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RESEARCH & RADIONAVIGATION
GENERAL LIGHTHOUSE AUTHORITIES
United Kingdom and Ireland

# A "Variable a" Approach to Flashing Light Apparent Intensity

## Conspicuity Modelling

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## Executive Summary

Since the invention of flashing signal lights, the question of how a flash of light compares with a continuous (‘fixed’ or ‘steady’) light has been pondered. The increase in intensity or efficiency, as a result of focussing or switching the light source, is offset by the fact that a flash of light is not seen so effectively by the observer due to the inertia of human visual perception.

The currently recommended method of quantifying the effects of a flashing light on human visual perception is a photometric quantity called effective intensity, which is the ‘fixed light equivalent’ of a flash of light. The definition of effective intensity intends the flash to be viewed at the threshold of visual perception, but that is not how marine aid to navigation (AtoN) lights are viewed. By international agreement, the range of marine AtoN lights is calculated from an observer illuminance above the threshold of perception. Therefore, the use of effective intensity is not valid for determining the range of a marine AtoN flashing light.

This report discusses models of effective intensity dating back over one hundred years. It also looks at experimental work carried out in the 1930s that studied flashing lights above the threshold of visual perception (supra-threshold). Further scientific studies carried out in the 1930s and 1960s suggested modifying the Blondel-Rey model for effective intensity so that it could be used at supra-threshold levels by linking the value of illuminance at the observer to a time-constant for visual inertia (often known as *a*) in the equation for the Blondel-Rey model. Since the term ‘effective intensity’ is only valid at the threshold of visual perception, it is suggested that the term assigned to perception of a flash above threshold be ‘apparent intensity’.

The use of apparent intensity should enable lighthouse authorities to model the effect of different flash profiles at levels of illuminance from 0.2 microlux (currently recommended for AtoN lights at night with no background lighting) to higher levels of illuminance. This is particularly pertinent for leading lights and lights with minor and substantial background lighting. This report also identifies a potential saving of energy by reducing the flash duration of lights.

However, the apparent intensity model described is crude and based on a limited set of experimental results some eighty years old. Recommendations include carrying out a repeat of the original 1930s experiment, extending the scope of the experiment to higher levels of illuminance and looking for models with a better fit to the experimental data.

## Author’s Note

The ideas in this document have been considered over many decades and it requires a vast amount of study and intimate knowledge to make sense of it all. I am deeply indebted to Dennis Couzin for his knowledge, guidance and continued enthusiasm in this subject.

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## Reference Documents


RD1 IALA Draft Recommendation E-200 part 2, “On Marine Signal Lights - Calculation, Definition and Notation of Luminous Range” – December 2008.

RD2 IALA Draft Recommendation E-200 part 4, “On Marine Signal Lights - Determination and Calculation of Effective Intensity” – December 2008.

RD3 CIE TC2-49 Draft Report, “Measurement of Effective Intensity of Flashing Lights”.

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# 1 Introduction

Ever since signal lights have been flashed, the question of how a flashing light compares with a continuous ('fixed' or 'steady') light has been pondered. Lighthouses in the nineteenth century benefited from using mirrors and lenses to focus the light from candles and oil lamps into pencil beams, thereby increasing the intensity of the light in a few horizontal directions. These pencil beams were then rotated so that the light could be seen all around the horizon. To the mariner at sea observing the light, it would appear to flash as the beams swept past the eye. The rotation speed of the optical apparatus and the physical placement of the mirrors or lenses could be varied to provide different rhythmically flashing characters, helping the mariner to identify individual lighthouses at night. However, the increase in intensity due to the focussing apparatus was offset by the fact that a flash of light was not seen so effectively by the mariner as a continuously shining light, this was due to the slow response of the human visual system.

**Figure 1 Rotating Multiple Pencil Beam Apparatus at Casquets Lighthouse**

Over the last century or more, several attempts have been made to model the effect of a flashing light upon the human visual system, the so-called 'effective luminous intensity'. All models give a 'fixed light equivalent' intensity of a flash of light and all models incorporate a factor for the visual inertia of the eye, a time constant to which we will assign the symbol $a$ for the purposes of this document.

There is a problem with any effective intensity model in that the definition of effective intensity is only valid at the achromatic threshold of visual perception. In practice, flashing lights are typically viewed well above this level where effective intensity models of human visual perception do not apply. This document proposes to investigate past experimental work done on flashing lights above threshold, to confirm the results by repeating these experiments and find suitable mathematical models to fit the results of the experiments. In particular, since we know that the perception of flashing lights varies with the level of illuminance at the eye of the observer, it is desirable to link the chosen model to the illuminance level.

