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Visual Perception of Non-rectangular Flashes at Threshold

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Executive Summary

The Research and Radionavigation Directorate (R&RNAV), is carrying out a series of visual experiments on flashing lights as part of its investigation into the conspicuity of marine aid to navigation signals. This latest experiment involved the observation of various flash shapes at the threshold of perception. The aim of the experiment was to try and find a link between the shape, and duration, of a flash and its apparent brightness. Results of observations were compared with established methods of effective intensity evaluation in order to assess their suitability for use as a measure of conspicuity. The results of the experiment are of interest to CIE technical committee TC2-49, currently studying the photometry of flashing lights and whose aim is provide a suitable effective intensity model.

Results of the experiment, using three observers, showed that the effective intensity of triangular flash profiles predicted by the Modified Allard Method did not compare favourably to the observed data. Whilst the perception of asymmetrical triangular flashes followed the Blondel-Rey model fairly closely, symmetrical triangle flash profiles were, on average, more readily perceived.

It was concluded that, although the Modified Allard Method has significant advantages in dealing with complex flash shapes and repeated flashes, its currently recommended impulse response function, q(t), is unsuitable for the determination of effective intensity of complex flash profiles. The Modified Allard Method with a 'shear q3' q(t) was found to be more appropriate but not ideal. However, differences in results between individual observers were considerable, giving a higher than desirable uncertainty to the average results. Recommendations include carrying out further observations with many more observers in order to augment the results of this experiment. Results of this experiment should be presented to the IALA Engineering Committee and the CIE technical committee TC2-49.

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Reference Documents

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RD2 BLAISE, M. P. 1972. The Effective Intensity of Short Flashes, IALA Bulletin 52, IALA, Paris.

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1 Background

How a human perceives a flashing light has been a subject of debate for centuries. In 1885, Bloch proposed a relationship between the duration of a flash of light and its perceived intensity, giving rise to Bloch's law of temporal summation[RD3]. This concept was counter to Allard's [RD1], some nine years earlier, that proposed a convolution of the flash shape with an exponential impulse response function. Blondel and Rey's 1911 proposal[RD4] for the perception of a flash of light, which became a widely used method for evaluating effective intensity over several decades, was based on Bloch's law.

In 1960, Luizov[RD9] proposed using a convolution method, similar to Allard's, but with an impulse response function based on a derivative of the Blondel-Rey formula. This had the advantage that the calculated effective intensity for rectangular flashes agreed with the Blondel-Rey method but that it could be applied to complex flash shapes and repeated flashes; something that proved impractical for other methods except Allard's. The Modified Allard Method[RD13], as Luizov's proposal came to be known, was presented to CIE in 2003 and adopted by IALA in 2008[RD10].

Although the Modified Allard Method yields the same effective intensity values as the Blondel-Rey method for rectangular flash shapes, one troubling aspect is that it does not obey Bloch's law. Non-rectangular flash shapes of equal temporal summation may yield quite different effective intensity values when the Modified Allard Method is applied and this is at odds with the widely accepted Blondel-Rey method. Bloch's law certainly holds true for flashes of a short duration but, other than Schmidt-Clausen's experiments[RD14], it has not been tested over a wide range of complex flash shapes or durations. In 1972, Blaise[RD2] suggested an experiment that would prove or disprove Bloch's law, which involved observation of flashes with an asymmetrical triangle shape. Two equal but chirally opposite triangular flash shapes would be observed. If they appeared to be the same brightness to the observer, Bloch's law would be vindicated. If brightnesses appeared unequal, Bloch's law would be disproved. Thus, Blaise proposed a simple test that until recently had not been carried out, with the exception of a limited experiment carried out in 2015 in Berlin[RD8].

2 Introduction

The experiment involved three observers carrying out observations of a series of flashing lights in complete darkness and adjusting the brightness of the flash until it could just be seen when looking directly at it (foveal threshold of perception). Flash profiles observed were: rectangle; asymmetrical triangle with rising edge (up triangle); asymmetrical triangle with falling edge (down triangle); and symmetrical triangle. Flash durations varied between 0.025 seconds and one second.

