a 200 mm diameter signal having a luminous intensity corresponding to the recommendations of the ITE for incandescent signals used in the United States (red = 5000 cd/m^2; yellow = 23,121 cd/m^2; green = 10,000 cd/m^2). Second, one of the LED stimuli should have the same luminance as the incandescent stimulus of the same color. Third, the other luminances of the LED stimuli should cover a wide range and include one that pilot trials showed could be expected to produce a clear increase in reaction time, typically around 1000 cd/m^2. Fourth, for the LED stimuli all three colors should have at least one luminance the same. Fifth, the LED stimuli should include luminances corresponding to one of the luminous intensities recommended for 200 mm traffic signals in Europe (European Committee for Standardization, 1998) and Japan (National Police Agency, 1986) (Europe, Performance Level 3: Red, Yellow and Green = 12,732 cd/m^2; Japan: Red, Yellow and Green = 7,639 cd/m^2). A comparison of these target luminances with the mean measured luminances shows that the target luminances are almost all within one standard deviation of the mean measured luminances.

For the green signal, some of the LED conditions (marked with an asterisk in Table 2) actually used the tungsten-halogen light source rather than a green LED, due to limitations of the apparatus. For these conditions, the light emitted by the tungsten-halogen light source was filtered to have a spectrum and CIE chromaticity coordinates similar to the light emitted by the green LED. This approach was taken because luminances greater than 5000 cd/m^2 could not be achieved with the single green LED in the integrating sphere.

Table 3 shows the signal luminances used in the third experiment. These signal luminances were not measured. Rather, the earlier measurements of LED luminances as seen by the subjects enabled the currents necessary to produce the given luminances to be predicted. These signal luminances were chosen to fit within the range 1000 cd/m^2 to 5000 cd/m^2 after the results of the first experiment revealed that the number of missed signals tended to increase markedly between 1000 cd/m^2 and 5000 cd/m^2.

The CIE 1931 chromaticity coordinates of the LEDs and incandescent light sources examined in the experiments are given in Table 4. Figure 5 shows the positions of these chromaticity coordinates for the different light stimuli used relative to the boundaries on the CIE 1931 chromaticity diagram defining the signal colors recognized by the ITE. All the signal colors used fall within the chromaticity coordinate boundaries, although there are differences between the LED and incandescent sources in the chromaticity coordinates produced, particularly for the green signal, where the light from the tungsten-halogen light source is much less saturated than from the green LED.

Table 2. The light sources used in the first experiment and the mean measured luminance (cd/m^2) together with the standard deviation.

Light Source	Luminance (cd/m^2) Mean	Luminance (cd/m^2) Standard Deviation
LED – Red	13,704	1264
LED – Red	8,205	736
LED – Red	5,319	402
LED – Red	3,626	273
LED – Red	2,115	146
LED – Red	1,049	58
Incandescent – Red	5,312	295
LED – Yellow	22,253	1,269
LED – Yellow	16,895	1,196
LED – Yellow	13,580	916
LED – Yellow	8,119	532
LED – Yellow	5,321	350
LED – Yellow	1,068	101
Incandescent – Yellow	22,567	965
Incandescent – Green*	11,819	784
Incandescent - Green*	9,334	614
Incandescent – Green*	7,171	432
Incandescent – Green*	6,352	559
LED – Green	4,596	225
LED – Green	1,018	45
Incandescent – Green	9,587	487

* Incandescent source filtered to provide similar color to green LED (see Table 4 and Figure 5).

Table 3. The light sources used in the third experiment and their signal luminances (cd/m^2).

Light Source	Luminance (cd/m^2)
LED – Red	1000
LED – Red	1500
LED – Red	2000
LED – Yellow	1000
LED – Yellow	1500
LED – Yellow	2000
LED – Yellow	3000
LED – Yellow	5000
LED – Green	1000
LED – Green	1500
LED - Green	2000
LED – Green	3000
LED – Green	4500

Table 4. CIE (1931) x,y chromaticity coordinates for the signal colors used.

Signal color	LED		Tungsten halogen	
	x	y	x	y
Red	0.7056	0.2932	0.7066	0.2919
Yellow	0.5707	0.4275	0.5793	0.4184
Green	0.0876	0.5064	0.2538	0.4222
Green (filtered tungsten halogen)	0.1209	0.4864		

2.3.2 Measurement of signal color, brightness, comfort and conspicuity

The measurements of perceived signal color were made in the second experiment, but using the same 21 combinations of light source, luminance and color used in the first experiment and specified in Tables 2 and 4. In this experiment, the subject viewed the tracking task and kept the needle in the green zone by adjusting the rotating knob on the response panel. While the needle was in the green zone, the right-hand signal was presented, as before, for 1000 ms. After the signal had been presented the subject was asked to say what color the signal light was from the available red, green or yellow, and to rate the brightness of the signal light, its conspicuity against the background and how uncomfortable it was. The ratings were made on ten-point scales, with the ends labeled “very dark / very bright,” “invisible / very conspicuous,” and “not at all uncomfortable / very uncomfortable.” Each subject was shown all the 21 combinations of light source, luminance and color of signal in a random order, once only, unless he/she requested to see a particular combination a second time, which happened rarely. The time taken to make all of these judgements was approximately 15 minutes.

2.4 Subjects

Ten subjects between the ages of 25 and 35 years and all with a current driving license were recruited from students and staff of the Lighting Research Center to take part in the first experiment. There were five males and five females. These subjects participated in the measurement of simple reaction times and missed signals.

Thirty subjects were recruited for the second experiment on color identification and brightness, conspicuity and comfort ratings. Some of them had taken part in the first experiment but the majority had not. These subjects had an age range of 22 to 54 years of age. There were 14 males and 16 females. More subjects were required for measuring the color identification and brightness, conspicuity and comfort ratings than for reaction time because of the greater variability common in such subjective measurements, relative to simple performance measurements such as reaction time.

Six of the 10 subjects who had taken part in the first experiment were available for the third experiment. The third experiment was undertaken to provide supplementary data on the effect of light source, signal luminance and color to that collected in the first experiment. There tend to be large individual differences in reaction time and missed signals, so only these six subjects could be used; no new subjects could be introduced at this time.

Each subject taking part in the first and third experiments was screened for visual function. Measurements of visual acuity, contrast sensitivity and color vision were made using a Landolt ring distance acuity chart, the Pelli-Robson threshold contrast chart and the Ishihara color vision test respectively. Only subjects with a visual acuity of 20/25 at 2.0 m, a contrast threshold below 0.1 and normal color vision participated. Subjects taking part in the second experiment on color identification and ratings of brightness, conspicuity and comfort experiment were not screened for visual function.

2.5 Training

Each subject commenced each experiment with a brief period of training. For the measurement of simple reaction times and missed signals in the first and third experiments, the subject undertook 10 simple reaction time measurements for one of the combinations of light source, color and luminance, selected at random. This was done to familiarize the subject with the apparatus.

For the measurement of signal color, brightness, conspicuity and comfort in the second experiment, every subject who had not done the reaction time experiment was shown all 21 combinations of light source, color and luminance. This showed each subject the complete range of conditions to which they were to be exposed.

3. Results

3.1 Reaction times

Reaction times are difficult to measure accurately, the greatest problem being the occasional long reaction time caused by inattention to the stimulus. To get a better measure of central tendency for the distribution of reaction times produced by each subject for each combination of light source, signal luminance and signal color, the data were treated as follows.

For each session of ten presentations of a signal produced by the same light source, at the same signal luminance and color, the median reaction time was calculated. The median is less sensitive to extreme values than the mean. Then the mean of the five median reaction times from the five sets of ten presentations made for the same light source, signal luminance and color was calculated, and so was the associated standard deviation.

The mean reaction time (and the associated standard deviation), for each color signal, for each subject, from the first and third experiments, is shown plotted against luminance in Appendix 1. Appendix 1 shows there are large differences between individual subjects in mean reaction time.

The mean reaction times for the LED signals, for each subject, plotted against the logarithm of the mean measured luminances were fitted with an equation of the form

$$y = ax^n + c$$

Where y = mean reaction time (ms)

x = signal luminance (cd/m^2)

c = minimum possible mean reaction time (ms), set at 200 ms

a and n are fitting constants.

Formulae of this type have commonly been fitted to reaction time data (Pieron, 1920; Pollack, 1968; Lit et al., 1971; Mansfield, 1973; He et al., 1997) and are consistent with the latency of the visual system response to stimuli of different luminous intensities (Vaughan et al., 1966). The minimum possible reaction time is also set by human physiology and has been shown to be around 200 ms (He et al., 1997). The values of the fitting constants for each subject, and the goodness of fit (r^2) to the data, for each subject, for each LED signal color, are given in Table 5.

Examination of Table 5 shows that while the variance explained (r^2) by the function fitted to the LED results is high for most subjects there are two (Subjects D and I for the red LED) where the variance explained is low. The poor fit for these subjects can be explained by the lack of variation in reaction time for the red LED signal.

Table 5. Fitting constants for an equation of the form $y = ax^n + 200$ fitted through the mean reaction times for each subject viewing the LED signals of a single color. Also given is the variance explained (r^2) for each fit and the reaction time for each subject at the luminances corresponding to the ITE recommended luminous intensities for 200 mm signals (green = 10,000 cd/m^2, yellow = 23,121 cd/m^2 and red = 5000 cd/m^2), (ITE, 1985).

