The Effect of Rise Time on the Detection of Traffic Signals

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Executive Summary

The rise time of a light source is the time it takes to reach full light output after application of power. Different light sources used in traffic signals have different minimum rise times. LEDs have minimum rise times in the order of nanoseconds, while incandescent lamps have minimum rise times in the order of tens of milliseconds. Whether these rise times are achieved in practice depends on the characteristics of the power supply applied to the light source. Measurements of the rise times of actual traffic signals showed that LED traffic signals had rise times of approximately 20 ms while incandescent traffic signals had a range of rise times from 90 ms to 200 ms. This study was undertaken to determine if such differences in rise times influence detection of the traffic signal, measured by the reaction time to onset of the traffic signal and percentage of missed signals.

The apparatus used was similar to that used in a previous study (Bullough et al. 1999). The apparatus was designed to simulate an approach to a traffic signal-controlled intersection in flat country in daytime. The subject sat 2.0 m from a large vertical wall with a luminance of 5000 cd/m^2. 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, 4 mm in diameter, simulating signal lights. Behind each circular aperture was a small integrating sphere. The interior of each integrating sphere was lit by light emitting diodes (LEDs). The resulting signal luminance and color could be changed by altering the LED used and reducing the current through the LED. In the experiment, signal luminances ranging from about 1,000 cd/m^2 to 8,000 cd/m^2 were used for red signals and from about 2,000 cd/m^2 to 21,000 cd/m^2 for yellow signals. These luminances cover the range that would be produced by signals conforming with the recommendations of the Institute of Transportation Engineers (ITE, 1985), used in North America. The chromaticity coordinates of the signals all fell within the relevant ITE and Commission Internationale de l'Eclairage (CIE) chromaticity limits. At each luminance, three different rise times were used, rise time being defined as the time taken to increase the light output from 10% to 90% of the maximum light output. The three rise times were 17 ms, 87 ms and 188 ms.

In the experiment, measurements were made of subjects' reaction times to onset and the number of missed signals for red and yellow LED signals. Both signal lights were always presented at the same luminance and color. The presentation time, i.e. the time for which the light output of the signal was above 90% of full light output, was the same for all rise times at 1075 ms. The presentation of the signal and the measurement of the response were both computer-controlled. Ten subjects, all with normal vision and of ages ranging from 25 to 60 years, made the

measurements, each subject seeing 50 presentations for 21 combinations of signal luminance, signal color and rise time. The data from one subject was dropped because this subject's responses were very different from those of the other nine subjects.

From the data collected from nine subjects, we conclude that:

- Rise time does affect the reaction time to the onset of the signal, reaction time being measured from the application of power to the signal. The longer the rise time, the longer the reaction time.

- At the ITE luminance for red signals, increasing the rise time from 17 ms to 87 ms adds 32 ms to the overall mean reaction time, measured from the application of power to the signal. Increasing the rise time from 17 ms to 188 ms adds 98 ms to the overall mean reaction time, measured from the application of power to the signal.

- The effect of different rise time profiles on reaction time, measured from the application of power to the signal, can be predicted using a model based on the following concepts:

  a) Reaction time can be considered as the sum of two components, a visual reaction time and a non-visual reaction time.

  b) The visual reaction time, which is the time taken to transfer the light stimulus to the brain, is determined by the time it takes to accumulate a constant energy level from the stimulus at the eye.

  c) The non-visual reaction time, which is the time taken to interpret the signal in the brain and to carry out the necessary response, is constant for the same decision to be made and the same response action.

  Predictions from this model fit the collected reaction time data well. The model also predicts the reaction time results for the red LED signal from the previous study (Bullough et al. 1999). This model can be used to compare the effect of different rise times on reaction time, without making reaction time measurements, provided the required constant energy level is known.

- Increasing signal luminance leads to an asymptotic decrease in reaction time for the red LED signal, at all rise times.

- The different rise times that were measured in this study have no effect on the percentage of missed signals.

The model described above has been developed for a red LED signal. Signal colors that differentially stimulate the visual photoreceptors, such as green signal colors, should follow the same principles, but the constant energy levels required for detection could be different, as indicated by the results for the yellow LED signal. Therefore, to predict the effect of rise time for other LED signals, another set of measurements would be required to establish the constant energy level for different signal colors.

The constant signal energy model can be applied to any situation in which reaction time to the onset of an illuminated signal is of interest. One example would be a driver's reaction to seeing the onset of the brake lights of a vehicle ahead. In this situation, pressing the brake pedal starts the braking action and applies power to the vehicle brake lights. For anyone following the braking vehicle, being able to detect the braking action more quickly would be a distinct advantage.

The advantage of being able to detect the onset of a traffic signal more quickly following the application of power to a traffic signal is less clear. This is because applying power to the traffic signal is, in and of itself, not a meaningful action because, unlike pressing the brake pedal of a vehicle, it makes no immediate difference to the traffic situation. There are two possible ways to consider this problem, one formal/legal and one perceptual. The formal/legal interpretation would be that the meaning of the signal becomes applicable the moment power is applied to the signal. For example, if power is applied to the red signal, traffic should stop from that moment on. If this interpretation is adopted then the increases in reaction time for longer rise times measured here are meaningful. The perceptual interpretation is that the meaning of the signal cannot be known until it can be seen. If this interpretation is adopted, the visual reaction time is a measure of how long it takes for the signal to become visible and the non-visual reaction time <u>alone</u> is the response to the onset of signal. The model described above shows that the non-visual reaction time is constant for all rise time and luminance conditions. Which of these two interpretations is appropriate is a matter of philosophical argument that could be raised in standards-setting discussions.

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1. Objective

The rise time of a light source is the time it takes the light source to reach full light output after application of power. Light emitting diodes (LEDs), which are a semiconductor light source, have a minimum rise time in the order of nanoseconds. Incandescent lamps have much slower rise times (tens of milliseconds) because they have to heat a filament to approximately 2,700 K to produce nominally white light. For a given voltage applied and filament length, the rise time of an incandescent lamp depends on the diameter of the filament: the thicker the filament, the longer the rise time. Both LEDs and incandescent lamps are used in traffic signals. Traffic signals fitted with these light sources can be expected to have different rise times, although the magnitude of that difference may be modified by the characteristics of the power supply systems used. The objectives of this study are to determine whether such a difference in rise time between LED and incandescent traffic signals does occur, and, if it does, what effect it has on traffic signal detection, as measured by a subject's reaction time to signal onset and percentage of missed signals.

2. Field Measurements

To determine whether rise time differences occurred in traffic signals fitted with LEDs and incandescent lamps, measurements was made of twenty-three red, yellow or green traffic signals operating on public roads in the Albany, New York, area. The measurements were made at night from a car parked facing the traffic signal, using a fast response luminance meter connected to a digital storage oscilloscope. The luminance meter was aimed at the traffic signal to be measured. The luminance of the signal was continuously recorded on the oscilloscope. A triggering feature of the oscilloscope was used so that when a change in the luminance of the signal was detected, the measurements of the signal luminance for a fixed period both before and after the moment of detection of luminance change were stored. Figure 1 shows plots of the rise time of LED and incandescent traffic signals measured in this way. The repetitive oscillations in light output are due to the 60 Hz oscillation of the power supply. The bold line represents the smoothed trend in light output achieved by mathematically filtering out the mains frequency oscillation. Table 1 gives the measured rise times of the traffic signals classified according to lamp type. Rise time is defined as the time it takes for the lamp to change from 10% to 90% light output, based on the smoothed light output. This definition is used rather than one based on 0% to 100% light output change because the fluctuation in light output close to the maximum would lead to large differences in rise time but little variation in light output over most of that time.

It is clear from Table 1 that differences in rise time do occur in traffic signals fitted with LEDs and incandescent lamps. The mean rise time for the three LED signals measured was 21 ms. The mean rise time for the twenty incandescent signals was 138 ms with a standard deviation of 38 ms and a range of 88 ms to 198 ms. The mean rise time for the LED signals agrees reasonably with measurements made by Lumileds on their 110 volt unit, which uses LEDs as the light source. The 110 volt unit had a rise time of 12 ms. The LED signal does not necessarily achieve the minimum rise time set by the properties of LEDs alone because the rise time of the combined LED / power supply system is set by the rise time of the power supply to the LEDs. So, depending on the characteristics of the power supply, a wide range of rise times is possible.