Described in section 3 is a crude method of linking an existing effective intensity model to the supra-threshold illuminance at the observer by varying the visual time constant $a$. It is only valid for a rectangular pulse or flash of white viewed against a dark background light and is only verifiable over a limited range of illuminance values. Furthermore, the fit of the model is less than ideal and the visual experimental data was taken from an experiment carried out some eighty years ago.

# 2 Effective Intensity Models

Given below are details of four well-known effective intensity models. In the accompanying equations, the original symbols have been unified so that comparison between models is simplified.

## 2.1 Allard

The first attempt at an effective intensity model was by Emile Allard in 1876, whose "Mémoire sur l'Intensité et la Portée des Phares” gave rise to a theoretical equation of:

$$I_e = I_0(1 - e^{-\frac{t}{a}}) \qquad \text{Equation 1}$$

where: $I_e$ is effective intensity of a pulse or flash of light in candelas

$I_0$ is peak intensity of a pulse or flash of light in candelas

$t$ is the duration of the pulse or flash in seconds

$a$ is a time constant of visual inertia in seconds (notionally 0.15s)

This model can be realised in hardware, it being the visual equivalent of an RC low-pass filter.

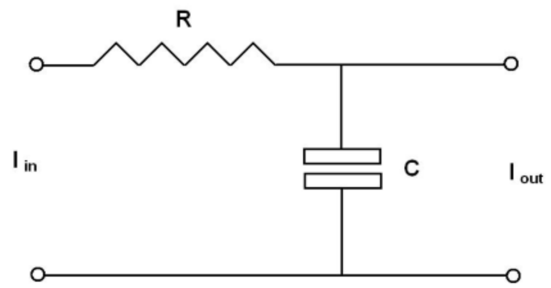
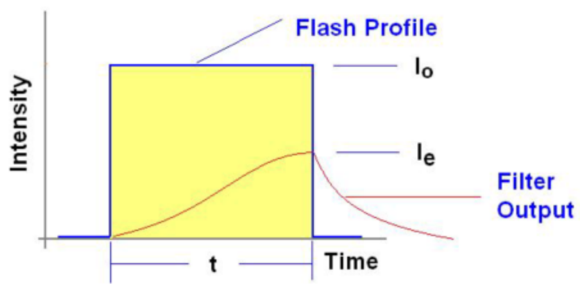



**Figure 2 Equivalent R-C Network of Allard’s Model**

Figure 2 shows an R-C network equivalent of Allard’s model where:

RC <=> $a$ $I_{in}$ max <=> $I_o$ $I_{out}$ max <=> $I_e$

In theory, this model could be used for multiple flashes or pulses as well as single flashes. The peak of the filter output is equivalent to the effective intensity whatever the input.




## 2.2 Blondel-Rey

The classic work on evaluation of effective intensity was that of André Blondel and Jean Rey in 1911. The formula based on their experimental observations was limited in its application to a single flash of rectangular or quasi-rectangular form:

$$I_e = \frac{I_0 t}{a+t} \qquad \text{Equation 2}$$

Blondel and Rey calculated a value of 0.21s for *a*.

Further work by Blondel and Rey provided another equation which extended Equation 2 to general flashes. This was expounded by Douglas (1957) whose equation can be written as:

$$I_e = \frac{J^*}{a+t^*}$$

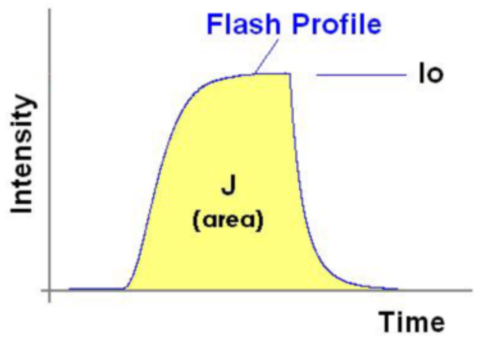
Here J* is the time integral of the intensity over a specially chosen time span. t* is the length of that time span, which is chosen so as to maximize the value of $I_e$ defined in the equation. This mathematically difficult computation, which requires an iterative process to solve, has not found much use in the maritime environment but is used in the aeronautical sector.