LED color	Subject	a	n	r^2	Reaction time (ms)
Green	A	3483	-0.383	0.97	302
Green	B	4847	-0.326	0.69	441
Green	C	22835	-0.512	0.86	404
Green	D	1423	-0.187	0.73	454
Green	E	2969	-0.253	0.97	489
Green	F	340955	-0.860	0.99	324
Green	G	10030	-0.393	0.92	469
Green	H	6769	-0.374	0.71	406
Green	I	404720	-0.933	0.92	275
Green	J	6918	-0.405	0.91	366
Yellow	A	3057	-0.358	0.88	284
Yellow	B	8655	-0.401	0.92	354
Yellow	C	14111	-0.501	0.80	292
Yellow	D	1202	-0.175	0.92	407
Yellow	E	1457	-0.165	0.85	478
Yellow	F	102413	-0.711	0.98	281
Yellow	G	3499	-0.291	0.93	388
Yellow	H	1996	-0.245	0.90	370
Yellow	I	479726	-0.984	0.82	224
Yellow	J	5306	-0.386	0.83	310
Red	A	1940	-0.350	0.88	298
Red	B	7014	-0.411	0.91	412
Red	C	1161	-0.231	0.88	362
Red	D	381	-0.047	0.10	455
Red	E	1779	-0.201	0.73	521
Red	F	231158	-0.878	0.94	331
Red	G	1030	-0.160	0.87	464
Red	H	1216	-0.201	0.94	419
Red	I	25370	-0.640	0.59	309
Red	J	1141	-0.226	0.84	366

While these are interesting data they do not give a simple answer to the question "How does changing the luminance of the signal from that corresponding to the ITE luminous intensity recommendation alter the reaction time?". To provide a simple answer, the fitted curve for each subject, for each signal color, was normalized to 100 at the luminance corresponding to the ITE recommendation for the color of the signal. The reaction times for each subject, for each signal color, at the ITE luminance for that color are given in Table 5. Then the y-values on the curve for each signal color, for each subject, were calculated for a stepped series of luminances. Then, the mean y-value and the associated standard deviation were calculated for each luminance and color, for the subjects as a group. The results for each color of signal are shown in Figures 6, 7 and 8 plotted against signal luminance. Best-fitting curves were also calculated for each signal color. These curves, which are also shown in Figures 6, 7 and 8, allow a prediction to be made of the percentage change in mean reaction time for a departure of signal luminance from the ITE luminance. The procedure in making the prediction is to calculate the ratio of the percentage reaction time at the proposed luminance to the percentage reaction time at the ITE luminance and to multiply by 100. The mean reaction times at the ITE luminances are green LED = 393 ms; yellow = 339 ms; red LED = 394 ms.

This same operation can be applied to any standard for luminous intensity of 200 mm traffic signals, provided the luminance of the signal falls within the range examined. Appendix 2 shows the results of using the fitted curves for each subject and normalizing to the Performance Level 2 of the draft European Standard for traffic signals (European Committee for Standardization, 1998).

To check the stability of the best-fitting curves shown in Figures 6, 7 and 8, additional best-fitting curves were calculated using the same procedure but using the mean reaction times plus and minus one standard deviation for each subject as source data. The results are shown in Appendix 3. The fact that the percentage changes in reaction time are similar for the same signal color for all three data sets (mean reaction time, mean reaction time plus one standard deviation and mean reaction time minus one standard deviation) for the same signal color, indicates the predictive equations for percentage change in reaction time are robust.

3.2 Missed signals

The mean number of missed signals out of ten (and the associated standard deviation) for each combination of light source, luminance and color seen by each subject in the first and third experiments are shown, plotted against mean measured luminance, in Appendix 4. As would be expected, the number of missed signals varies markedly between individuals and increases as the luminance of the signal decreases. To provide an overall estimate of the probability of a signal of a given luminance and color being missed, the percentages of signals missed out of the total of 500 presentations made for each light source, luminance and signal color combination in the first experiment (five sessions, 10 presentations per session, 10 subjects) and for the 300 presentations made for each light source, luminance and signal color in the third experiment (five sessions, 10 presentations per session, six subjects) were calculated. Figure 9 shows the percentage of signals missed by the subjects as a group, for each luminance and signal color, for the LED and incandescent light sources. It is clear that the percentage of signals missed tends to increase with decreasing signal luminance and that this trend is most pronounced for the green LED signal and least for the red LED signal, over the range of luminances covered.

The best-fitting non-linear regression curves through the percentage of missed signals in Figure 9 are different for the three signal colors.

For the green LED signal, the best fitting curve is

$$y = 148.6\ e^{-0.0009x} + 2.655\ e^{-0.0001x}$$

For the yellow LED signal, the best fitting curve is

$$y = (-16.71 + 0.0016x) / (1 - 0.0014x)$$

For the red LED signal, the best fitting curve is

$$y = -3.60 / (1 - 0.0013x)$$

In all three equations

y = Percentage of missed signals

x = Signal luminance (cd/m^2)

The proportions of variance explained (r^2) by the fitted curves are green LED = 0.98; yellow LED = 0.99; red LED = 0.94. It should be emphasized that the these fitted curves have no theoretical basis and have been constructed simply to enable predictions to be made of the percentage of missed signals at different luminances within the range used. These equations should not be used outside the range of luminances examined for each signal color. These luminance ranges are given in Table 2. For convenience, the percentage of missed signals predicted by these equations for each signal color, for 500 cd/m^2 steps in signal luminance, over the range of luminances used for each signal color, are given in Appendix 5.

3.3 Color identification

For each of the 21 combinations of light source, luminance and signal color seen by the 30 subjects doing the second experiment, the color of the signal given by the subject was recorded and, if in error, the erroneous color listed. To provide an overall estimate of the probability of a signal color being correctly identified, the percentage of signal colors correctly identified by the 30 subjects for each light source, luminance and signal color combination was calculated. Table 6 shows the percentage of signal colors correctly identified by the 30 subjects as a group, at each luminance, for the LED and incandescent light sources. The smallest difference that can occur in the percentage correct color identification for any light source, signal luminance and signal color combination is 3.3%.

From Table 6 it is clear that the percentage of correct color identification is high for all conditions, even though the signal is seen off-axis. There is a slight trend for the percentage of signal colors correctly named to deteriorate at lower signal luminances for the yellow signal. Cochran Q tests were used to determine if the percentages of signal colors correctly identified were different for the LED and incandescent signals of the same nominal color and similar luminance. There were no statistically significant differences in percentage correct color identification for LED and incandescent signals of the same nominal color and similar luminance.

The patterns of the mistakes in color identification were consistent. Of the 10 misidentifications for the green signal made over 210 presentations (30 subjects, seven luminances), nine times the signal was said to be yellow and only once was it said to be red. Of the nine misidentifications for the red signal made over 210 presentations all nine involved the red signal being called yellow. Of the 16 misidentifications of the yellow signal made over 210 presentations, all 16 involved the yellow signal being called red. This pattern of misidentification is what would be expected from the separation of the chromaticity coordinates for the different signal colors shown in Figure 5. When it occurs, the green signal is mistaken for yellow rather than red because yellow is closer to green than is red. As for the yellow and red signals, the red and yellow signals are much closer together on the chromaticity diagram than either is to green.

This experiment requires the subjects to identify the signal color when the signal appears off-axis. In practice, once the signal had been detected off-axis, the subject would likely look directly at the signal. It is expected that the ability to identify the signal color would be enhanced when the signal is viewed directly.

Table 6. Percentage of signals of each color correctly identified by all the subjects as a group, for each luminance.

Light source	**Mean measured luminance (cd/m^2)**	**Percentage correct color identification (%)**
LED - Red	13,704	100
LED - Red	8,205	93
LED - Red	5,319	93
LED - Red	3,626	97
LED - Red	2,115	97
LED - Red	1,049	93
Incandescent – Red	5,312	97
LED – Yellow	22,253	100
LED – Yellow	16,895	90
LED – Yellow	13,580	97
LED – Yellow	8,119	93
LED – Yellow	5,321	83
LED – Yellow	1,068	83
Incandescent – Yellow	22,567	100
Incandescent – Green*	11,819	100
Incandescent – Green*	9,334	93
Incandescent – Green*	7,171	100
Incandescent – Green*	6,352	93
LED – Green	4,596	90
LED – Green	1,018	93
Incandescent – Green	9,587	97

* Incandescent source filtered to provide similar color to green LED (see Table 4 and Figure 5)

3.4 Ratings of brightness and conspicuity

The mean ratings of brightness and conspicuity (and the associated standard deviations) for each combination of light source, luminance and signal color were calculated. These means and standard deviations are listed in Appendix 6. Figures 10 and 11 show the mean ratings of brightness and conspicuity plotted against the mean measured luminance of the signal on a logarithmic scale, for each signal color. As would be expected from the literature (Bodman et al., 1980; Wyszecki and Stiles, 1982), the brightness of the signal for each color shows a linear relationship to the logarithm of the luminance of the signal. The mean brightness ratings are higher for the red signal than for the yellow or green signals at all luminances (Figure 10). The same type of relationship holds for the ratings of conspicuity (Figure 11). This similarity for conspicuity is expected because the simple, invariant nature of the field against which the signal was seen makes conspicuity equivalent to visibility, which is determined by the luminance of the signal and hence its brightness. If the background had contained other light sources and signals, similar in size and color, such as might occur in a city at night, then a different relationship between rated conspicuity and signal luminance might have occurred. The best-fitting logarithmic functions plotted for each signal color in Figures 10 and 11 were fitted through the data for the LED light sources only. Table 7 shows the constants for the linear equations of the form,

$$y = a \ln(x) + b$$

Where

y = mean rating of brightness or conspicuity (possible range 1 –10)

x = signal luminance (cd/m^2)

a and b are fitting constants

Table 7. Fitting constants for an equation of the form $y = a.\ln(x) + b$ plotted through the mean ratings of brightness and conspicuity for the LED signals of a single color. Also given is the variance explained (r^2) for each fit.

LED Color	a	b	r^2
Brightness			
Red	1.94	-10.18	0.98
Yellow	1.75	-10.10	0.99
Green	1.64	-9.12	0.96
Conspicuity			
Red	2.04	-10.72	0.98
Yellow	1.81	-10.68	0.99
Green	1.53	-8.52	0.99

3.5 Ratings of comfort

The mean rating of comfort (and the associated standard deviation) for each combination of light source, luminance and signal color was calculated. These means and standard deviations are listed in Appendix 6. Figures 12, 13 and 14 show the mean ratings of comfort plotted against mean measured luminance on a logarithmic scale, for each signal color. Linear, best-fitting lines are shown for each of the LED signal colors. Figure 12 is for all 30 subjects. The trend evident in Figure 12 is for little change in comfort ratings as the luminance of the signal changes. At the highest measured mean luminance (22,567 cd/m^2 for the yellow incandescent signal) the mean rating of comfort is 2.5, which on the 1 – 10 scale used corresponds to a comfortable condition.