As for the incandescent signals, the minimum rise time is set by the characteristic of the filament, but longer rise times can still be achieved depending on the characteristics of the power supply. The essential difference between the LED and incandescent light sources is that the LED has an intrinsically much shorter rise time than the incandescent. Whether advantage is taken of this to produce a short rise time depends on the design of the power supply.

From these field measurements we decided to examine the effect of three different rise times on the detection of a traffic signal: 17 ms to be representative of the rise times of LED signals; 87 ms to be representative of the fastest incandescent signals; and 188 ms to be representative of the slowest incandescent signals.

Table 1. Rise times in milliseconds, measured as the time taken to change from 10% to 90% light output, for LED traffic signals and incandescent traffic signals.

Light source and signal color	**Rise time (ms)**
LED - red	13
LED - red	17
LED - red	32
Incandescent - yellow	88
Incandescent - green	89
Incandescent - yellow	89
Incandescent - yellow	90
Incandescent - yellow	100
Incandescent - green	118
Incandescent - red	120
Incandescent - green	121
Incandescent - red	123
Incandescent - red	124
Incandescent - green	137
Incandescent - red	140
Incandescent - yellow	144
Incandescent - green	150
Incandescent - yellow	174
Incandescent - green	182
Incandescent - yellow	185
Incandescent - green	190
Incandescent - yellow	191
Incandescent - yellow	198

3. Method

This study used the same apparatus and a similar method to that described in Bullough et al. (1999), to measure individual's ability to detect a simulated traffic signal in daytime. The ability to detect the traffic signal was measured as the reaction time to the onset of the signal and the percentage of missed signals. Based on our previous work, we hypothesized that longer rise times would lengthen reaction times and percentages of missed signals, particularly at low signal luminances; because longer rise times would make traffic signals less conspicuous.

There are two aspects of the apparatus and method that are different from the description in Bullough et al. (1999). First, in this study LED light sources were used to mimic the rise time of both incandescent and LED traffic signals. We could not accurately recreate the control systems that incandescent traffic signals use, but we were able to create rise time profiles with LEDs that matched both LED and incandescent rise times for complete traffic signal systems observed in the field. Figure 2 shows the simulated rise times used in this experiment.

Second, this study concentrated mainly on testing the reaction to the red traffic signals, for several reasons. First, the red signal is more interesting from a behavioral point of view, since missing or reacting slowly to a red signal is more likely to produce adverse consequences for drivers than missing or reacting slowly to a yellow or green signal. Second, with LEDs, we were able to recreate a range of luminances for red signals that included the luminance implied by the ITE standard luminous intensity recommendation (5000 cd/m^2 for a 200 mm diameter signal, (ITE, 1985)) as well as luminances low enough to produce a significant deterioration in the subject's ability to detect the signal. Third, testing red signals at a wider range of rise times and luminances was an economical way of gathering more information than testing all three signal colors at fewer rise times and luminances. To check whether signal color interacts with rise time, we also tested yellow traffic signals at one high and one low luminance. Table 2 gives the combinations of rise time, signal color, and signal luminance used for this study.

Table 2. Signal colors, luminances, and rise times used in this study.

Signal Color	Luminance (cd/m^2)	Rise time (ms)
Red	1000	17
Red	1000	87
Red	1000	188
Red	2000	17
Red	2000	87
Red	2000	188
Red	3000	17
Red	3000	87
Red	3000	188
Red	5000	17
Red	5000	87
Red	5000	188
Red	8000	17
Red	8000	87
Red	8000	188
Yellow	2000	17
Yellow	2000	87
Yellow	2000	188
Yellow	21000	17
Yellow	21000	87
Yellow	21000	188

3.1 Apparatus

Intersection simulation

To simulate a driver's view along a straight road in flat country, subjects sat facing a vertical wall (2.44 m x 2.44 m, subtending 50° both vertically and horizontally at the subject's position, shown in Figure 3). The upper part of this wall, simulating the sky, was painted matte white (reflectance = 0.87); the lower part, representing the ground, was matte gray (reflectance = 0.17). The dividing line between the parts was 1.10 m above the floor.

Subjects performed a tracking task using a small meter mounted at the vertical center of the wall, just above and touching the horizontal division. The meter was 4.75 cm tall by 1.9 cm wide, subtending 1.4° vertically and 33 min arc horizontally at the subject's position. It contained a horizontal indicator that could be moved by changing the voltage applied to the meter. Subjects attempted to keep the indicator within a fixed range that had been painted green on the meter (the areas outside the range were painted red). The tracking task required continuous adjustment, which kept the subject's attention focused on the meter.

The system that controls the voltage to the meter applied a randomly selected target voltage from 0 to 10 V. The system changed the input voltage at a fixed rate until the target voltage was reached. Then the system chose a new random target voltage and repeated the process. If the subject did nothing, the indicator's position within the meter varied continuously. The subject attempted to keep the indicator within the green target range by continuously adjusting the voltage applied to the meter. The target range occupied a vertical linear range of 1.25 cm, corresponding to an angular dimension of 21 min arc at the subject's position.

Simulated traffic signals appeared to the subjects through two small circular apertures (4 mm in diameter) located 2.5° vertically above the dividing line and 2.5° horizontally to the right and left of the center of the meter. The 2.5° horizontal and vertical deviations corresponded to the deviation from normal to the face of a traffic signal of the maximum in the luminous intensity distribution recommended by the ITE (ITE, 1985). The size of the apertures was scaled to subtend the same angle at the subject's position that a 200-mm diameter traffic signal subtends when seen at 100 m. This distance is considered to be the minimum distance at which traffic signals must be clearly seen when driving on an urban road (Schreuder, 1981; Janoff, 1991).

Light conditions within the enclosed laboratory where the experiment took place simulated daytime light levels. The luminance on the vertical wall surface was set to 5000 cd/m^2 in the area containing the tracking task meter and signal apertures. Two ceiling-mounted 1000-W sulphur lamps aimed at the vertical wall were used to light the wall surface. One of the lamps could be dimmed. Each lamp had a diffusing panel in front of it, and one lamp had a magenta filter to match more closely the chromaticity of the other lamp. A white curtain hung behind the lamps, shielding the subjects' view of the lamps and restricting the vertical angle subtended by the "sky" portion of the wall at the subjects' eyes to 20°.

The lamps produced a continuous spectrum. The CIE 1931 x, y chromaticity coordinates of the vertical wall were $x = 0.3782$, $y = 0.3460$. This chromaticity is slightly on the purple side of the black-body locus and corresponds to a correlated color temperature of 3846 K. The chromaticity coordinates of the color of the vertical wall varied slightly across the surface, but did not create any obviously perceivable color difference.

Traffic Signal Simulation
LED traffic signals of varying color and luminance were simulated with a small integrating sphere whose interior was visible through each aperture in the vertical wall. The use of the sphere ensured that the signal luminance was insensitive to small head movements, so the subject's head did not have to be fixed using a chinrest or bite bar. The integrating sphere could be lit internally by one of three different, permanently-installed LEDs, corresponding to a red, yellow, or green traffic signal. The luminance of the integrating sphere could be varied by changing the current through the LEDs. An electromechanical shutter mounted across the exit port of the integrating sphere controlled the exposure of the traffic signal to the subject. The shutter had an opening time of 3.5 ms. For this experiment, the shutter was set to open and disabled.

Labview™ software controlled the presentation of different combinations of signal luminance, signal color, and rise time in random order for each subject. The same combination was presented through both apertures at the same time, simulating an identical pair of signals. Power was applied to the LEDs to produce the three rise times, 17 ms, 87 ms, and 188 ms, to maintain the lamp at full light output for a set period and then to reduce the light output in a symmetrical manner to the initial rise. This meant that the fast rise time signal also had a fast fall time and the slow rise time had a slow fall time. This approach was used because the light output of an incandescent lamp takes longer to decline once power is removed than the light output of an LED, because the filament has to cool. The set period over which the light output was maintained at 90 % of the maximum was 1075 ms for all three rise times.