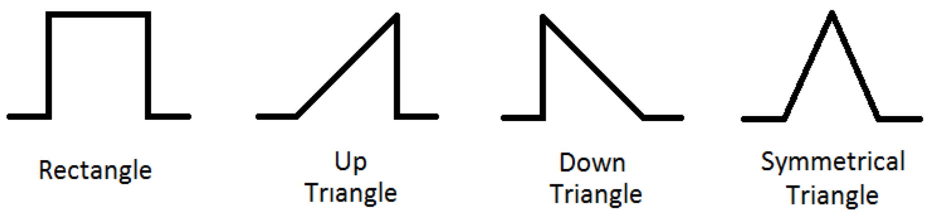


Figure 1 Flash Profiles used in the Experiment

All observers were experienced and had previously been used in visual experiments for R&RNAV in the same location, the dark room in the R&RNAV Lights Laboratory at Harwich, UK.

3 Terminology

3.1 effective intensity (of a flashing light), I_{eff}, I_e

luminous intensity of a fixed light, of the same relative spectral distribution as the flashing light, which would have the same luminous range as the flashing light under identical conditions of observation[RD5]

3.2 flashing light

rhythmic light in which every appearance of light (flash) is of the same duration and the total duration of light in a period is clearly shorter than the total duration of darkness

NOTE: The term "eclipse" is used for the interval of darkness between two successive distinct appearances of light. [RD5]

3.3 flash (of light)

brief appearance of light, the intensity of which starts from a negligible amount, increases to a significant level, and falls to a negligible amount[RD5]

3.4 flash duration

period of time in which all the flash waveform necessary for determining the effective intensity of the flash is included[RD5]

3.5 flash profile

characteristic variation of instantaneous luminous intensity over the course of time during an appearance of light (flash)

3.6 fovea

central part of the retina, thin and depressed, which contains almost exclusively cones and forming the site of most distinct vision[RD5] (hence foveal vision)

NOTE: The fovea subtends an angle of about 0.087 radians (5°) in the visual field[RD5]

3.7 impulse response function, $q(t)$

the output signal of a system that results when an impulse is applied to the system input

for the human visual system, it is a hypothetical output signal in the human visual system, as a function of time t, in response to an instantaneous visual input stimulus (CIE proposed definition)

3.8 luminous range

greatest distance at which a given signal light can be recognised in any particular circumstances, as limited only by the atmospheric transmissivity and by the threshold of illuminance at the eye of the observer[RD5]

NOTE: Typically taken as the distance at which a point source can be detected achromatically

3.9 time-integrated luminous intensity, *J*

the definition can also be expressed as: time-integral of the (instantaneous) luminous intensity, *I(t)*, over a given duration, *Δt* (CIE proposed definition)

NOTE: time-integrated luminous intensity is expressed in candela seconds

3.10 train of flashes

group of two or more flashes, followed by a period of darkness, within a period of a flashing light[RD5]

3.11 visual time constant, *a*

duration related to the human visual processing of a light signal, when a point source is focussed on the fovea at about the threshold of detection[RD5]

NOTE: Although there is no precisely-defined value for the visual time-constant, a value of 0.2s is commonly used in effective intensity models for a dark-adapted observer.

4 Scope

The scope of this experiment was the observation of artificially produced point source white lights, flashing and steady, at the achromatic threshold of human foveal vision. Flash profiles were rectangular or triangular, of duration between 0.025 seconds and one second. The eclipse time between flashes was one second. The flash frequency therefore varied between 0.5Hz and nearly 1Hz. Observations were carried out in complete darkness with binocular vision by a dark-adapted observer. All observations were carried out with a reference, or fixation, light to ensure that the observer viewed the point light source in foveal vision.

5 Objectives

The objective of this experiment was to investigate how humans perceived a variety of flash shapes and durations at the threshold of perception in foveal vision. Of particular interest was the difference in perception between triangular flashes of different shapes but of the same durations, peak intensities and time-integrated intensities. The results of the visual observations were to be compared with predicted results from the various standard methods of determining effective intensity to assess the suitability of those methods.

6 Equipment

Experiments were carried out with equipment used in previous R&RNAV experiments[RD11, RD12] but modified to exhibit a variety of different flash shapes. The Bentham ILFD20QH brightness matching equivalence rig was modified for threshold perception, rather than brightness matching for which the equipment was originally designed. The 3000K halogen lamp used for the flashing light source within the Bentham rig was replaced by a 1W 3000K warm white LED driven by a programmable flash generator specifically built for the purpose. The flashing pattern shutter, originally used to generate rectangular flash profiles by interrupting a steady light, was set permanently open.