The apparent lack of effect of luminance on visual comfort is deceptive. Figures 13 and 14 show the same data when the subjects are divided into two sets, one set that showed little change in mean discomfort ratings as signal luminance decreased (Figure 13) and one set that showed a tendency to increase the mean discomfort rating with decreasing signal luminance (Figure 14). We speculate that the most probable reason for this divergence between subjects at low signal luminances occurs because of ambiguity in the question. Specifically, the aspect of discomfort to be considered was ambiguous, although it was assumed the subjects would interpret it to mean visual discomfort. The divergence between subjects at low signal luminances would be expected if the first set of subjects were indeed interpreting the question to mean, "Was the signal light visually uncomfortable?", but the second set was interpreting the question to mean, "Am I comfortable with my ability to see the signal?". If this interpretation of the basis of the subjects' judgements is correct, Figure 13 suggests that none of the mean measured luminances used caused any visual discomfort and Figure 14 suggests that the subjects who were concerned with their ability to see the signal were always more comfortable with the red signal than with the yellow or green signal.

4. Discussion

This discussion is organized around a number of questions of relevance to a specifiers of luminous intensity for traffic signals.

4.1 Is there a difference between the mean reaction times, mean number of missed signals, percentages of correct color identification, and the mean brightness and conspicuity ratings for tungsten halogen and LED traffic signals of the same luminance and the same nominal color?

Matched pair t-tests were conducted comparing the mean reaction times and mean number of missed signals for the 10 subjects for both light sources at similar luminances for each signal color. The mean measured luminances of the signal used were red = 5319 cd/m^2 (LED) and 5312 cd/m^2 (incandescent); yellow = 22,253 cd/m^2 (LED) and 22,567 cd/m^2 (incandescent); green = 9,334 cd/m^2 (filtered incandescent) and 9,587 cd/m^2 (incandescent). Cochran Q tests were applied to the percentage correct color identifications for both light sources of the same nominal color and similar luminance. The differences between the mean reaction times, mean number of missed signals and the percentage of correct color identification, for the two light sources, were not statistically significantly different for any of the signal colors. The same analysis was applied to the brightness and conspicuity ratings at the same luminances. Again, there were no statistically significant differences. We conclude that there is no difference in mean reaction time, nor in mean number of missed signals, nor in percentage correct color identification, nor on mean rated brightness or conspicuity, for an incandescent and LED simulated traffic signal of the same luminance and the same nominal color.

4.2 Is there a difference in the ability to detect red, yellow and green traffic signals at the luminances corresponding to the ITE recommendations?

Single-factor, repeated-measures analyses of variance were applied to the mean reaction times of all 10 subjects, for both incandescent and LED light sources at the luminances closest to those corresponding to the ITE recommendations. The mean luminances used were LED: red = 5319 cd/m^2; yellow = 22,253 cd/m^2; green = 9,334 cd/m^2; Incandescent: red = 5312 cd/m^2; yellow = 22,567 cd/m^2, green = 9587 cd/m^2. The luminances corresponding to the ITE recommendations are red = 5000 cd/m ^{2}, yellow = 23,121 cd/m^2, green = 10,000 cd/m^2. The analyses of variance for the LED and incandescent light sources, separately, both showed a statistically significant difference in mean reaction times for the different signal colors (both $p<0.01$). The means of the mean reaction times at the luminances closest to those corresponding to the ITE recommendations were 418 ms (green LED) and 410 ms (green incandescent); 373 ms (yellow LED) and 375 ms (yellow incandescent); 400 ms (red LED) and 399 ms (red incandescent).

For the percentage of missed signals, Figure 9 shows that at the signal luminances corresponding to the ITE recommendations, the percentage of signals missed is low for all three LED signal colors. Specifically, the best-fitting curves show that at the luminances corresponding to the ITE recommendations, the percentages of missed signals are: 1% for the green LED, 0% for the yellow LED and 0.7% for the red LED. However, it should be noted that in these comparisons, the signals differ in both luminance and color. When the three LED signal colors have the same low luminance, such as 2000 cd/m^2, the percentage of signals missed is very different; specifically 27% for the green LED, 8% for the yellow LED and 2% for the red LED. We conclude that at the luminances corresponding to the ITE luminous intensity recommendations there is a difference in the ability to detect the red, yellow and green signals, principally in the reaction time to onset.

4.3 What would be the effect of changing the signal luminance from that corresponding to the ITE recommendations for each signal color?

The effect of changing the signal luminance from that corresponding to the ITE recommendations depends on the direction of the change. For a reduction in signal luminance, the mean reaction time will be increased and the ratings of brightness and conspicuity will be reduced by any reduction in luminance (Figures 6, 7, 8, 10 and 11). A small reduction in luminance from the ITE values will have little effect on the percentage of signals missed (Figure 9) but eventually the reduction will be great enough to cause an increase in the number of missed signals. These changes are true for all three nominal signal colors. For an increase in signal luminance, the mean reaction time will be reduced and the ratings of brightness and conspicuity will be increased by any increase in luminance (Figures 6,7,8, 10 and 11). For the percentage of missed signals an increase in signal luminance above the ITE recommendations will have little effect (Figure 9). These changes are true for all three nominal signal colors.

The magnitude of the effect of a change in signal luminance on reaction time, percentage of missed signals and rated brightness and conspicuity can be predicted from the equations fitted to the data. For example, the consequences of reducing the luminous intensities required for LED signals from those for incandescent signals (ITE 1985) by 15%, as in the interim LED standard (ITE 1998), are shown in Table 8.

Table 8. Predicted changes in mean reaction time, percentage of missed signals, rated brightness and rated conspicuity as a consequence of reducing the luminance of the LED signals by 15%, as was done in the ITE interim standard (ITE, 1998)

Measure	Red LED	Yellow LED	Green LED
Change in reaction time (%)	+2.4%	+2.9%	+4.1%
Change in percentage of missed signals	From 0.7% to 0.8%	No change	From 1.0% to 1.2%
Change in rated brightness (scale 1 = very dark, 10 = very bright)	From 6.34 to 6.03	From 7.48 to 7.20	From 5.98 to 5.72
Change in rated conspicuity (scale 1 = invisible, 10 = very conspicuous)	From 6.66 to 6.32	From 7.51 to 7.21	From 5.57 to 5.32

We hope that similar exercises using the equations fitted through the data will contribute to a well-informed discussion of any proposed changes to traffic signal standards.

4.4 What are the luminances of the yellow and green LED signals that are equivalent to the red LED signal at the luminance recommended by the ITE, for mean reaction time, percentage of missed signals and brightness and conspicuity?

The red LED signal has been in field use in the United States for a number of years without apparent complaint. This can be taken as evidence that the reaction time to, percentage of missed signal for, and brightness and conspicuity of, a red LED signal that conforms to the ITE recommendation are satisfactory in practice. The luminance of the yellow and green LED signals that have the same mean reaction time as the red LED signal at 5000 cd/m^2, for each subject, can be calculated from the power functions fitted to each subject's reaction time data and shown in Table 5. The process is to first determine the mean reaction time to the red LED signal at 5000 cd/m^2, for each subject. Then the luminances needed to give the same mean reaction time for the yellow and green LED signals are calculated for each subject. Table 9 shows the equivalent luminance for each subject calculated in this way and the overall median equivalent luminance and the overall mean equivalent luminance and the associated standard deviation. From Table 9 it can be seen that, regardless of whether the median or the mean is used, the luminance of the yellow LED could be reduced but the luminance of the green

LED signal would need to be increased above the luminance implied by the current ITE recommendations to have the same mean reaction time as the red LED signal at 5000 cd/m ^{2}.

Table 9. Predicted luminances (cd/m ^{2}) for yellow and green LED signals to give the same mean reaction time as the red LED signal at 5,000 cd/m^2.

Subject	Yellow LED	Green LED
A	11,333	13,890
B	9,837	12,532
C	7,007	9,761
D	7,216	10,489
E	14,733	11,070
F	9,564	6,577
G	10,264	19,039
H	9,800	26,214
I	8,476	10,496
J	8,723	9,795
	Median = 9,682	Median = 10,783
	Mean = 9,695	Mean = 12,986
	Standard Deviation = 2,217	Standard Deviation = 5,680

A similar approach can be used for the percentage of missed signals. For the red LED signal at 5000 cd/m^2, the predicted percentage of missed signals is 0.66%. The luminances required to produce the same percentage of missed signals as the red LED signal at the ITE luminance are 14,000 cd/m^2 for the green LED signal and 6,900 cd/m^2 for the yellow signal.

A similar operation can also be applied to the ratings of brightness and conspicuity. Specifically, the process is first to use the linear fits shown in Figures 10 and 11 and Table 7 to obtain the mean ratings of brightness and conspicuity for the red LED signal at 5,000 cd/m^2. Then the luminances that give the same mean ratings of brightness and conspicuity are calculated for the yellow and green LED signals. For brightness ratings, the equivalent luminances are 12,043 cd/m^2 for the yellow LED and 12,443 cd/m^2 for the green LED. For the conspicuity rating, the equivalent luminances are 14,435 cd/m^2 for the yellow LED and 20,299 cd/m^2 for the green LED. Again it is evident that luminance of the yellow LED signal could be reduced from the present recommended luminance but the luminance of the green LED signal would need to be increased above the luminance implied by the ITE recommendations to have the same ratings of brightness and conspicuity as the red LED signal at 5000 cd/m ^{2}.

We conclude that higher signal luminances are needed for the yellow and green signal colors relative to the red to ensure they produce the same reaction time, percentage of missed signals and rated brightness and conspicuity as a red signal at the ITE luminance. This is consistent with the approach used by the ITE in its recommended luminous intensities for different signal colors (ITE, 1985; ITE, 1998) but not for the draft European standard, where all three signal colors have the same minimum luminous intensity and hence the same luminance. One argument to justify the use of the same signal luminances for red, yellow and green signal colors could be that longer reaction times, more missed signals and lower brightness and conspicuity ratings are acceptable for yellow and green signals than for red signals because it is more important to be able to see the signal to stop than to see the signal to go. A consideration of this argument is an essential part of determining standards for the luminance of traffic signals.