Reaction Time Apparatus
In front of the subject, a small table held the response panel (see Figure 3). The response panel contained a flip switch on the left side and a rotating knob on the right side. The state of the flip switch was used to determine the detection of the signal; subjects held the switch down and released it when they detected the light. The rotating knob offset the voltage applied to the tracking task meter; subjects used the knob to keep the horizontal indicator within the green area on the meter.

In the previous experiment (Bullough et al. 1999), subjects could have heard the opening of the electromechanical shutters at the onset of the signal and hence be warned about its occurrence, but to avoid this happening, the subjects wore headphones that presented a masking white noise. In this experiment, there was no need to wear the headphones because the shutter was disabled. However, the earphones were worn for the sake of consistency with the earlier experiment and because the white noise served an additional purpose. Specifically, the white noise served as a prompt and feedback on the tracking task. The sound pressure level of noise increased noticeably if the subject let the horizontal indicator on the tracking task move into the red area and dropped when the indicator returned to the green area. An increase in sound pressure level also affirmed that the subject had made a reaction time response, while a decrease indicated that the flip switch was correctly held down in readiness for the next response.

3.2 Subjects

Ten subjects between the ages of 25 and 60 were recruited from students and staff at the Lighting Research Center. Six males and four females participated. Subjects were screened for visual function; their visual acuity was tested with the Landolt ring distance acuity chart, their contrast sensitivity with the Pelli-Robson threshold contrast chart, and their color vision with the Ishihara test. Criteria for participation were visual acuity of 20/25 at 2.0 m, a contrast threshold below 0.1, and normal color vision.

3.3 Procedure

Subjects viewed 21 combinations of rise time, signal color, and signal luminance in a single session. The combinations were presented in random order; but each combination was presented 10 times consecutively. Subjects completed 5 sessions, so that each combination accumulated 50 reaction times. Subjects completed each session in approximately 40 minutes.

The first session for each subject began with a brief training period, consisting of 10 presentations of a single combination of signal color, luminance and rise time, and corresponding measurements of reaction times.

Subjects sat 2.0 m from the vertical wall, viewing the tracking task at near-normal incidence. They were instructed that their goal was to keep the horizontal indicator on the tracking task within the green zone by adjusting the rotating knob on the response panel. They were also instructed to press and hold down the flip switch, thereby alerting the control software to start the time sequence for presenting the stimulus traffic signals. Both signals were of the same color, luminance and rise time and were presented at the same time. Presentation occurred at some randomly selected time between 2 and 5 seconds after the subject pressed down the flip switch. The control software would not present the signal lights unless the horizontal indicator on the tracking task was in the green zone.

When subjects detected the onset of the signal lights, they released the flip switch, which turned off the signals. Reaction time was measured as the time interval between the application of power to the signals and the release of the flip switch. Reaction times shorter than 150 ms were ignored, it being assumed that these were due to anticipation. If the subjects did not release the flip switch before the signal luminance started to decline at the end of the presentation period, a missed signal was counted. Because of the different rise times and the fixed presentation time, this meant that there were different periods of time available for detecting the signal for the different rise times. Specifically, for the 17 ms rise time, the time available for a response was 1090 ms. For the 87 ms rise time, 1200 ms was available for responding and for the 187 ms rise time, 1325 ms was available for a reponse.

4. Results

4.1 Reaction times

Reaction times are greatly influenced by a subject's state of attention and concentration, so an individual's data can show a large amount of variability, including the occasional very long reaction time. This implies that the mean reaction time may not be as good an indicator of a subject's responses as the median reaction time. Therefore, for each subject, a median reaction time was calculated for each session of 10 presentations of a signal at the same rise time, color, and luminance and the five medians were then averaged to produce a mean reaction time. One subject's reaction time data were markedly longer and the subject's percentage of missed signals was considerably higher than all the other subjects for the same conditions. This subject's data were excluded from the analyses as atypical responses. Figure 4 shows the mean reaction times for each of the remaining nine subjects, for all combinations of the signal luminance and rise time, for the red signal. Mean reaction times for all the individual subjects are given in Appendix A. It is evident from Figure 4 that all the subjects show a similar trend of increasing mean reaction time with decreasing signal luminance, for each rise time condition; that increasing signal rise time tends to increase mean reaction time; that there are large differences in mean reaction time between individuals, for the same signal luminance and rise time conditions; and that the individuals who have the fastest and slowest mean reaction times generally maintain their positions relative to each other over all three rise times and all signal luminances except the lowest.

Table 3 shows the overall mean reaction time (averaged from the mean reaction times for nine subjects) and the associated standard deviation, for each combination of signal luminance, color, and rise time. The standard deviations are large relative to the differences between the mean reaction times for the different signal luminance and rise time conditions, but this is because the standard deviations include the differences between individuals evident in Figure 4.

Table 3. Overall mean reaction times in milliseconds (and the associated standard deviations) for different signal luminances, colors and rise times.

Color	**Luminance (cd/m^2)**	**Rise time = 17 ms**	**Rise time = 87 ms**	**Rise time = 188 ms**
Red	1,000	534 (91)	586 (93)	684 (98)
Red	2,000	470 (75)	523 (75)	590 (62)
Red	3,000	435 (76)	494 (69)	565 (78)
Red	5,000	419 (71)	451 (76)	517 (64)
Red	8,000	404 (77)	446 (76)	494 (75)
Yellow	2,000	528 (90)	618 (95)	656 (71)
Yellow	21,000	397 (76)	423 (81)	467 (75)

The mean reaction times for the red signal were submitted to a two-way, repeated-measures analysis of variance, where the factors were rise time and luminance. This analysis removes the differences between individuals from the error term and showed significant main effects for luminance (F (4, 32) = 19.7, $p = 0.002$) and for rise time (F (2, 16) = 127, $p < 0.001$). The main effects were that decreasing signal luminance led to longer reaction times and a longer rise time also led to a longer reaction time. There was no interaction between luminance and rise time (F

(8, 64) = 1.75, $p = 0.223$). Examination of Table 3 shows that at the ITE luminance for red signals (5000 cd/m^2), increasing the rise time from 17 ms to 87 ms adds 32 ms to the overall mean reaction time and increasing it from 17 ms to 188 ms adds 98 ms to the overall mean reaction time for the red signal.

The mean reaction times for the yellow signal were also analyzed with a two-way, repeated-measures analysis of variance with the same factors. The analysis showed significant main effects for luminance (F (1, 8) = 47.1, $p < 0.001$) and for rise time (F (2,16) = 38.1, $p < 0.001$). The main effects were as before; the higher luminances had the shorter reaction times and the longest rise time had the longest reaction time. For this signal color, the interaction between luminance and rise time approached significance (F (2, 16) = 8.37, $p = 0.020$) probably because of the greater change in reaction time with increased luminance for the 87 ms rise time than for the other rise times. More data at a more extensive range of luminances would be required before we could determine if this finding is robust or simply a type 2 error caused by the large variations in reaction time that would be likely at low signal luminances.

4.2 Missed signals

The percentage of signals missed in all five sessions of 10 presentations of a signal at the same rise time, color, and luminance was calculated for each subject. The same subject who had the much longer reaction times also had many more missed signals than the other subjects even at higher luminances, so this subject's data were again excluded from consideration.

Table 4 shows the overall percentage of missed signals (calculated from all nine subjects as a group) for each combination of signal luminance, color and rise time. The percentage of missed signals for the individual subjects are given in Appendix B.

Table 4. Overall percentage of missed signals for different signal luminances, colors and rise times.