6.1 The Modified Bentham ILFD20QH Fixed/Flashing Light Equivalence Rig

The modified Bentham ILFD20QH Fixed/Flashing Light Equivalence Rig comprised a box which contained an integrating sphere with a single 0.63mm diameter pinhole output aperture. One tungsten halogen source and one LED light source input light to the integrating sphere, each via a slit, the width of which could be adjusted to determine the amount of light entering the sphere. The LED light source could be flashed with a number of different profiles and durations controlled by the program in the Programmable Flasher PF1. Shutters controlled which light source, steady or flashing, illuminated the integrating sphere. An internal photometer measured the luminance of the light within the integrating sphere when either shutter was opened. The internal photometer was originally calibrated for a halogen light source but, because of errors in the photometer spectral response, measurement of an LED leads to an error due to differences in the LED spectrum. This error was measured and a spectral correction factor (SCF) of 1.16667 was calculated and applied to LED measured values.

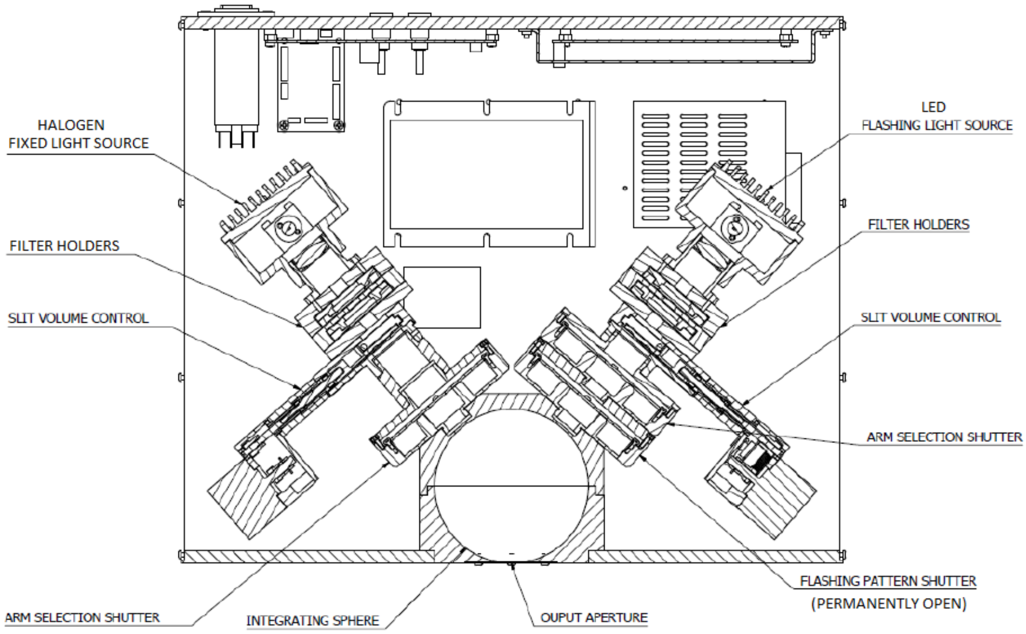


Figure 2 Modified Bentham ILFD20QH Optical Layout

6.2 Bentham ILFD20QH Software

Overall control of the Bentham ILFD20QH was achieved via a USB port connected to a personal computer (PC) with bespoke software installed. The software was used to set up an experiment exhibiting selected flash profiles and rhythms at adjustable levels of illuminance at the eye of the observer. The measured luminance from within the integrating sphere was converted to observer illuminance by the program, using the pinhole area and an observation distance of 2.2 metres.

A game controller was connected to the PC via another USB port; this allowed the observer to toggle between steady and flashing lights as well as to adjust the brightness level of the flashing light. The up/down buttons, used to adjust the brightness of the flashing light, had some random delays built into their operation. Therefore, the observer could not predict the degree of increase or decrease achieved when pressing the up/down buttons.

The brightness of the steady light was preset by the experimenter via the software to 0.2 microlux at the observer.

6.3 Programmable Flasher PF1

The PF1 was a programmable light flasher capable of producing flashes of light of any shape or duration. It was designed for use in visual experiments at relatively low levels of observer illuminance and came pre-programmed with six different flash profiles, each of which had eight or nine flash durations ranging from 25 milliseconds to one second. The pre-programmed flash profiles were rectangular, rectangular with pulse-width modulation (PWM), up triangle (leading edge sloping), down triangle (trailing edge sloping), symmetrical triangle (both leading and trailing edges sloping) and Gaussian, any one of which could be selected by a rotary switch. Examples of flash profiles used in this experiment are shown in Annex 2.