4.5 Are there any differences in response to the green signal when the incandescent or LED light sources are used to create the same luminance?

The reason for asking this question is that the difference in chromaticity coordinates for the incandescent and LED light sources is greatest for the green signal, the LED green signal being more saturated than the incandescent green signal. As discussed above, there are no statistically significant differences between the mean reaction times, mean number of missed signals or percentage correct colors identified for the green LED and green incandescent signals at similar luminances. However, Figures 10 and 11 do suggest that the green incandescent signal is rated as less bright and less conspicuous than the green LED signal, at the same luminance. As discussed above, a t-test of these differences shows no statistically significant difference. However, a z-test used to determine if the mean ratings of brightness and conspicuity for the green incandescent signal are different from the rating predicted from the best fitting line through the ratings for the green LED signals, at the same luminance, does produce a statistically significant difference ($p<0.05$), and the direction of the difference is what would be expected from the saturation of the colors produced by the LED and incandescent light sources. The green incandescent signal is seen as less bright and conspicuous than the green LED signal. These results constitute a hint that there is a difference in response to the green LED and incandescent signals at the same luminance that deserves further investigation, because by increasing the saturation of the green single color it might be possible to decrease signal luminance somewhat without increasing reaction time and the percentage of missed signals.

4.6 How do these results compare with previous work?

This question may be answered at several different levels. Starting at the level of vision science, the trend in mean reaction time with luminance is of the expected form, following the Pieron law (Pieron, 1920). This law suggests that the exponent of the power law governing the relationship between simple reaction time and stimulus intensity should be around –0.33. Table 5 shows there are clearly wide differences between individuals but the mean exponent is –0.46 for the green LED signals, -0.42 for the yellow LED signals and –0.33 for the red LED signals.

Another aspect of vision science refers to the wavelength dependence of simple reaction time. It is well established that the simple reaction time of dark-adapted observers to the onset of equal luminance stimuli is independent of wavelength (Holmes 1926, Pollack, 1968). This is assumed to occur because in the dark-adapted condition, any signal has a luminance difference as well as a color difference from the background. While the luminance difference and the color difference will stimulate the achromatic and chromatic channels of the visual system respectively, the achromatic channel is faster and so will determine the reaction time. The response of the achromatic channel is independent of wavelength. A similar independence from wavelength is shown even when the subject is not dark-adapted, provided there is a luminance difference between the signal and the background (Nissen and Pokorny, 1977). However, when there is no luminance difference so that only the chromatic channel can be stimulated, the reaction time does become sensitive to wavelength, the reaction time being longest at 570 nm and shorter towards the extremes of the visible spectrum (Nissen and Pokorny, 1977; Bowen, 1981). In the conditions examined here, where in some conditions the luminance of the signal is very close to that of the background and for other conditions there are large differences in luminance between the signal and the background, the simple reaction time is likely to be determined by both the achromatic and chromatic channels. Further, Ueno et al. (1985) indicate that a bright white adapting background depresses the sensitivity of the achromatic channel relative to the chromatic channel. Given the 5000 cd/m^2 background used here it seems reasonable to suppose that the chromatic channel of the visual system is dominant. If this is so then the red signal should consistently give shorter reaction times than the green signal, at the same luminance.

As for previous research on the detection of signals, Cole and Brown (1966) used a very similar method for studying the reaction time and the number of missed signals for red signals of different luminance. In the Cole and Brown (1966) experiment, the subject viewed a wall subtending 23° vertically and 33° horizontally on which was painted a schematic road scene. The part of the scene simulating the sky had a luminance of 5000 cd/m^2. A red signal was placed almost 3° to the left of the average direction of view and 1.5° above eye level. Reaction times and missed signals were measured when the subject looked directly at the signal and also when doing a tracking task. Figure 15 shows the mean reaction times measured over a similar range of signal luminances by both Cole and Brown (1966) and the mean reaction times for the luminances used in our first and third experiment. It should be noted that there are different numbers of subjects contributing to the mean reaction times depending on whether the data comes from the first or third experiment. The trend in mean reaction time is similar in both studies, but the absolute reaction times are longer for the Cole and Brown (1966) study than in the present study. Why this should be so is uncertain, given the presence of a number of differences between the two experimental procedures, but one notable difference is that the subject's body movement used to signal detection of the signal in the Cole and Brown (1966) study was to remove his or her foot from a pedal while, in our experiments, the response was given by simply moving a finger to release a flip switch. As for missed signals, Cole and Brown showed no missed signals at signal luminances above 1000 cd/m^2 while the percentage of missed red signals in these experiments tended to increase below about 3000 cd/m^2. The reason for this difference is probably the fact that in Cole and Brown (1966) the subject was allowed 2.7 s to respond before the signal was said to be missed. In these experiments, only 1.0 s was allowed before the signal was counted as missed. At 60 miles per hour, a driver will have traveled 28 m in 1.0 s. This is a significant proportion of the 100 m distance from the intersection simulated in both experiments.

Finally, the conclusion that higher luminances are needed for yellow and green signals relative to red signals for equal detection is widely recognized. Fisher and Cole (1974) recommend that the ratio of luminous intensities for green to red signals should be 1.33 and for yellow to red signal should be 3.0. Overall, we conclude that the results obtained in this experiment are consistent with previous research.

5. Caveats

The results presented here were obtained under a specific set of conditions. First, the background luminance was set to simulate a bright sky. The discussion above suggests that for night-time conditions, the reaction times measured would be independent of wavelength so the same reaction times should be found for all signal colors at the same luminance. Second, if the signals have the same luminance as those used here, it is likely that rated discomfort will increase in night-time conditions. We are conducting further experiments to examine this prediction. Third, the subjects were doing a tracking task at the same time as detecting the signal. While this approach was chosen because it seemed to be more representative of the multiple activities involved in driving, there is little doubt that faster reaction times that were less sensitive to the signal luminance would have been obtained if the signal had been viewed directly (Cole and Brown, 1966). Fourth, the subjects used here were young. It is likely that higher luminances would be needed for the detection of signals by older subjects. Fifth, the rise time of the signals for both incandescent and LED light sources were the same, being controlled by the electromechanical shutters. The faster rise time of the LED signal may have an effect on reaction time and missed signals. We will investigate this possibility in a future experiment.

These caveats emphasize the importance of conducting further measurements under different conditions, especially night time, and with older subjects, before making any specific performance recommendations for signal luminances

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7. References

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Figure 1: A schematic elevation of the apparatus.

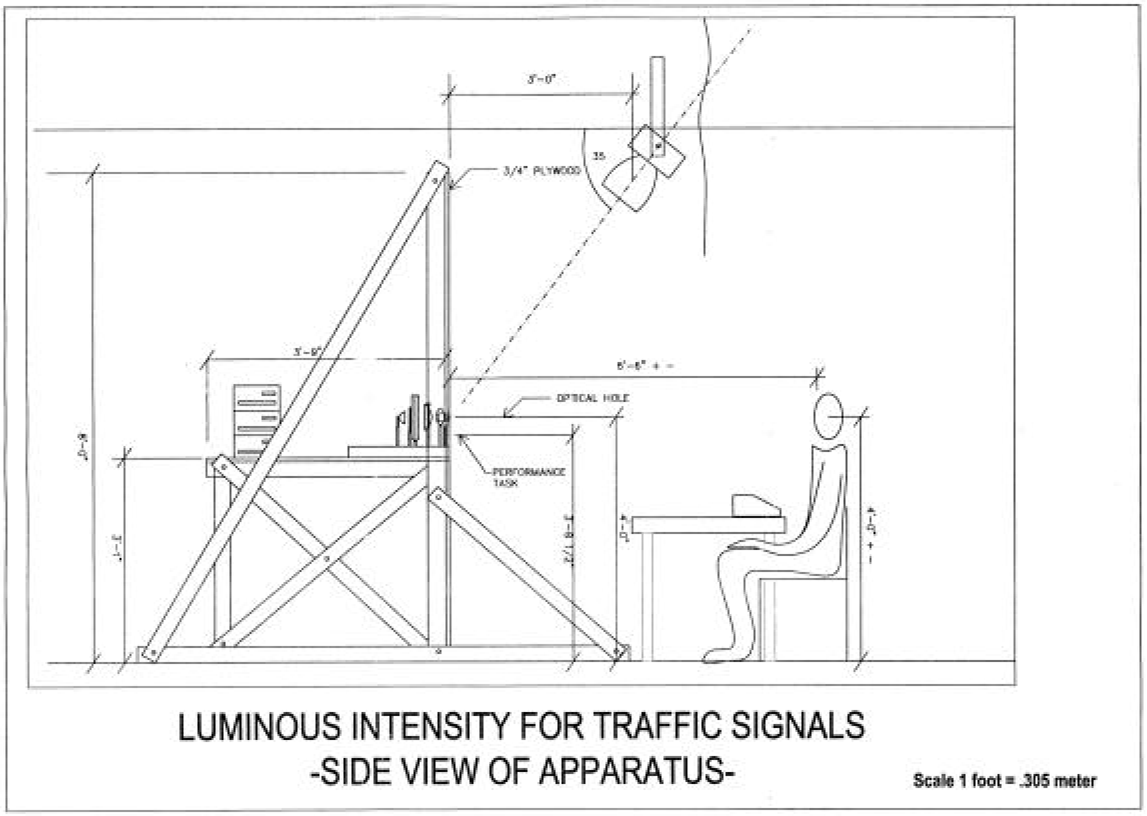
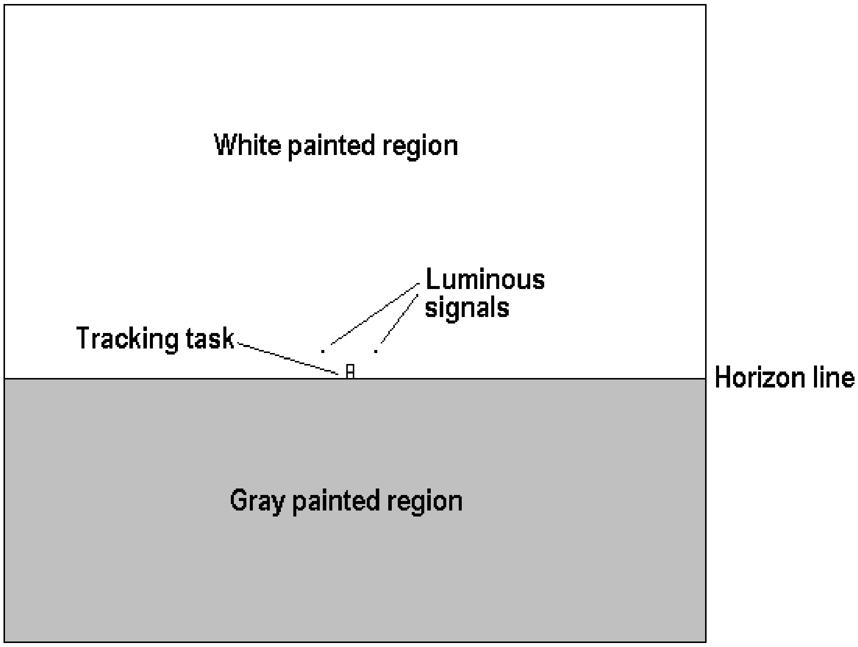


Figure 2: A view of the vertical wall from the subject's position.