## 2.3 Schmidt-Clausen

In 1968, Hans-Joachim Schmidt-Clausen carried out experiments to verify the method of Blondel and Rey and to extend its use to flash shapes other than rectangular. His study concluded that the integrated intensity, *J*, could be used instead of the product of $I_0$ and *t* in his 'form factor' method:

$$Ie = \frac{J}{a + \frac{J}{I_0}} \qquad \text{Equation 3}$$

where: *J* is the integral of intensity with respect to time for the duration of the flash $\int_{t_0}^{t_n} i(t)dt$ (i.e. the area under the flash profile in candela.seconds)




Schmidt-Clausen gave several values of *a* depending on the colour of the light being viewed and the background luminance, both of which he experimented with. However, a value of 0.2s was recommended for achromatic viewing. This model was still only suitable for single flashes.

## 2.4 Modified Allard

In 2005, after prolonged discussions within the Commission Internationale de l'Eclairage (CIE), an improved effective intensity model was proposed by Dennis Couzin and Yoshi Ohno. This was after concerns had been raised about errors that were inherent in the

Schmidt-Clausen model when dealing with complex flash shapes and rapid trains of flashes. It was recognised that significant work had been undertaken by the Russian physicists A.V. Luizov and K.N. Bulanova in the 1960s. L&B recognised the power of Allard's model because it could deal with any shape of flash and even repeated flashes (unlike B-R and S-C). The problem was that the Allard model did not agree with visual experimental results carried out at the threshold of perception. L&B proposed that a mathematical convolution of the flash profile and an eye response function be used, the peak value of which would be effective intensity:

$$I_e = \max[i(t) \otimes q(t)] \qquad \text{Equation 4}$$

where $I_e$ is effective intensity

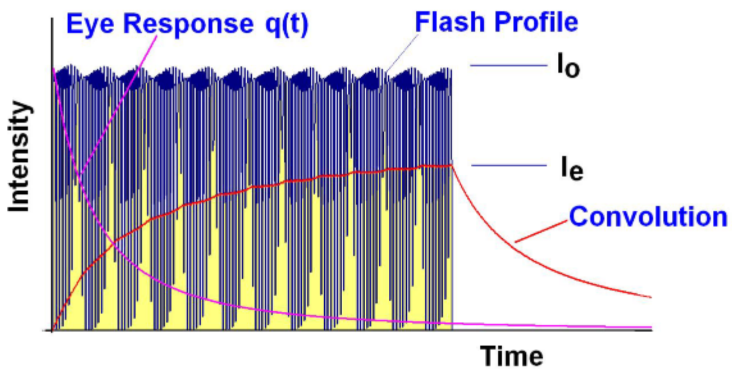
*i(t)* is the variation in intensity of the flash profile

*q(t)* is the eye response function where:

$$q(t) = \frac{a}{(a+t)^2} \qquad \text{Equation 5}$$

where: *q* is the efficiency of the eye's response at time *t*

Note: Allard's model can be considered as a convolution where $1-e^{-\frac{t}{a}}$ was the original *q(t)*




At the time of writing, the CIE recommended value for *a* is 0.2s for achromatic viewing. This model agrees with Blondel Rey and Schmidt-Clausen for rectangular pulses at threshold but is also valid for complex flash profiles and repeated flashes at threshold.

The Modified Allard method is therefore another extension of Blondel-Rey (equation 2) to general flash forms. It has had empirical confirmation for several flash shapes and pulse train frequencies.

## 3 Above Threshold Levels of Illuminance

All of the models so far proposed are based on the performance of the human eye at the threshold of visual perception; where the observer can just perceive a flash or pulse of light. The value of illuminance at the eye of the observer for a steady light under these threshold conditions ($E_t$) varies considerably between observers but a value of 0.05 microlux is a reasonable estimate. This causes a problem when using an effective intensity model for marine aid to navigation (AtoN) flashing lights because an internationally agreed value of 0.2 microlux was decided upon in 1933 as the value of illuminance at the observer's eye. An illuminance of 0.2 microlux was recognised as the minimum level required to detect, recognise and identify a marine AtoN light at sea – but it is significantly higher than the threshold of perception levels used for the effective intensity models described above. An illuminance value of 0.2 microlux is recommended by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) for the calculation of the nominal range of a marine AtoN light at night.

IALA make further recommendations regarding illuminance at the observer:

- for the use of leading lights – 1.0 microlux;
- lights viewed against minor background lighting – 2 microlux;
- lights viewed against substantial background lighting – 20 microlux.