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	3.6%	3.4%	3.6%
Red	2,000	0.9%	0.7%	0.2%
Red	3,000	0.5%	0.2%	0.2%
Red	5,000	0.2%	0.0%	0.5%
Red	8,000	0.2%	0.0%	0.0%
Yellow	2,000	3.6%	2.7%	3.8%
Yellow	21,000	0.0%	0.0%	0.7%

The percentages of missed signals for the red signal were submitted to a two-way, repeated-measures analysis of variance, where the factors were rise time and luminance. The analysis showed a significant main effect for luminance (*F* (4, 32) = 7.52, *p* = 0.025), but not for rise time (*F* (2, 16) = 0.280, *p* = 0.61). Increasing luminance led to a decreasing percentage of missed signals but increasing rise time made no difference. There was no interaction between luminance and rise time (*F* (8, 64) = 0.243, *p* = 0.64).

The percentages of missed signals for the yellow signal were also analyzed with a two-way, repeated-measures analysis of variance with the same factors. This analysis showed the same pattern of significances as the red signal. There was a statistically significant main effect for luminance (*F* (1, 8) = 11.4, *p* = 0.010) but not for rise time (*F* (2,16) = 1.20, *p* = 0.31) and there was no interaction between luminance and rise time (*F* (2, 16) = 0.162, *p* = 0.70). Increasing signal luminances led to a decrease in the percentage of missed signals.

5. Discussion

The lack of an effect of rise time on the percentage of missed signals is not too surprising. To miss a signal, the subject would have to fail to respond to the signal while it is being presented. For all three rise times, the signals were presented above 90% of full light output for 1075 ms. Thus, for the percentage of missed signals, the different rise times, the longest of which was 188 ms, affect only a small part of the total time available for response.

This is not the situation for the reaction times, where the increase in the signal luminance is the stimulus driving the reaction time. In this situation, differences in rise time are expected to modify reaction time. However, there is a problem with the measurement of reaction time when the rise time is slow. This problem is defining when the light source can be said to be lit. Specifically, the overall mean reaction times given in Table 3 are based on measurements from the moment the power is applied to the LED, but this is not the moment when the luminance of the signal is enough to be perceived. To deal with this uncertainty, it is necessary to develop a more detailed model of reaction time.

The model is based on the concept that the measured reaction time (RT_m) is the sum of two components, a visual reaction time (RT_v) and a non-visual reaction time (RT_{nv})

$$RT_m = RT_v + RT_{nv}$$

The visual reaction time is the time it takes for the light received from the signal to be transformed to an electrical signal in the retina and transmitted up the optic nerve to the visual cortex. The non-visual component includes the time required for information perceived at the visual cortex to be processed and for neural signals to be sent to the muscles that control the hand on the flip-switch. The differences in rise time of the signal examined in this study can be expected to influence the visual reaction time but not the non-visual reaction time, which can be assumed to be constant for the same display and the same decision to be made. A clue to the effect of rise time can be obtained from Bloch's Law, which states that for single, brief (< 100 - 200 ms) flashes of light, any combination of luminance and time that has the same product produces the same perception (Boff and Lincoln, 1988). The existence of Bloch's Law is evidence of temporal summation occurring in the human visual system and suggests that the effect of the different rise times on reaction time might be modeled by considering that a constant amount of energy—that is, luminance integrated over time—must be received before a subject can detect the signal. The following equation represents the constant signal energy model:

$$k = \int L(t)\, dt$$

where k is a constant, and L(t) is the luminance of the signal that varies with time (t). The integration occurs from time zero, which is when the power is applied to the signal, to the visual reaction time. This approach of combining both luminance and time to estimate the effect of a stimulus on reaction time is consistent with the laws of simple reaction times expounded by Teichner and Krebs (1972).

To refine this constant signal energy model, the non-visual reaction time was adjusted to minimize the sum of the least square differences between the values of the constant k for the different combinations of rise time and luminance for the red signal. Figure 5 shows the reaction times calculated from the model for the red signal, for the different signal luminances and rise times. Also shown are the measured overall mean reaction times. The fit of the model to the measured overall mean reaction times is good, for a constant (k) of 170.5 cd.s/m^2. The corresponding non-visual reaction time is 367 ms.

While the model fits the measured reaction time data well, it is not enough to demonstrate its validity. To do that, the model has to successfully predict a set of independently-collected reaction time data. This possibility was tested by applying the model to the measured reaction time results for the red LED signals described in Bullough et al. (1999). This experiment used the same apparatus and procedure as was used here but involved a different set of subjects. The main difference of that study from the present study was that the onset of the signal was controlled by an electromechanical shutter with an opening time, and hence a signal luminance rise time, of 3.5 ms. The same value of constant signal energy (k = 170.5 cd.s/m^2) developed from the present experiment was used in the predictions of reaction times, but to get the best fit the constant non-visual reaction time had to be adjusted to 357 ms. This is not unreasonable because Bullough et al. (1999) used a different group of subjects covering a younger age range (25 to 35 years of age). In fact the non-visual reaction time of 357 ms from the Bullough et al. (1999) is only slightly different from the non-visual reaction time of 367 ms found in the present experiment for red LEDs. Figure 6 shows the predicted reaction times for the red LED signals in Bullough et al. (1999) and the actual measured reaction times collected in that experiment. The agreement between the reaction times predicted by the model and the independently-measured reaction times is good. This strengthens the validity of the model.

From the constant signal energy model, one can calculate visible reaction time for any combination of signal luminance and rise time, up to some maximum rise time yet to be determined. This can be done without making any reaction time measurements, provided the constant (k) is known. For the red LED signal used here, k = 170.5 cd.s/m^2. Figure 7 illustrates the process schematically. Figure 7 shows two signals with different rise times. The energy required for detection of the signal is given by the area under the rise time curve, so the visual reaction time (RT_v) at which the signal is detected is the time at which the area under the rise time curve reaches the constant value (k). Mathematically, the visual reaction time can be calculated by summing the luminance over small intervals of time starting when the power is applied until the sum, in $cd.s/m^2$, reaches the value of the constant (k). To determine the effect of different rise times on overall reaction time, all that is required is to calculate the visual reaction times for the two rise times and then to take the difference, because the non-visual reaction time is constant.

6. Caveats

The constant signal energy model proposed herein is useful for handling the reaction time to the onset of signals with different rise times, no matter how they arise, from either the inherent properties of the light source or the design of the power supply. However, it should be appreciated that different signal colors will produce different values of the constant (k) when the spectrum of the light source stimulates different combinations of photoreceptors. As evidence of this, the method described above was applied to the overall mean reaction times from the yellow LED signals, using the same fixed non-visual reaction time of 367 ms as was found for the same group of subjects for the red LED signals, because the task is the same for the yellow signals. Figure 8 shows the fit between the measured reaction times and the reaction times predicted by the constant signal energy model for the yellow LED signals at the two luminances and three rise time combinations used. The fit is reasonable, but to achieve this fit, the constant k had to be 285 $cd.s/m^2$, which is rather different from the 170.5 $cd.s/m^2$ found for the red LED signal. It would be useful to determine what the values of k would be for other signal colors, especially green.

The constant signal energy model can be applied to any situation in which reaction time to the onset of an illuminated signal is of interest. One example would be a driver's reaction to seeing the brake lights of a vehicle ahead. In this situation, pressing the brake pedal starts the braking action and applies power to the vehicle brake lights. For anyone following the braking vehicle, being able to detect the braking action more quickly would be a distinct advantage.

The advantage of being able to detect the onset of a traffic signal more quickly following the application of power to a traffic signal is less clear. This is because applying power to the traffic signal is, in and of itself, not a meaningful action because, unlike pressing the brake pedal of a vehicle, it makes no immediate difference to the traffic situation. There are two possible ways to consider this problem, one formal/legal and one perceptual. The formal/legal interpretation would be that the meaning of the signal becomes applicable the moment power is applied to the signal. For example, if power is applied to the red signal, traffic should stop from that moment on. If this interpretation is adopted then the increases in reaction time for longer rise times measured here are meaningful. The perceptual interpretation is that the meaning of the signal cannot be known until it can be seen. If this interpretation is adopted, the visual reaction time is a measure of how long it takes for the signal to become visible and the non-visual reaction time alone is the response to the onset of signal. The model described above shows that the non-visual reaction time is constant for all rise time and luminance conditions. Which of these two interpretations is appropriate is a matter of philosophical argument that could be raised in standards-setting discussions.