View of Apparatus from Subject's Position

Figure 3: The optical system used to generate the signal lights.

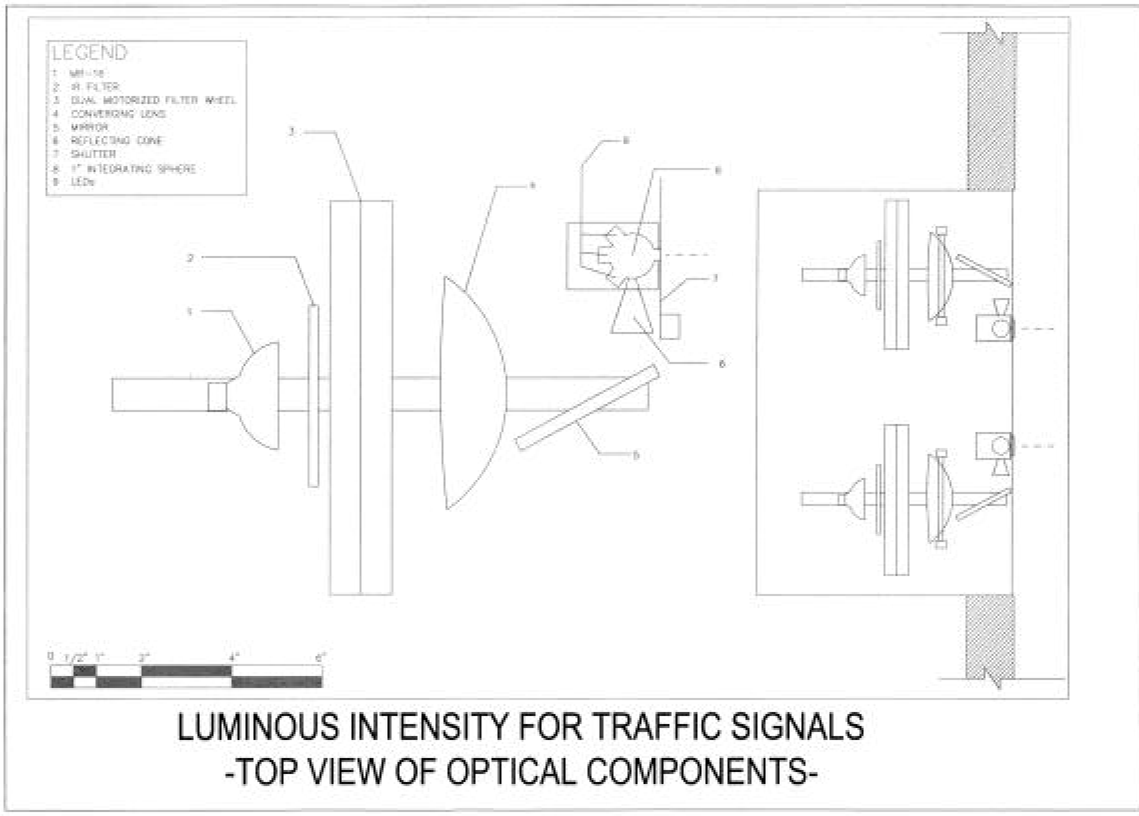


Figure 4: A contour plot of the luminance distribution on the "sky" part of the vertical wall as seen from the subject's position.

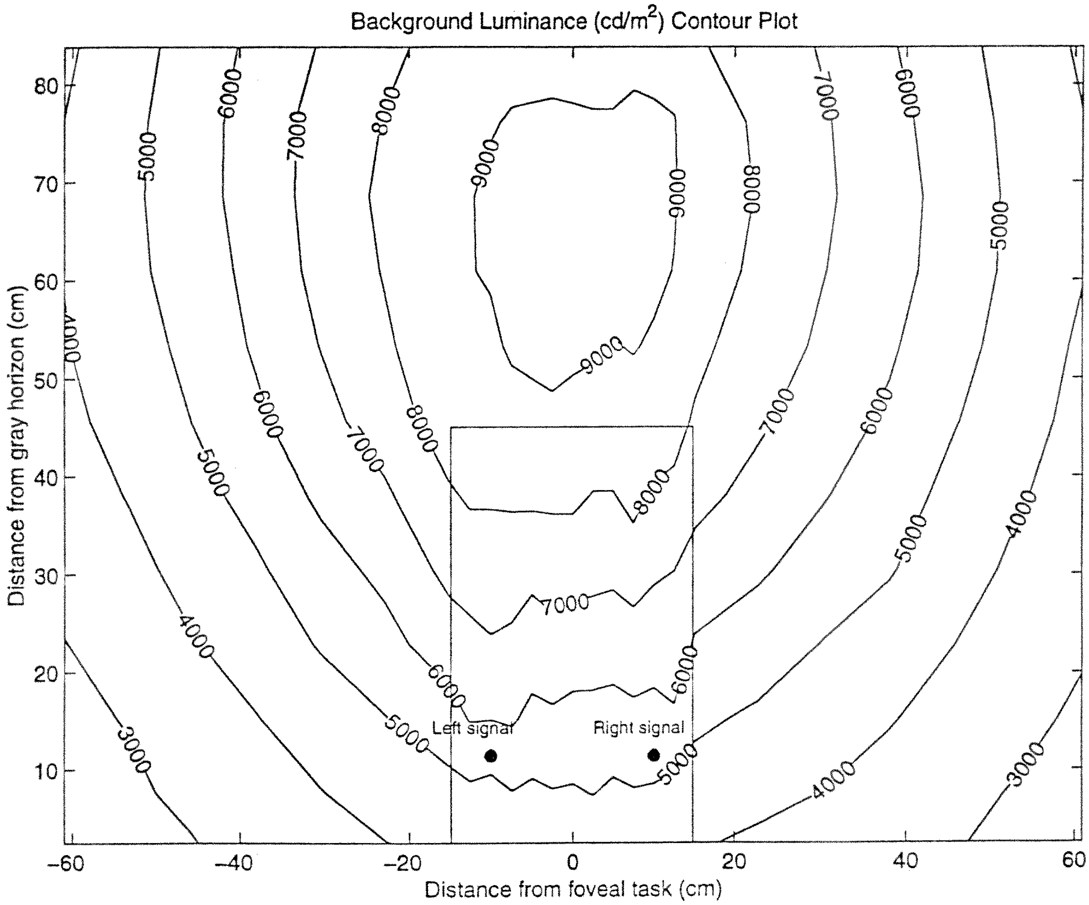


Figure 5: The CIE chromaticity coordinates of the red, yellow and green incandescent and LED signal colors and the background. Also shown are the chromaticity boundaries recommended by the ITE for each signal color. The two smaller figures are enlargements of the yellow (left) and red (right) areas of the chromaticity diagram.