The power supply for the PF1 was a 12V 500mA plug-in type with a 2.1mm coaxial DC plug that fitted the DC socket on the PF1; there was no separate on/off switch. The LED provided came with a length of cable fitted with a phono plug allowing connection to the PF1.

Controls

RPUDSG	-	flash profile selector, **R**ectangle, **P**WM, **U**p triangle, **D**own triangle, **S**ymmetrical triangle, **G**aussian
Q/S	-	flash duration order, **Q** = quick flash first, **S** = slow flash first
Reset	-	program reset after selecting flash profile or order
Steady	-	when pressed, brings on a steady light of fixed intensity (when programmed)
Vary	-	controls the intensity of the flash
F/M	-	**F** = repeated (selected) flash with a one second eclipse, when switching to **M** the light continuously displays the peak intensity of the flash depending on the 'Vary' control setting.

Connections

LED	-	LED socket (phono)
USB	-	USB connection (3.5mm stereo jack)
12V	-	12VDC power input (coaxial 2.1mm)

Although designed as a stand-alone device, the PF1 was modified for use with the Bentham ILFD20QH Rig. This involved:

- disabling the 'Vary' control because the intensity was controlled by the observer operating the game controller to vary the slit width within the Bentham Rig;
- ignoring the 'Steady' control because it was not needed for threshold experiments;
- ignoring the USB connection, needed to gather measurement results, because the Bentham ILFD20QH measured and stored the results of the experiment.

A 3000K white LED, driven by the PF1 was used to replace one of the tungsten halogen light sources (flashing) in the Bentham Rig.

Figure 3 PF1 Programmable Flasher

6.4 Fixation Light

Although the majority of observations were carried out in complete darkness, a fixation light was used for all observations. The fixation light was designed to ensure that the observer kept the pinhole aperture in foveal vision.

A light source was constructed that consisted of a sheet of 5mm thick clear cast acrylic sheet with a 60mm diameter hole in its centre. One side of the hole was given a slight 45 degree chamfer. At either side of the sheet, the edge was drilled with a 3mm diameter hole into which a 650nm red LED was fitted. The whole of the surface of the sheet was blackened except for the chamfer. The LEDs were wired in series and supplied from a variable current power supply. The sheet was then placed directly in front of the Bentham ILFD20QH such that the pinhole was at the centre of the 60mm hole in the sheet.

When lit, the fixation light formed a thin annular red light, 60mm in diameter, around the pinhole and concentric with it. At the observer distance of 2.2 metres, the subtense angle of the fixation light ring was approximately ±0.8 degrees of arc.

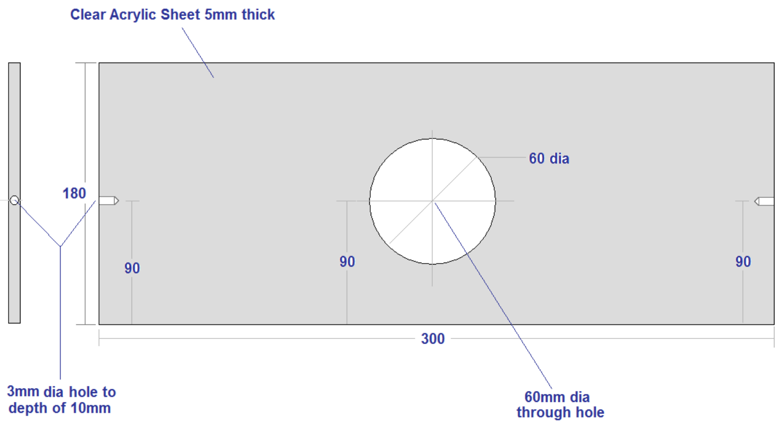


Figure 4 Fixation Light Drawing

7 Experiment Setup

The experiment was set up in a darkened room with the modified Bentham ILFD20QH in one corner and a seat for the observer in the opposite corner. The experimenter was seated alongside the Bentham ILFD20QH, where the PC keyboard and visual display unit (VDU) were installed. The PF1 Programmable Flasher was installed alongside the keyboard.