Since the term ‘effective intensity’ has the specific definition of being at the threshold of visual perception, it cannot be used to define how a flash of light is perceived above that threshold. Instead, it is proposed that the term ‘apparent intensity’ (as used by Toulmin-Smith and Green) should be used along with the Symbol $I_a$. Furthermore, since the value of $I_a$ for a given flash shape will vary with the level of illuminance at the eye of the observer, it has been suggested by Dennis Couzin that $I_a,E_c$ be used, where $E_c$ is the illuminance at the eye of the observer in microlux. Of particular interest to lighthouse authorities and IALA is the value of $I_a,0.2$ (0.2 microlux being the internationally agreed value of $E_c$) – the apparent intensity of a flashing AtoN light at its nominal range.

In 1933, Toulmin-Smith and Green used brightness matching in their visual experiments into the perception of rectangular flash shapes at various illuminance levels at the eye of the observer. Although there is some scepticism about observers' judgements of brightness equality between flashes and steady lights, this is the judgement which underlies the Broca-Sulzer effect (1910), which has been studied by several good perceptual psychologists, so the judgements are considered reliable.

T-S&G used flash lengths from 0.05s to 0.5s and produced a set of curves normalised for three observers (see figure 3).

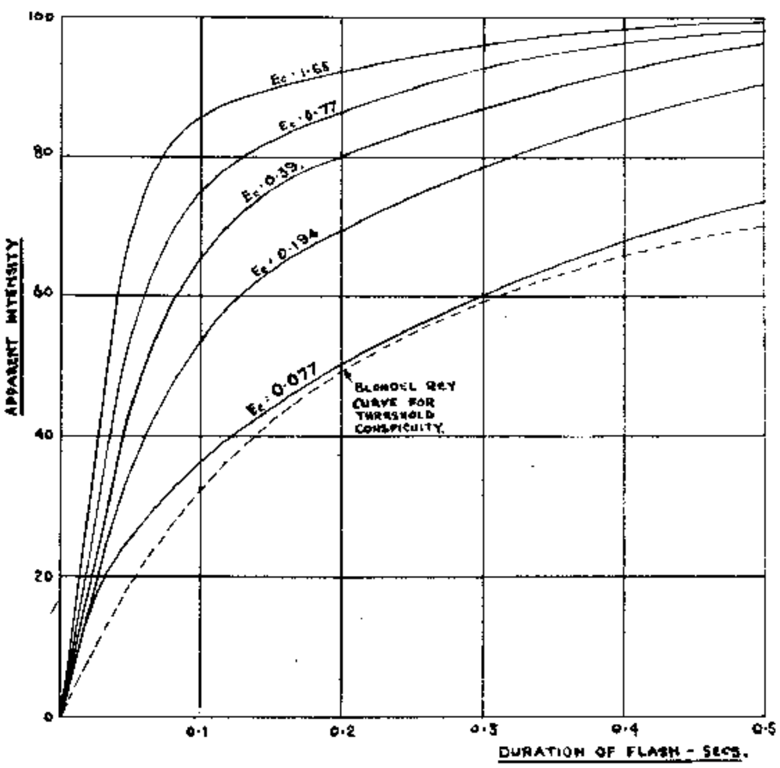



**Figure 3 Toulmin-Smith and Green’s Results of Experiment of Flashes above Threshold ($E_c$ is the illuminance in microlux)**

It can be seen that one of the illuminance values they chose was 0.194 microlux – close to 0.2 microlux! Dennis Couzin discovered further work by Hampton that suggested linking the Blondel-Rey formula to the results of T-S&G. The formula suggested by Hampton was:

$$\log a = -1.63 - 0.81 \log E_c$$ Equation 6

where: *a* is a time variable of visual inertia in seconds

$E_c$ is the illuminance at the observer's eye in microlux

In order to test Hampton's equation, the original graph by Toulmin-Smith and Green was redrawn digitally and the Blondel-Rey formula (equation 2), with the value of *a* modified by Hampton's formula (equation 6), was used to calculate the apparent intensity ($I_a$,$E_c$) values using the original T-S&G illuminance values (0.077, 0.194, 0.39, 0.77 and 1.55 microlux). A peak intensity $I_0$ value of 100cd was used for flash durations (*t*) varying from 0 to 0.5 seconds.

Plots of the digitised T-S&G data along with plots of the modified B-R apparent intensity model (dotted lines) are shown in figure 4. The plot of the Blondel-Rey effective intensity values for threshold is also shown.