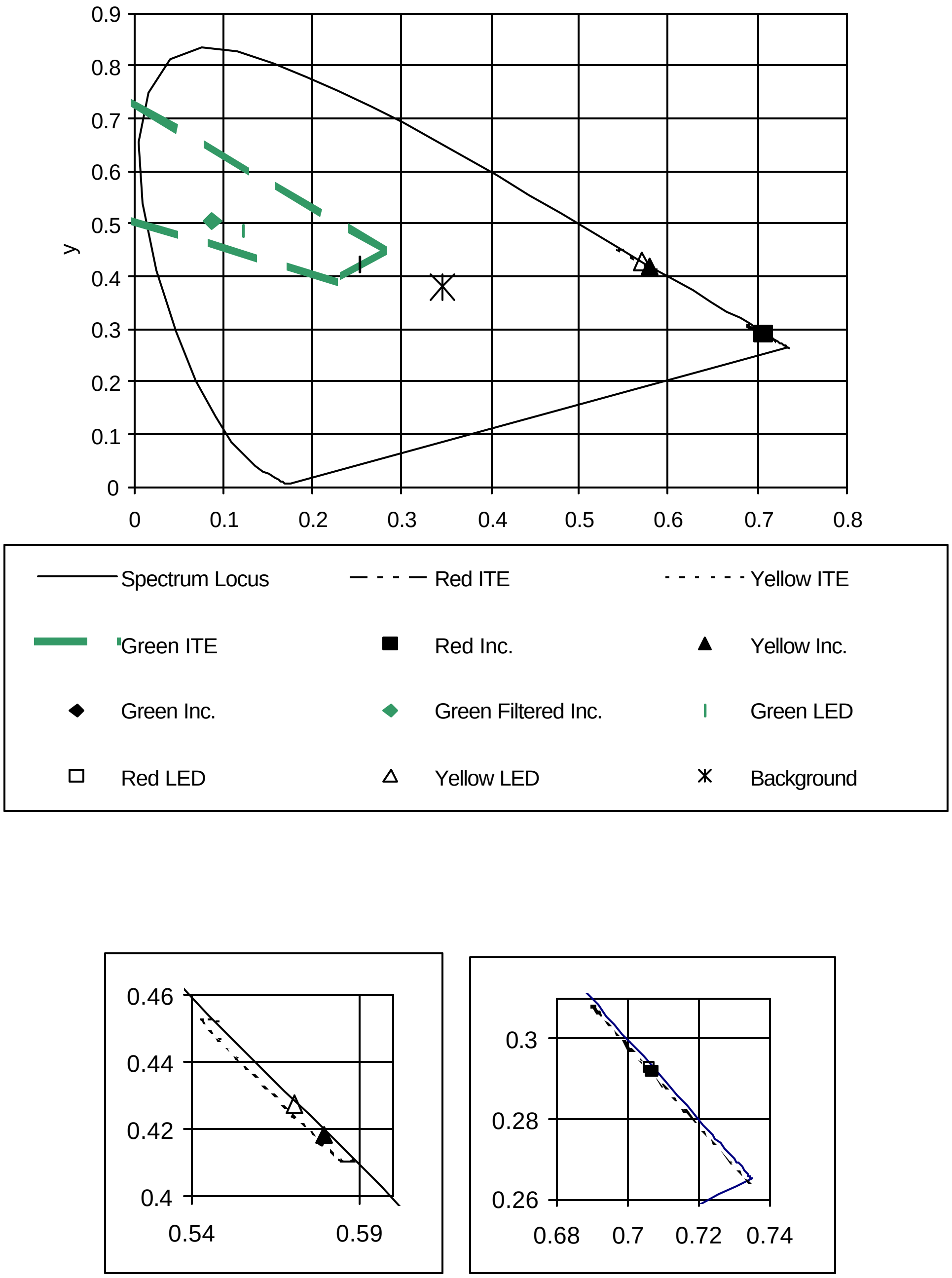


Figure 6: The percentage change in mean reaction time for the green LED signal. 100% reaction time is at a luminance of 10,000 cd/m^2.

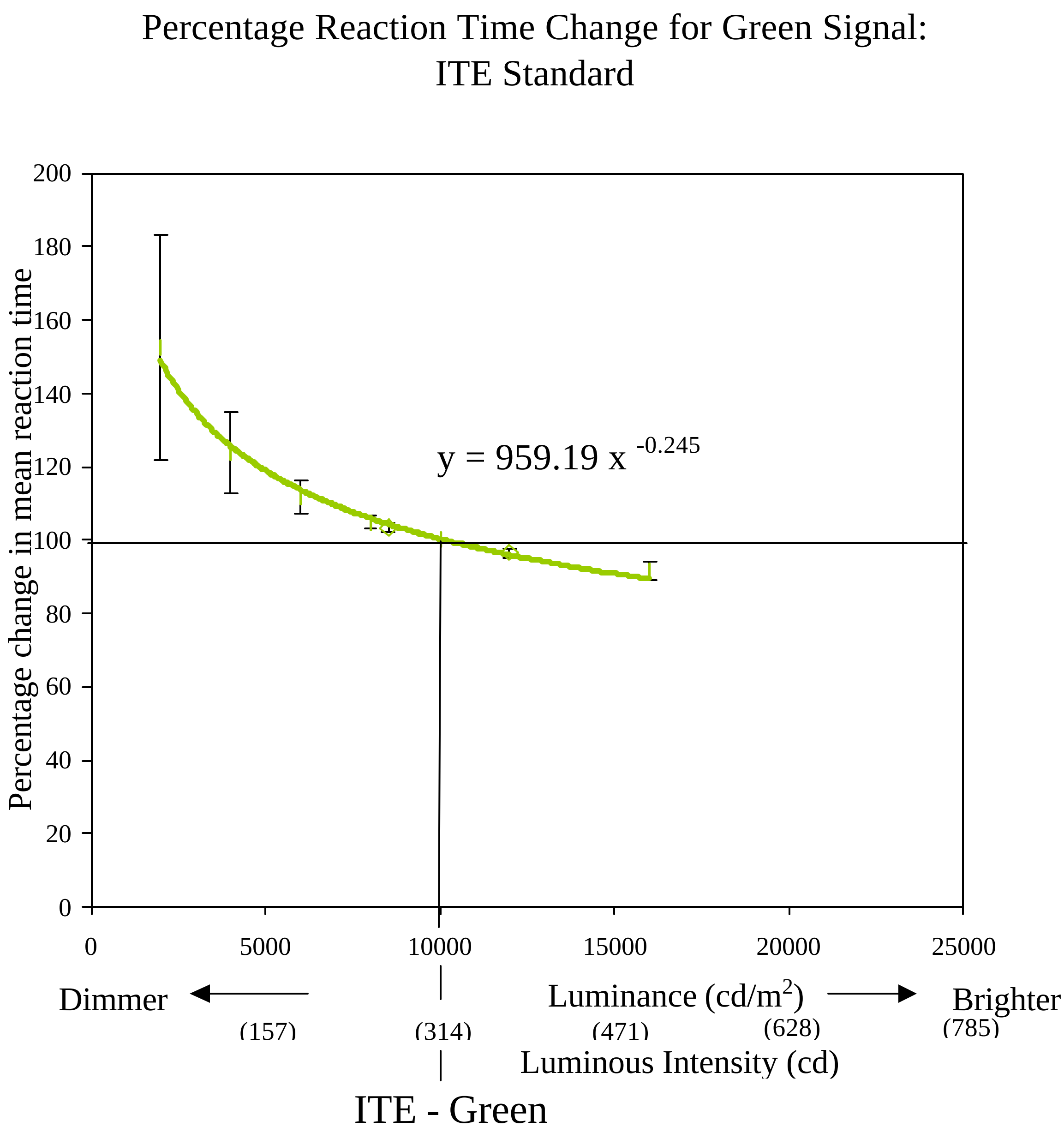


Figure 7: The percentage change in mean reaction time for the yellow LED signal. 100% reaction time is at a luminance of 23,121 cd/m^2.

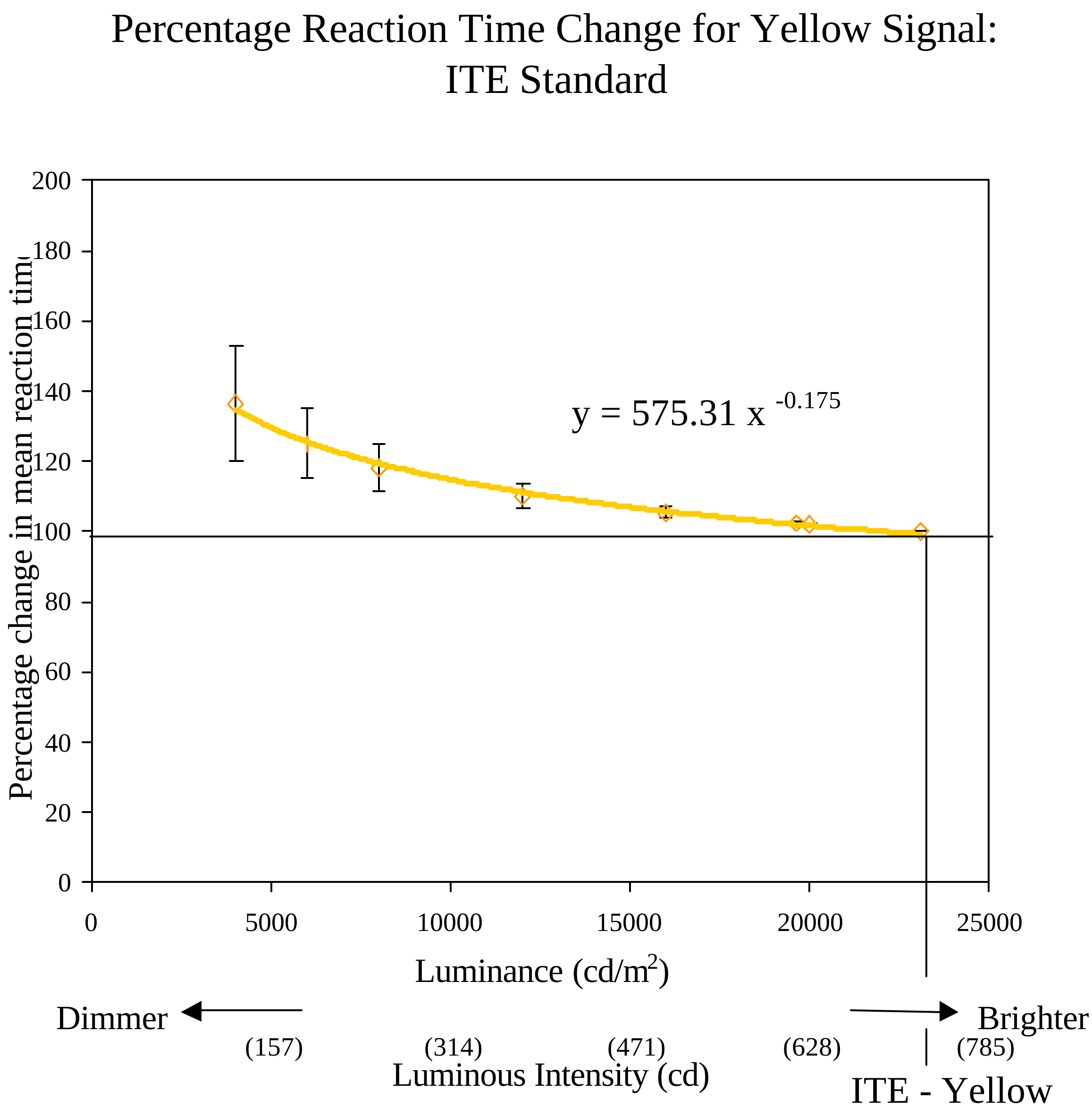


Figure 8: The percentage change in mean reaction time for the red LED signal. 100% reaction time is at a luminance of 5000 cd/m^2.