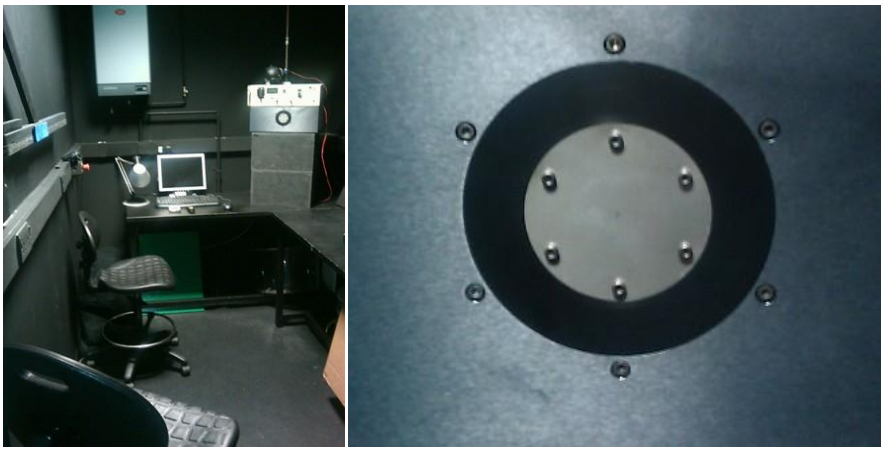


Figure 5 Left: Observer's View of Equipment; Right: Close-up of Pinhole

A hinged bar was installed which could be swung across the dark room and locked into place. The observer could adjust his seating position so that his forehead rested on a padded area on the bar, thereby ensuring his eyes were at the correct height and distance (2.2 metres) from the pinhole.

Figure 6 Left: Observer in Position Right: Experimenter in Position

All light sources within the dark room were disabled and all light from outside was excluded. The VDU was switched off once the experiment was under way.

8 Method

8.1 Experimental Procedure

Preparation

The equipment was switched on and allowed to stabilise for ten minutes. The observer was seated and his position adjusted until he was comfortable and in the correct position with his forehead resting on the padded area of the hinged bar. The programmed experiment was initiated by pressing the 'Run' prompt, after which the VDU screen was switched off. All lights were extinguished and the room checked for stray light.

The observer then waited fifteen minutes to achieve dark adaptation of vision. After a final check for stray light and adopting a comfortable position, the task of visual observation commenced by lighting the fixation light and adjusting its brightness until it could only just be seen. At this level of illuminance, the red annular ring could only be seen in direct vision, not in peripheral vision, which made it difficult to locate in a dark room with no other visual reference.

For this experiment, the usual method of brightness matching successive steady and flashing lights, for which the Bentham equipment was designed, was not used. Instead, the steady light, set to 0.2 microlux illuminance, was only used by the observer to locate the fixation light, the white steady point source being visible in peripheral vision.

Threshold Tests

The observer increased the illuminance of the flashing light until it could be seen clearly. He then reduced the illuminance until it disappeared and slowly increased the illuminance until it could just be seen. This process was repeated several times until the observer was satisfied that the illuminance was just at threshold and ensuring that the final control was always an increase in illuminance. The experimenter then switched the PF1 'F/M' switch to 'M' and prompted the Bentham ILFD20QH to measure the absolute photometric peak value of the flashing light which was automatically stored in the program. Occasionally, due to fatigue or lapse of concentration, the observer rested with eyes closed or lowered. When resuming observations, it was sometimes necessary to toggle to the steady light in order to relocate the red fixation light.

At the end of each observation session consisting of eight or nine flashes of varying duration, the flashing character was replaced by a steady light, the illuminance of which could be controlled by the observer. The same method of increasing, decreasing and increasing the illuminance of the light was used to determine the threshold illuminance value of a steady light.

Recording

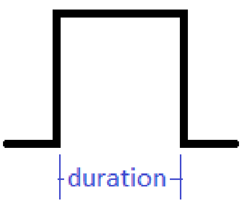
At the completion of observations, comments were made where applicable and saved with the results.

8.2 Flashing Light Experiment Profiles

The following flash profiles and durations in seconds were used. The eclipse time between the end of one flash and the start of the next was always one second. The flash duration was the time between the start of the flash and the end of the flash.