7. Acknowledgements

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Appendix A

Mean reaction times for each subject at each combination of signal luminance, color and rise time.

Subject 1

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	482	544	641
Red	2,000	480	515	585
Red	3,000	443	492	561
Red	5,000	409	439	511
Red	8,000	370	432	493
Yellow	2,000	480	586	688
Yellow	21,000	364	419	521

Subject 2

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	430	466	575
Red	2,000	375	424	481
Red	3,000	352	402	464
Red	5,000	344	366	442
Red	8,000	321	374	409
Yellow	2,000	465	481	546
Yellow	21,000	311	331	377

Subject 3

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	543	567	673
Red	2,000	529	617	650
Red	3,000	516	563	641
Red	5,000	506	545	579
Red	8,000	508	543	582
Yellow	2,000	533	630	675
Yellow	21,000	507	536	544

Subject 4

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	520	511	619
Red	2,000	458	476	565
Red	3,000	433	481	550
Red	5,000	452	466	506
Red	8,000	420	473	491
Yellow	2,000	482	604	605
Yellow	21,000	408	424	472

Subject 5

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	437	689	879
Red	2,000	345	432	539
Red	3,000	297	378	450
Red	5,000	304	338	405
Red	8,000	294	315	377
Yellow	2,000	432	562	713
Yellow	21,000	279	301	348

Subject 6

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	707	760	805
Red	2,000	589	644	696
Red	3,000	540	595	694
Red	5,000	521	538	606
Red	8,000	514	544	602
Yellow	2,000	684	810	778
Yellow	21,000	480	536	574

Subject 7

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	524	589	630
Red	2,000	508	521	572
Red	3,000	472	503	599
Red	5,000	445	511	568
Red	8,000	444	488	529
Yellow	2,000	519	627	620
Yellow	21,000	454	455	487

Subject 8

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	649	628	697
Red	2,000	498	549	620
Red	3,000	404	522	539
Red	5,000	375	378	506
Red	8,000	352	394	438
Yellow	2,000	671	705	732
Yellow	21,000	359	375	421

Subject 9

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	519	521	634
Red	2,000	452	535	606
Red	3,000	460	506	594
Red	5,000	417	485	530
Red	8,000	414	453	524
Yellow	2,000	476	553	636
Yellow	21,000	407	433	464

Subject 10 (This subject's data were dropped from the analysis).

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	732	905	933
Red	2,000	725	748	784
Red	3,000	625	704	804
Red	5,000	656	700	763
Red	8,000	634	672	741
Yellow	2,000	684	717	920
Yellow	21,000	595	672	808

Appendix B

The percentage of missed signals for each subject for all combinations of signal luminance, color and rise time.

Subject 1

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	0%	2%	2%
Red	2,000	0%	0%	0%
Red	3,000	0%	0%	0%
Red	5,000	0%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	0%	2%	6%
Yellow	21,000	0%	0%	0%

Subject 2

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	0%	2%	0%
Red	2,000	0%	0%	0%
Red	3,000	0%	0%	0%
Red	5,000	0%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	0%	0%	2%
Yellow	21,000	0%	0%	0%

Subject 3

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	0%	2%	0%
Red	2,000	0%	0%	0%
Red	3,000	0%	0%	0%
Red	5,000	0%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	0%	2%	0%
Yellow	21,000	0%	0%	0%

Subject 4

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	0%	0%	0%
Red	2,000	0%	0%	0%
Red	3,000	0%	0%	0%
Red	5,000	0%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	2%	0%	2%
Yellow	21,000	0%	0%	2%

Subject 5

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	4%	4%	10%
Red	2,000	0%	0%	0%
Red	3,000	0%	0%	0%
Red	5,000	0%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	0%	0%	4%
Yellow	21,000	0%	0%	0%

Subject 6

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time =	Rise time = 188 ms
Red	1,000	6%	2%	6%
Red	2,000	6%	2%	2%
Red	3,000	2%	0%	2%
Red	5,000	0%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	10%	12%	4%
Yellow	21,000	0%	0%	4%

Subject 7

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	16%	10%	8%
Red	2,000	2%	2%	0%
Red	3,000	2%	0%	0%
Red	5,000	0%	0%	2%
Red	8,000	2%	0%	0%
Yellow	2,000	2%	4%	4%
Yellow	21,000	0%	0%	0%

Subject 8

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	2%	6%	2%
Red	2,000	0%	0%	0%
Red	3,000	0%	0%	0%
Red	5,000	0%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	6%	4%	8%
Yellow	21,000	0%	0%	0%

Subject 9

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	4%	2%	4%
Red	2,000	0%	0%	0%
Red	3,000	0%	0%	0%
Red	5,000	2%	0%	0%
Red	8,000	0%	0%	0%
Yellow	2,000	2%	0%	4%
Yellow	21,000	0%	0%	0%

Subject 10 (This subject's data were dropped from the analysis).

Color	Luminance (cd/m^2)	Rise time = 17 ms	Rise time = 87 ms	Rise time = 188 ms
Red	1,000	20%	24%	22%
Red	2,000	15%	8%	6%
Red	3,000	10%	10%	18%
Red	5,000	12%	12%	14%
Red	8,000	12%	14%	24%
Yellow	2,000	12%	12%	16%
Yellow	21,000	4%	6%	14%

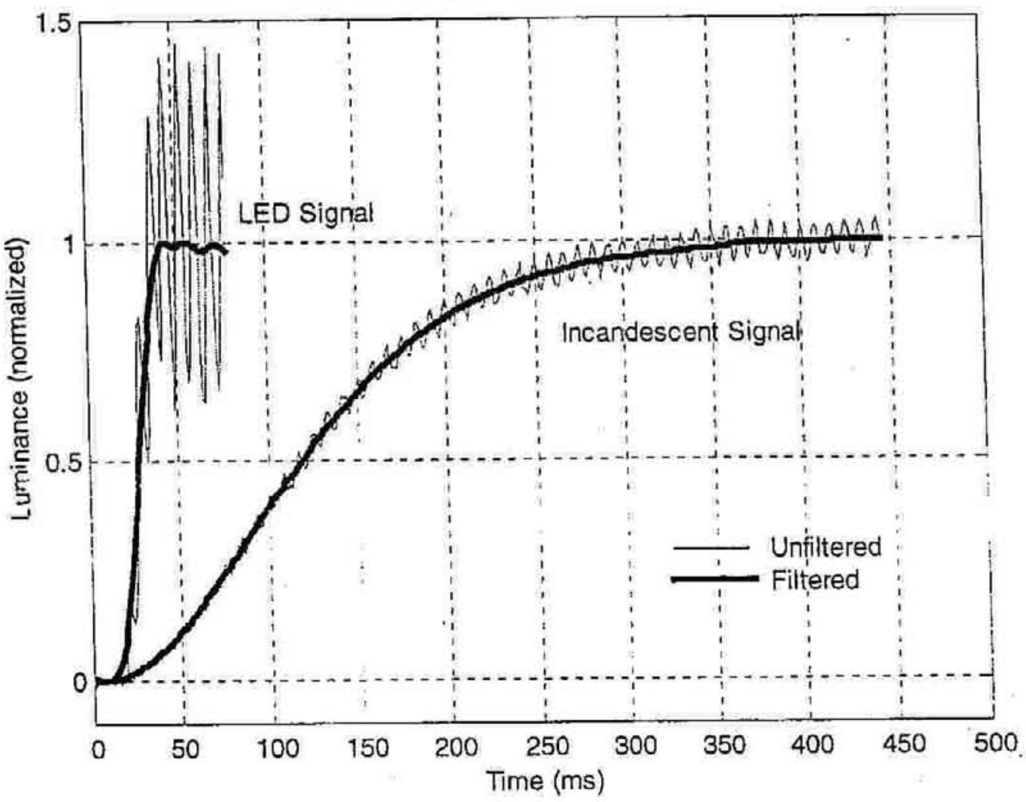

Figure 1. Rise times of a LED and an incandescent traffic signal measured in the field. The light line is the instantaneous signal luminance. The bold line is the trend in signal luminance smoothed through a filter.