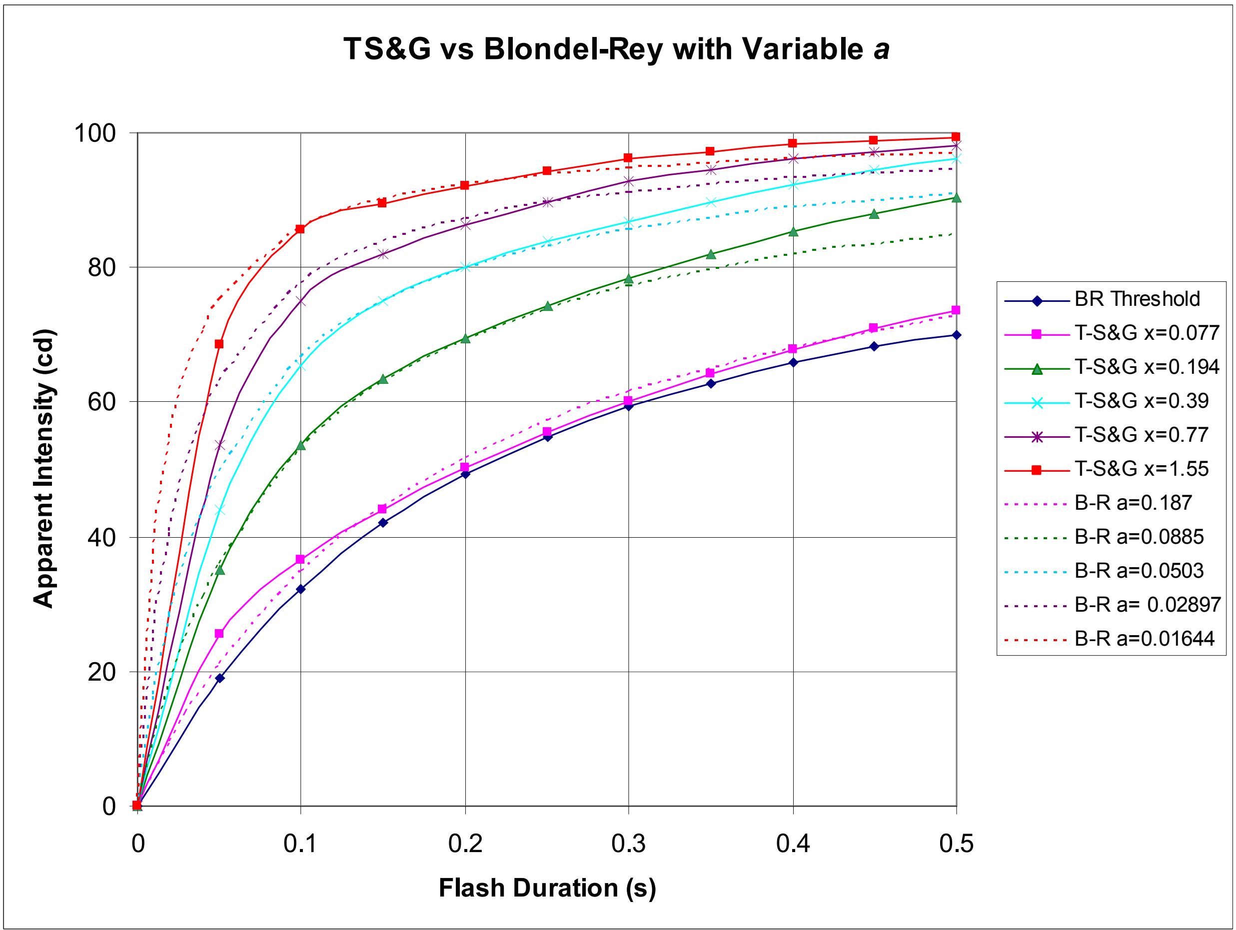



**Figure 4 Graph showing the Blondel Rey model with *a* calculated from $E_c$ (dotted lines) compared with the original Toulmin-Smith and Green Results (solid lines)**

# 4 Conclusions

- The method described in section 3 of linking the existing Blondel-Rey effective intensity model to the supra-threshold illuminance at the observer by varying the visual time constant *a* is only verified for rectangular pulses or flashes of white light against a dark background.