Rectangular Flash Profile

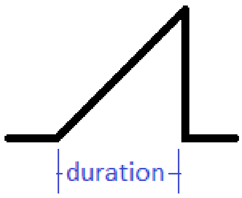
Forward	fl 0.025	freq 0.98Hz
	fl 0.05	freq 0.95Hz
	fl 0.1	freq 0.91Hz
	fl 0.2	freq 0.87Hz
	fl 0.3	freq 0.77Hz
	fl 0.4	freq 0.71Hz
	fl 0.5	freq 0.67Hz
	fl 0.7	freq 0.59Hz
	fl 1.0	freq 0.50Hz
	Steady	



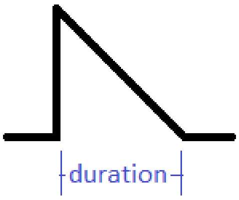
Reverse	fl 1.0	freq 0.50Hz
	fl 0.7	freq 0.59Hz
	fl 0.5	freq 0.67Hz
	fl 0.4	freq 0.71Hz
	fl 0.3	freq 0.77Hz
	fl 0.2	freq 0.87Hz
	fl 0.1	freq 0.91Hz
	fl 0.05	freq 0.95Hz
	fl 0.025	freq 0.98Hz
	Steady	

Up Triangle Flash Profile

Forward	fl 0.05	freq 0.95Hz
	fl 0.1	freq 0.91Hz
	fl 0.2	freq 0.87Hz
	fl 0.3	freq 0.77Hz
	fl 0.4	freq 0.71Hz
	fl 0.5	freq 0.67Hz
	fl 0.7	freq 0.59Hz
	fl 1.0	freq 0.50Hz
	Steady	
Reverse	fl 1.0	freq 0.50Hz
	fl 0.7	freq 0.59Hz
	fl 0.5	freq 0.67Hz
	fl 0.4	freq 0.71Hz
	fl 0.3	freq 0.77Hz
	fl 0.2	freq 0.87Hz
	fl 0.1	freq 0.91Hz
	fl 0.05	freq 0.95Hz
	Steady	

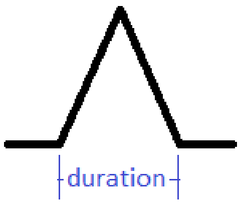


Down Triangle Flash Profile



Forward	fl 0.05	freq 0.95Hz
	fl 0.1	freq 0.91Hz
	fl 0.2	freq 0.87Hz
	fl 0.3	freq 0.77Hz
	fl 0.4	freq 0.71Hz
	fl 0.5	freq 0.67Hz
	fl 0.7	freq 0.59Hz
	fl 1.0	freq 0.50Hz
	Steady	
Reverse	fl 1.0	freq 0.50Hz
	fl 0.7	freq 0.59Hz
	fl 0.5	freq 0.67Hz
	fl 0.4	freq 0.71Hz
	fl 0.3	freq 0.77Hz
	fl 0.2	freq 0.87Hz
	fl 0.1	freq 0.91Hz
	fl 0.05	freq 0.95Hz
	Steady	

Symmetrical Triangle Flash Profile



Forward	fl 0.05	freq 0.95Hz
	fl 0.1	freq 0.91Hz
	fl 0.2	freq 0.87Hz
	fl 0.3	freq 0.77Hz
	fl 0.4	freq 0.71Hz
	fl 0.5	freq 0.67Hz
	fl 0.7	freq 0.59Hz
	fl 1.0	freq 0.50Hz
	Steady	
Reverse	fl 1.0	freq 0.50Hz
	fl 0.7	freq 0.59Hz
	fl 0.5	freq 0.67Hz
	fl 0.4	freq 0.71Hz
	fl 0.3	freq 0.77Hz
	fl 0.2	freq 0.87Hz
	fl 0.1	freq 0.91Hz

fl 0.05 freq 0.95Hz

Steady

It can be seen therefore, that the observer was required to carry out nine or ten observations per session. The steady light observation always came at the end of a session; its presence informed the observer and the experimenter that it was the final observation for that session. A total of three observers were used, each carrying out four sessions on each of four flash profiles, a total of forty eight sessions. A further four sessions were carried out by two observers on the symmetrical triangle flash profile in order to confirm the unexpected results emanating from the observations of this profile.

9 Results and Discussion

The illuminance at the observer, at the peak of the flash was plotted against the duration of the flash for the four different profiles. The illuminance values were then used to obtain relative effective intensity values by comparing them to an average steady light illuminance ($E_{s\infty}$). Similarities and differences were noted between the relative effective intensity of flashes for each observer and an average of all observers taken.