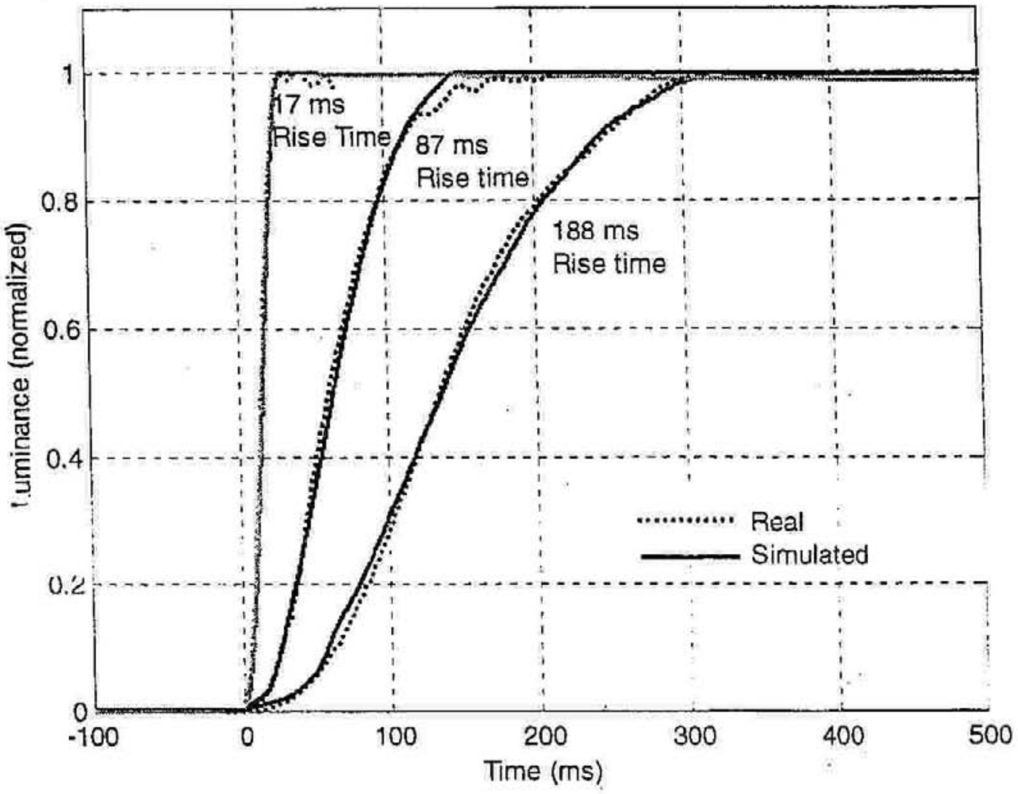

Figure 2. Smoothed rise time profiles for real LED and incandescent traffic signals measured in the field and the simulations of the same signals used in the experiment.