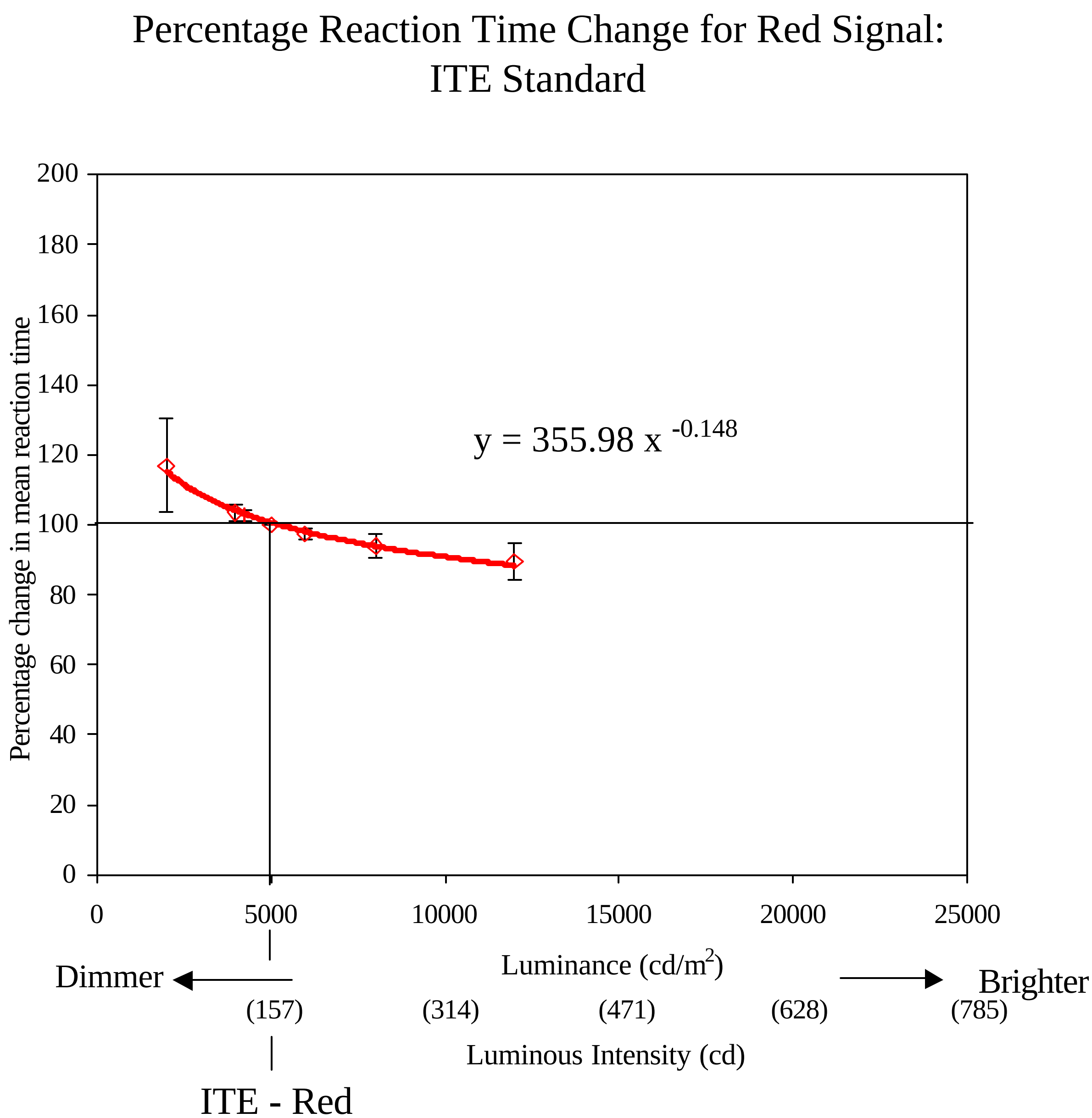


Figure 9: Percentage of signals missed by all subjects as a group for each signal color and luminance.

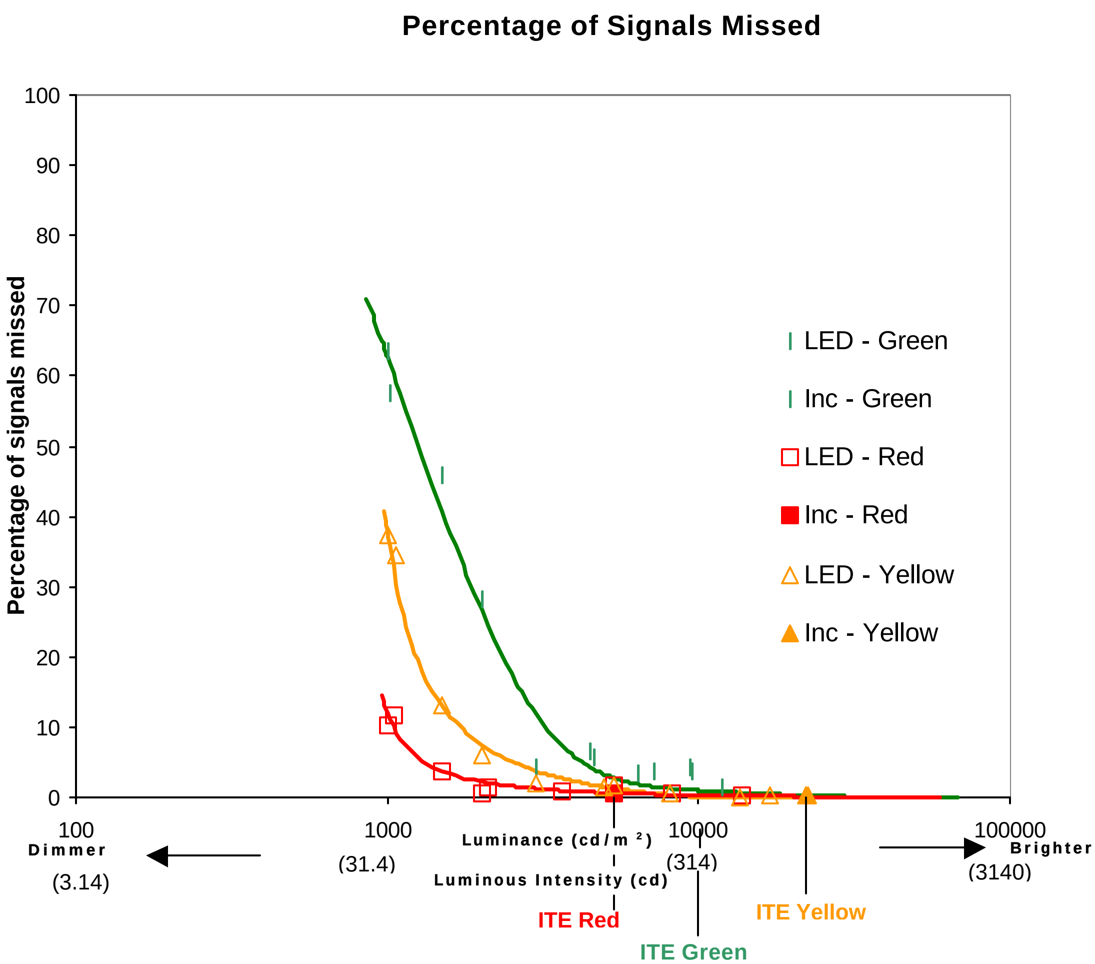


Figure 10: Mean brightness rating for each color and luminance combination plotted against signal luminance. The lines are fitted through the mean ratings for the LED signals only.

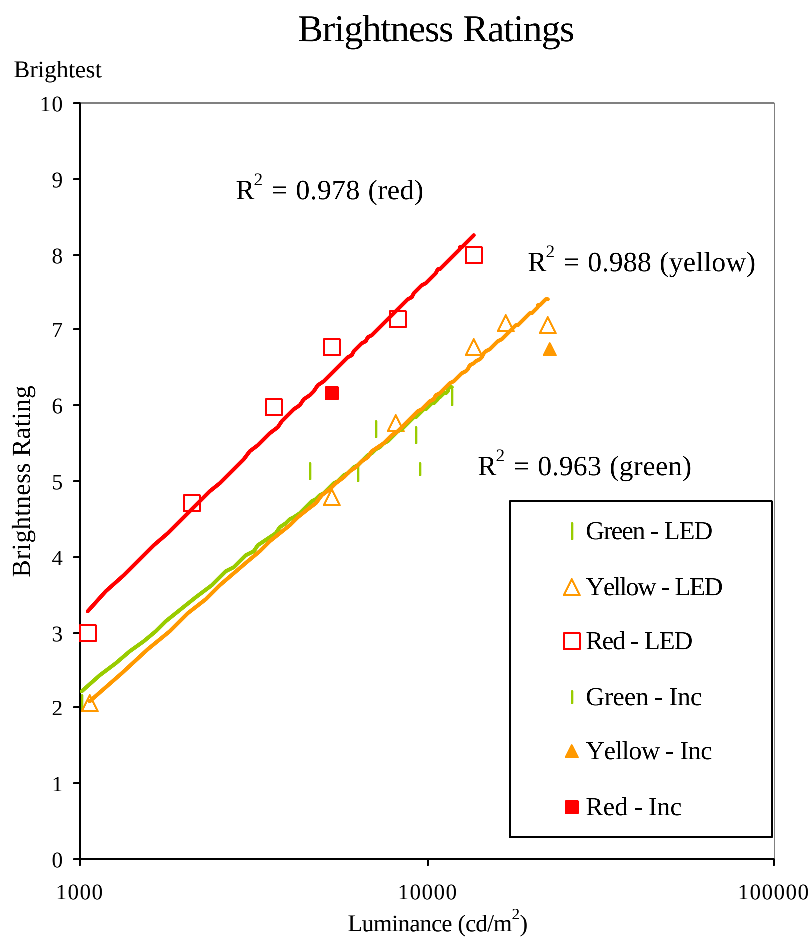


Figure 11: Mean conspicuity rating for each color and luminance combination, plotted against signal luminance. The lines are fitted through the mean ratings for the LED signals only.