9.1 Observer Illuminance (microlux)

Shown in Figure 7 to Figure 9 are the results of observations by each of the three observers for each of the four flash profiles observed at the threshold of perception. The graphs show the average illuminance per observer for each flash profile, in microlux - at the peak of the flash, E_0, against the flash duration in seconds. Each flash profile had a total of four observations but Observers I and L carried out a second series of four observations on the symmetrical triangle flash profile. Axes are logarithmic and the axes for Observer M are slightly offset because the thresholds for that observer were somewhat lower than the other two. Error bars on the graphs show the standard error of all observations per observer, for each profile.

Shown in Table 1 are the average illuminance values of a steady light, $E_{s\infty}$, at the threshold of perception for each observer. Errors shown in Table 1 are the standard errors for all steady light observations per observer.

Raw illuminance values for all observations are shown in Annex 1. Previous studies into flashing light perception have often been devoid of detailed observer data and this has limited further study. Hopefully, the information given may be of some use to other interested parties.

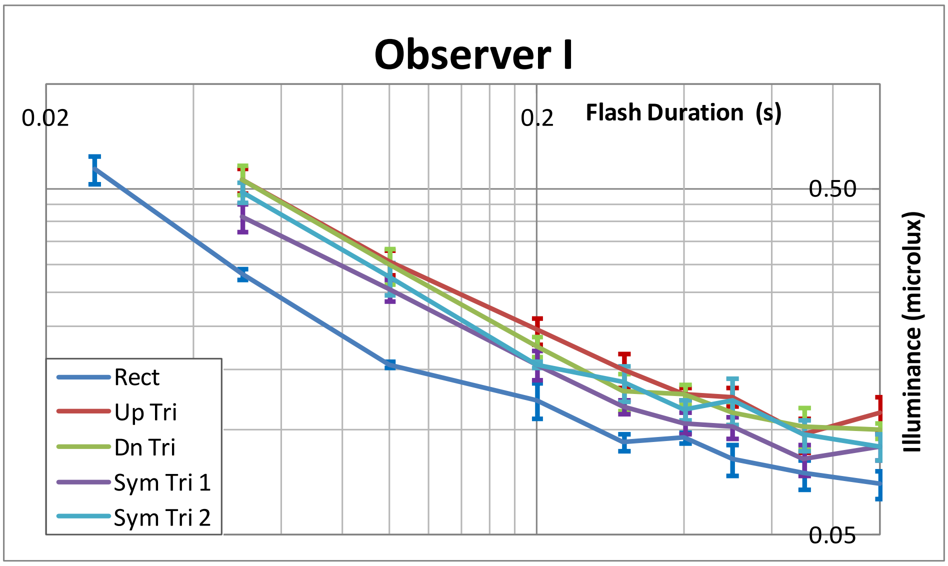