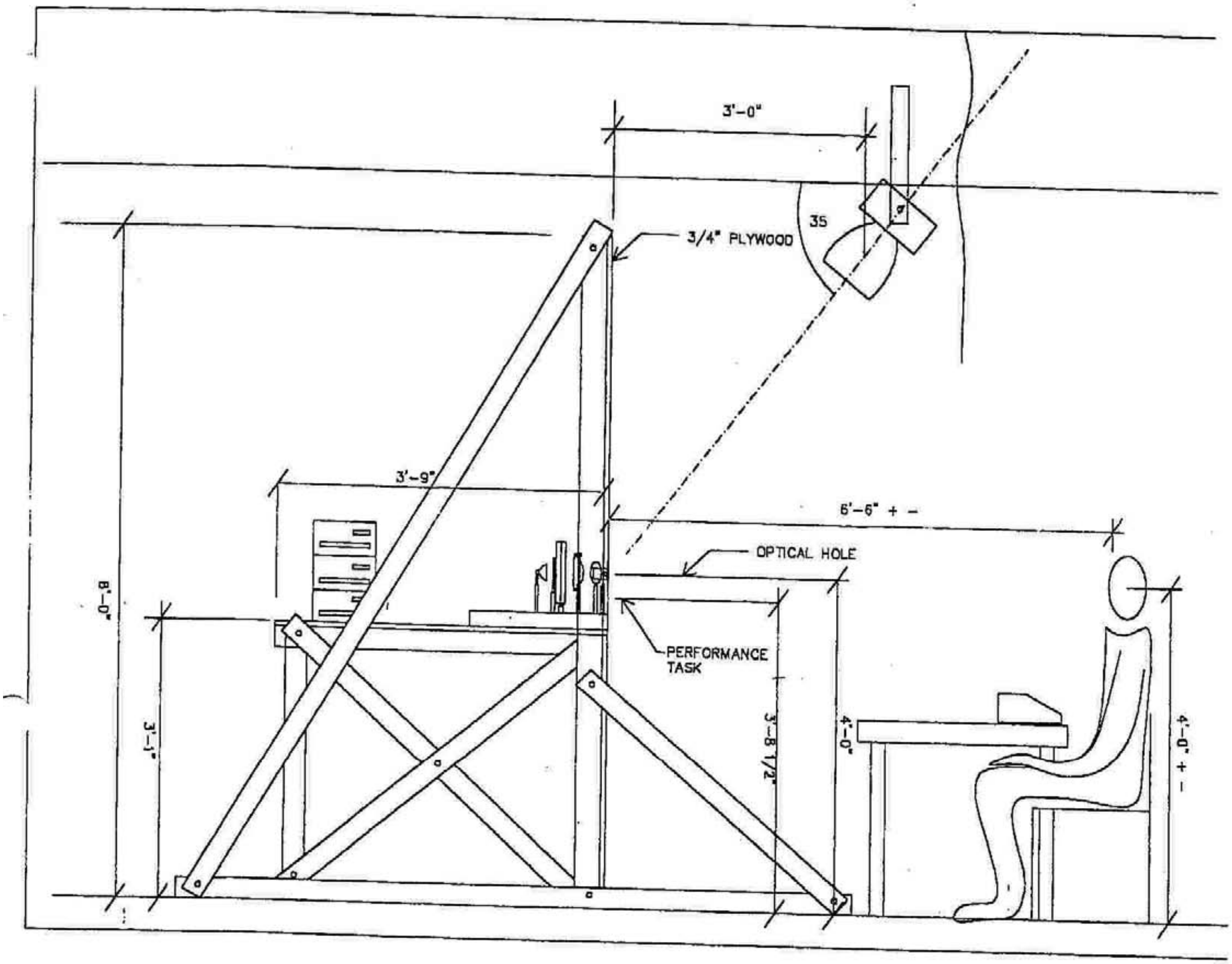

Figure 3. A schematic elevation of the apparatus

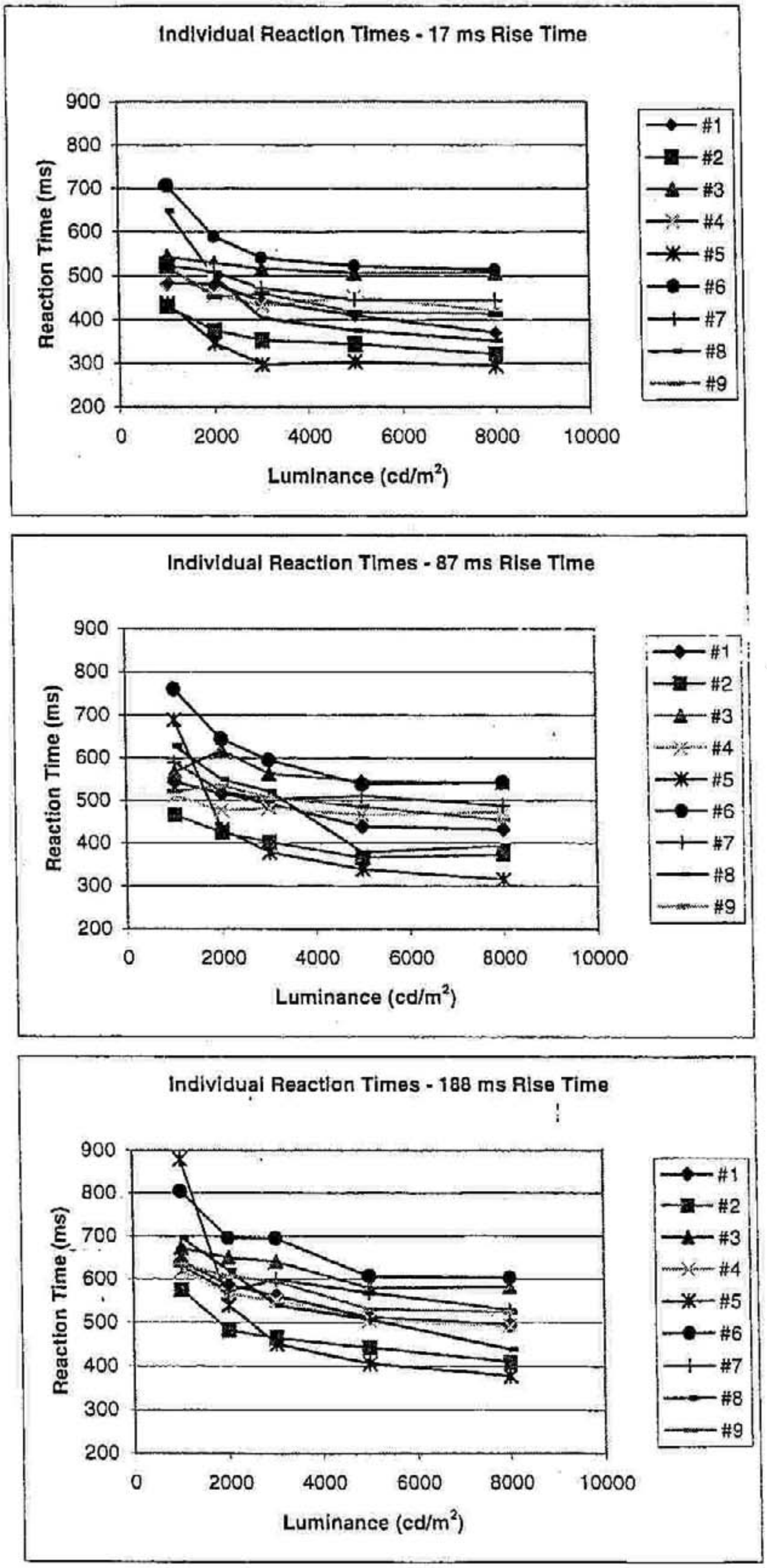

Figure 4. The mean reaction time for each subject, for each combination of the signal luminance and rise time, for the red signal. The key identifies the individual subjects numbered 1 to 9.

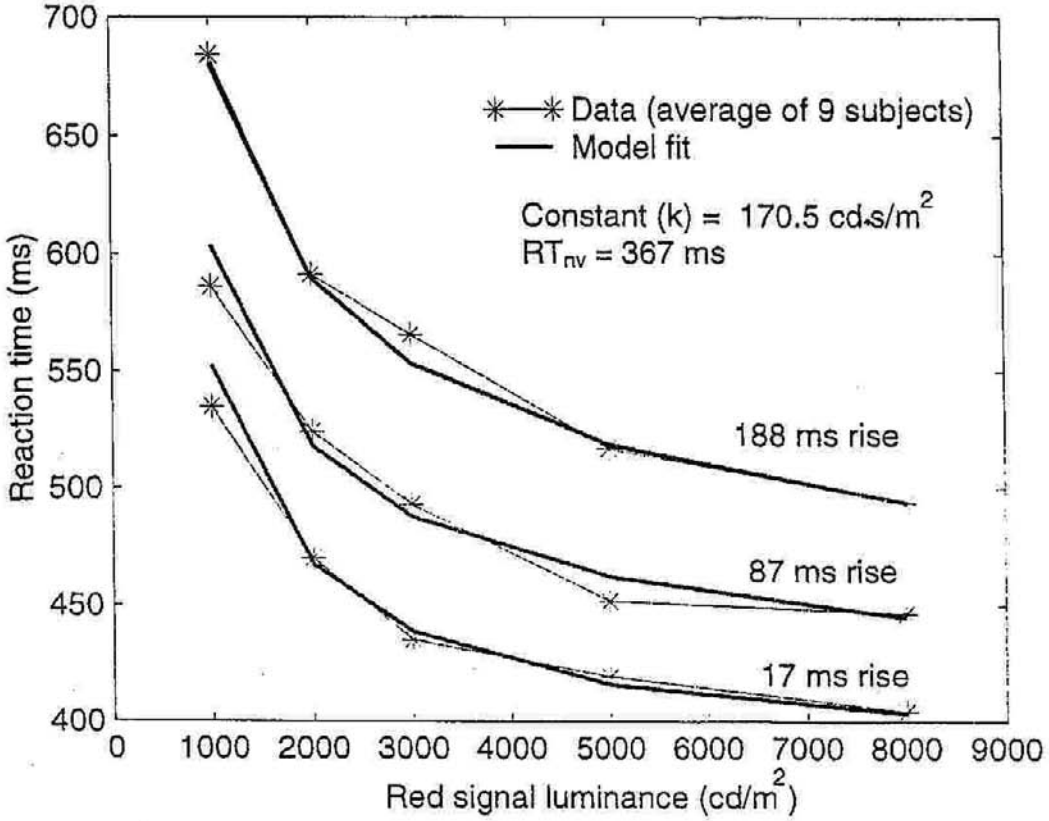

Figure 5. Overall mean reaction times for the red signal, for different signal luminances and rise times. Also shown are the predicted reaction times for the same conditions based on the constant signal energy model of visual reaction time. The variance in mean reaction time explained by the model is greater than 97% for all three rise times.

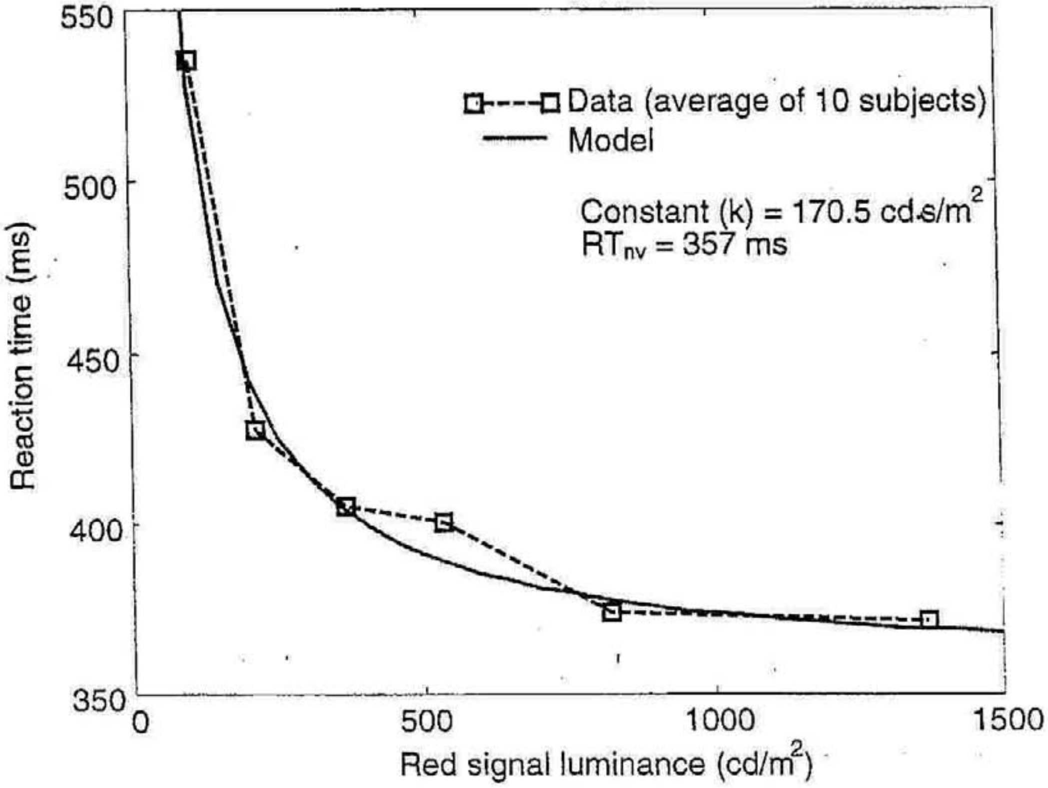

Figure 6. Mean reaction times for the red LED signal data from Bullough et al. (1999) and the predicted reaction times from the equal signal energy model, using the same constant (k = 170.5 cd.s/m^2). The non-visual reaction time for this group of subjects is 357 ms.