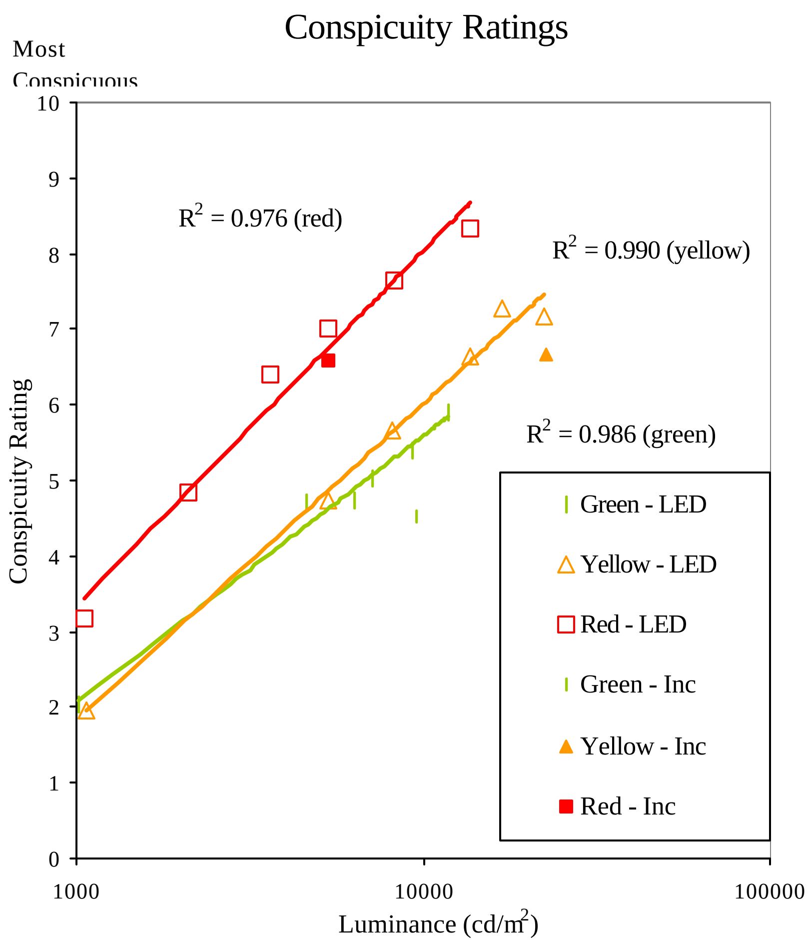


Figure 12: Mean discomfort rating for each color and luminance combination, plotted against signal luminance. The lines are fitted through the mean ratings for the LED signals only.

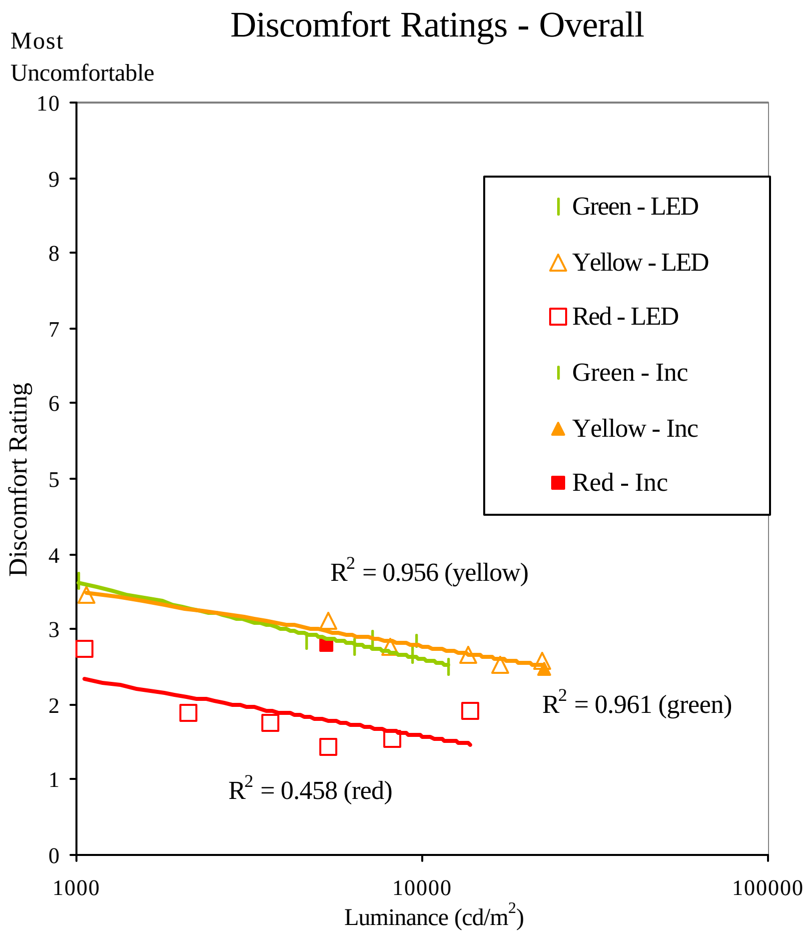


Figure 13: Mean discomfort rating for each color and luminance combination, plotted against signal luminance, for the 20 subjects who showed little change with signal luminance. The lines are fitted through the mean ratings for the LED signals only.

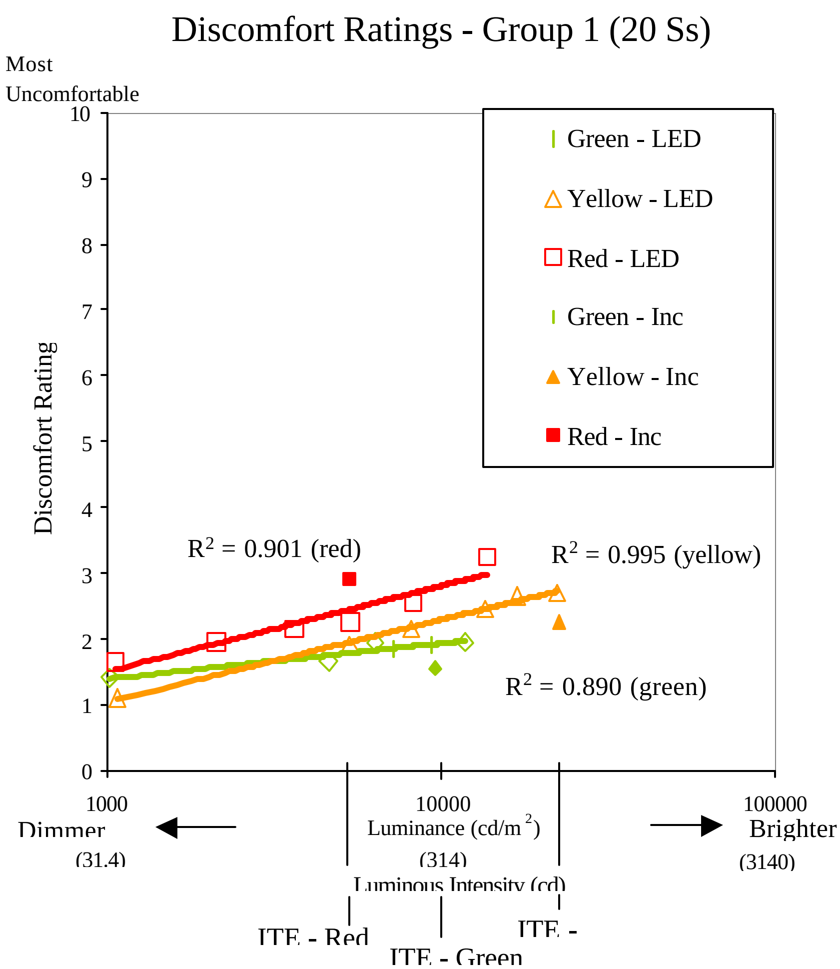


Figure 14: Mean discomfort rating for each color and luminance combination, plotted against signal luminance, for the 10 subjects who showed increased discomfort with lower signal luminances. The lines are fitted through the mean ratings for the LED signals only.

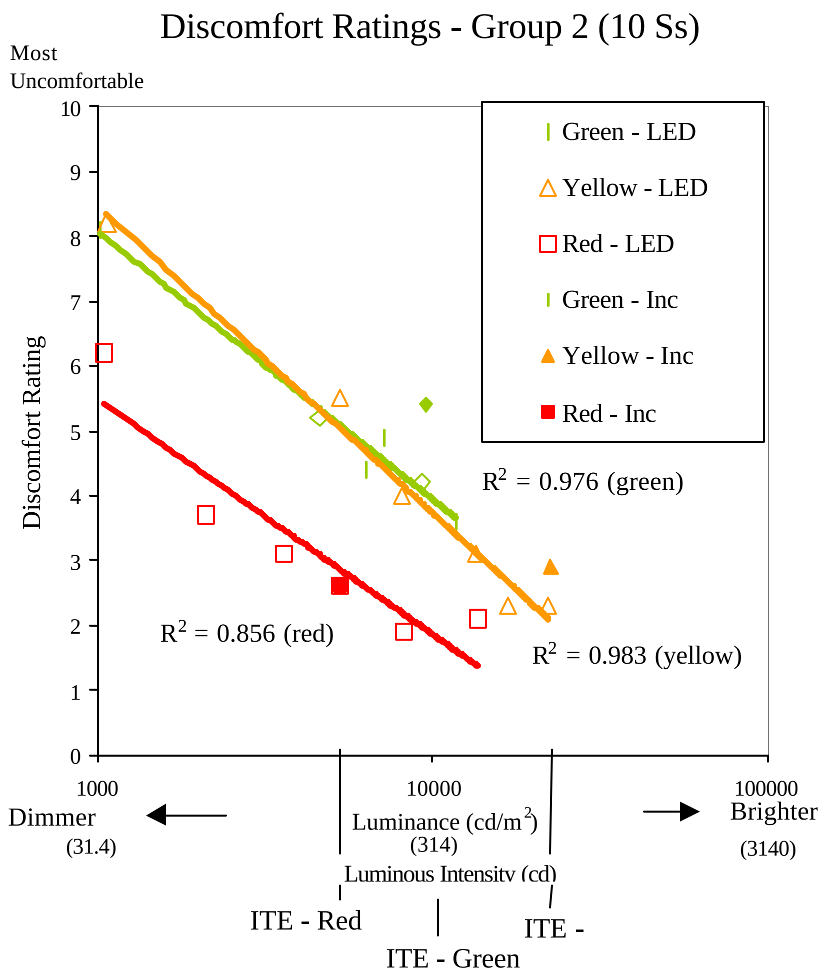


Figure 15: Mean reaction times from Cole and Brown (1966), experiment 1, and from the first and third experiments.