- The method is only verified over a limited range of illuminance values from 0.077 microlux to 1.55 microlux from the data available.
- It has been noted that the flash duration range in the original T-S&G experiments only went as low as 0.05s.
- The T-S&G data was taken from an experiment carried out in 1933 and the original raw data was not available.
- The fit of the model to each of the original T-S&G data curves is less than ideal but for supra-threshold flashes, especially the 0.2 microlux illuminance level, it is an improvement on the currently recommended effective intensity model at threshold.
- Modern LED flashing lights typically have a rectangular flash profile, the effective intensity of which can be approximated by the Blondel-Rey method.
- If the proposed apparent intensity model at supra-threshold illuminance levels is used to evaluate the performance of flashing LED lights instead of the existing effective intensity model, shorter flashes will be favoured. This means that a short flash will have a greater apparent intensity compared to its effective intensity – or that the flash can be shortened to maintain the same range thereby saving energy. Improvements to flashes of different length are summarised as follows:

**Table 1 Comparing Effective and Apparent Intensity**

| Flash Duration (seconds) | Effective Intensity *Ie* (at threshold) for *Io* = 100cd (cd) | Apparent Intensity *Ia* (at 0.2 microlux) for *Io* = 100cd (cd) | % Increase in Intensity between *Ia* (0.2 microlux) and *Ie* (threshold) |
|---|---|---|---|
| 0.05 | 19 | 35 | 85% |
| 0.1 | 32 | 54 | 66% |
| 0.15 | 42 | 63 | 51% |
| 0.2 | 49 | 69 | 41% |
| 0.25 | 55 | 74 | 36% |
| 0.3 | 59 | 78 | 32% |
| 0.4 | 66 | 85 | 30% |
| 0.5 | 70 | 90 | 29% |

- As a rule of thumb, when changing from an effective intensity model to an apparent intensity model based on an illuminance of 0.2 microlux, for flashes up to 0.5s, the flash duration can be halved to achieve the same nominal range.
- The usable range of leading lights (sometimes referred to as range lights) is calculated from an observer illuminance of 1.0 microlux, as recommended by IALA. Their rhythmic characters tend to contain long flashes so that it is easier for the mariner to align the front and rear lights. At such high levels of illuminance, and with flash durations longer than one second, the apparent intensity ($I_a$,*1.0*) can be taken to be the same as the peak intensity $I_0$.

## 5 Recommendations

- It is recommended that the experiments of Toulmin-Smith and Green be repeated and results compared with those from the original experiments to verify the original results.

- If possible, the repeat experiment(s) should also extend the scope of the original experiments to an illuminance value ($E_c$) of 20 microlux in suitable steps (e.g. 2, 5, 10, 15, 20).
- Experiments should be carried out using *experienced* observers under the following conditions:
  - a point light source (≤1' of arc);
  - white (D65) light source;
  - viewed against a black background;
  - viewed foveally in complete darkness with dark adapted observers;
  - rectangular flash profiles from 0.01s to 1s.
- The results of the experiment(s) should be studied in order to find a mathematical model of apparent intensity with a close fit to experimental results.
- If these experiments are successful, further experiments should be carried out with:
  - complex flash profiles (white light);
  - background luminance (white);
  - different coloured lights;
  - different coloured background.

  However, the number of variables for these further tests will increase significantly, as will the potential for error.

# 6 Glossary of Terms

| | |
|---|---|
| Luminous Range<br>(CIE Definition) | The maximum distance at which a point source of light can be detected achromatically |
| Luminous Range<br>(IALA Definition) | The maximum distance at which a light can be seen, as determined by the luminous intensity *I* of the light, the meteorological visibility *V* and the threshold of illuminance $E_t$ at the eye of the observer. At this distance, the illuminance *E* at the observer's eye is reduced to the threshold value $E_t$ |
| Threshold of Illuminance (International Lighting Vocabulary Definition) | Smallest illuminance (point brilliance), produced at the eye of an observer by a light source seen in point vision, which renders the source perceptible against a background of given luminance; the illuminance is considered on a surface element that is normal to the incident rays at the eye.<br>*Note. – For visual signalling the light source must be rendered recognizable, and hence a higher threshold of illuminance is to be expected.* |
| Effective Intensity | The luminous intensity of a fixed (steady) light, of the same relative spectral distribution as a flashing light, which would have the same luminous range as the flashing light under identical conditions of observation |
| Flash duration | The total time duration for which a flash of light is exhibited |
| Flash profile | The variation in luminous intensity of a flash of light with respect to time |
| Achromatic threshold | The illuminance at the eye of the observer at which light is just detectable. At this level no colour is discernable and a steady light flickers in and out of vision. |
| Fovea | The area consisting of a small depression in the centre of the retina where vision is most acute. |
| Foveal Vision | Central or direct vision where the object in view is focussed on the fovea. |