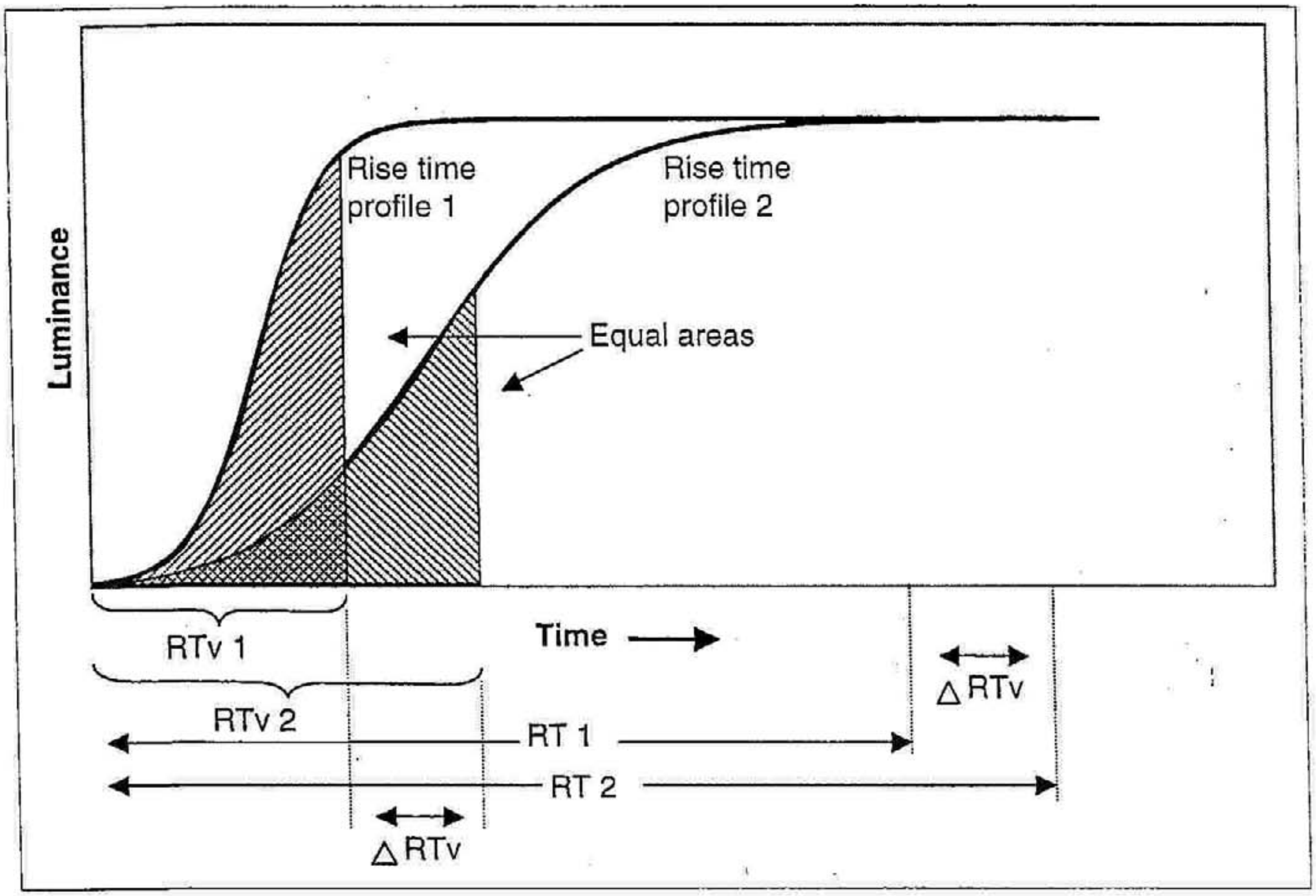

Figure 7. A schematic illustration of the process to estimate the effect of differences in rise time profile on the differences in reaction time.

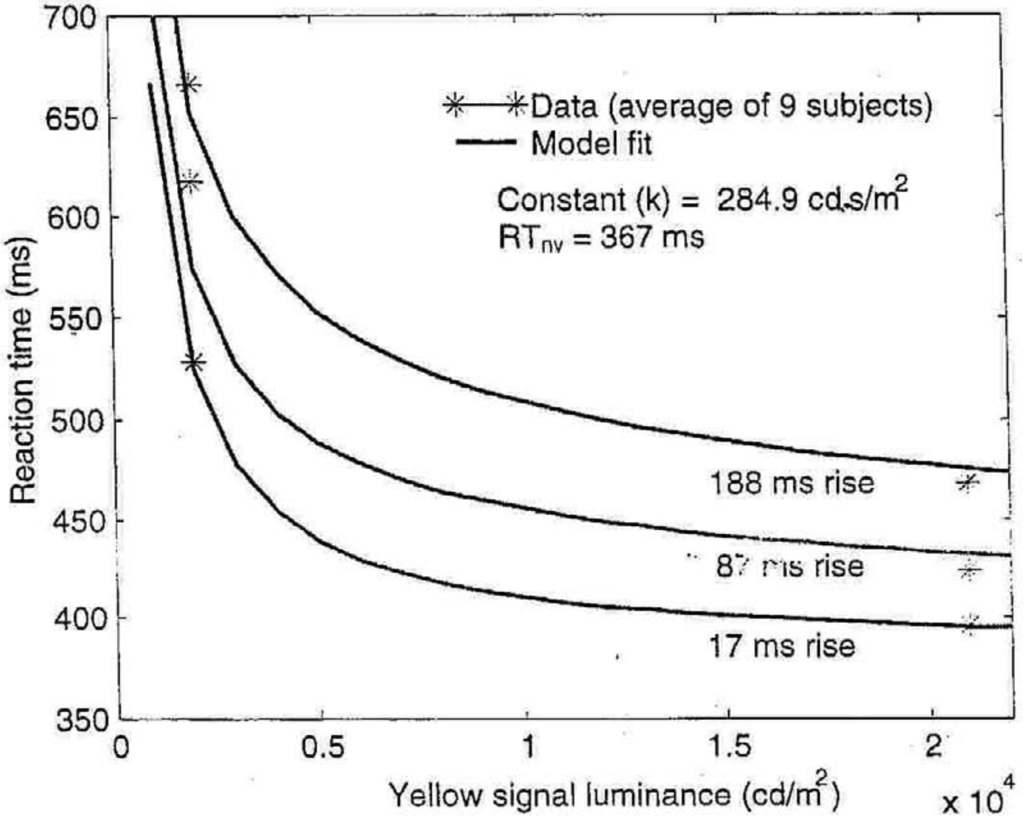

Figure 8. Overall mean reaction times for the yellow LED signal, for different signal luminances and rise times. Also shown are the predicted reaction times for the same conditions based on the constant signal energy model of visual reaction time. The horizontal axis values are multiplied by 10^4, i.e., the value 2 corresponds to $2 \times 10^4 = 20{,}000$ cd/m^2.