Figure 7 Threshold Illuminance values for Observer I

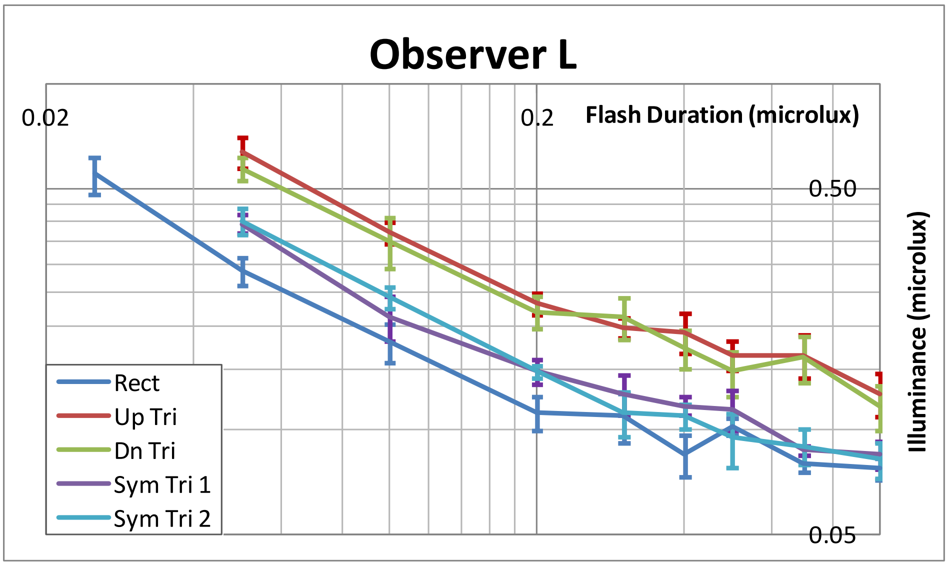


Figure 8 Threshold Illuminance values for Observer L

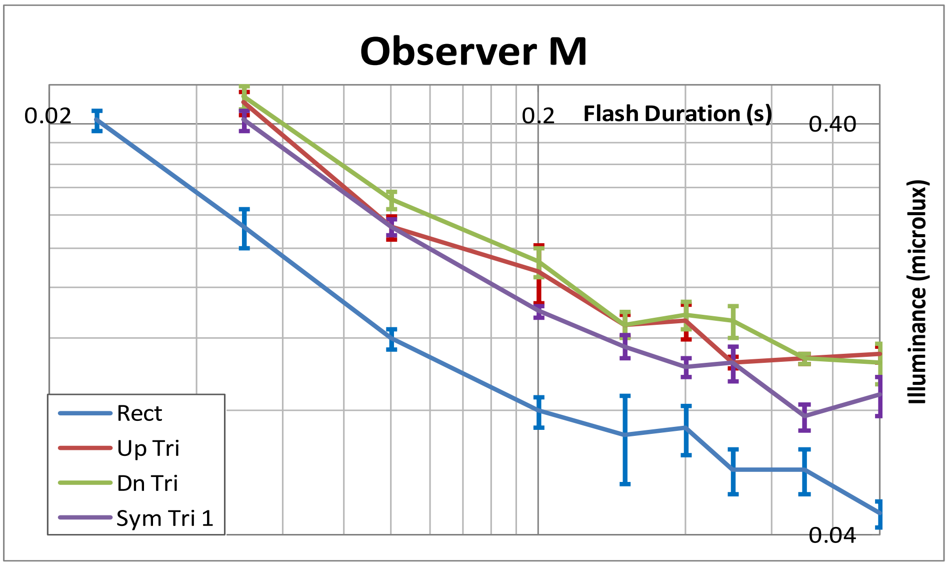


Figure 9 Threshold Illuminance values for Observer M

Observer	Average $E_{s\infty}$ (microlux)	St Error
I	0.060	0.0041
L	0.057	0.0033
M	0.042	0.0014

Table 1 Average Steady Light Threshold Illuminance (Es∞) for Each Observer

9.2 Relative Effective Intensity

In order to derive the relative effective intensity of the observed flash, an average of the steady illuminance level for each observer was divided by the of the peak illuminance of each flash.

$$I_{eff\ rel} = \frac{E_{s\infty}}{E_0}$$

Although there are many ways to calculate the effective intensity at threshold, this method was chosen because it was used in a previous experiment Figure 10 to Figure 12 show the relative effective intensity for each observer for each of the flash profiles observed; error bars show the combined standard errors for flash and steady observations. In Figure 13 the graph shows the average for all observers. Further graphs in section 9.3 show comparisons with existing effective intensity models. Annex 3 gives examples of impulse functions used in the convolution methods.

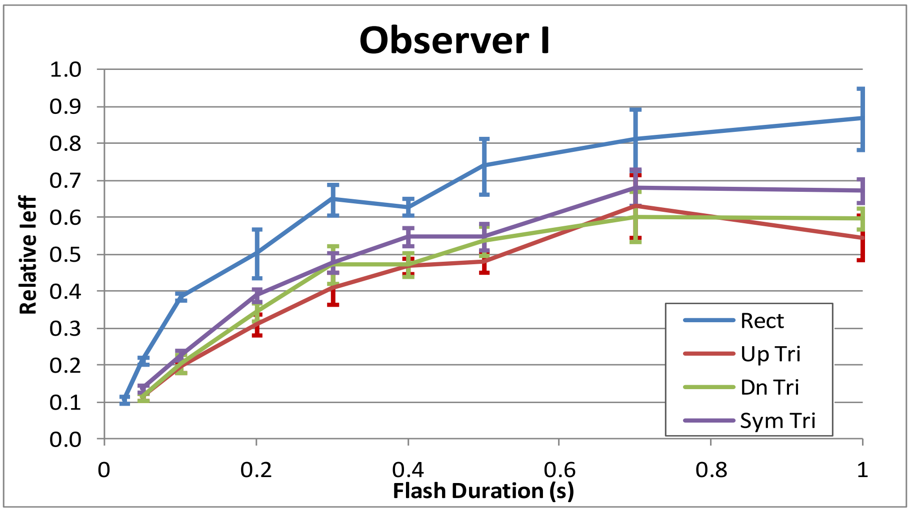


Figure 10 Average Relative Effective Intensity for Observer I

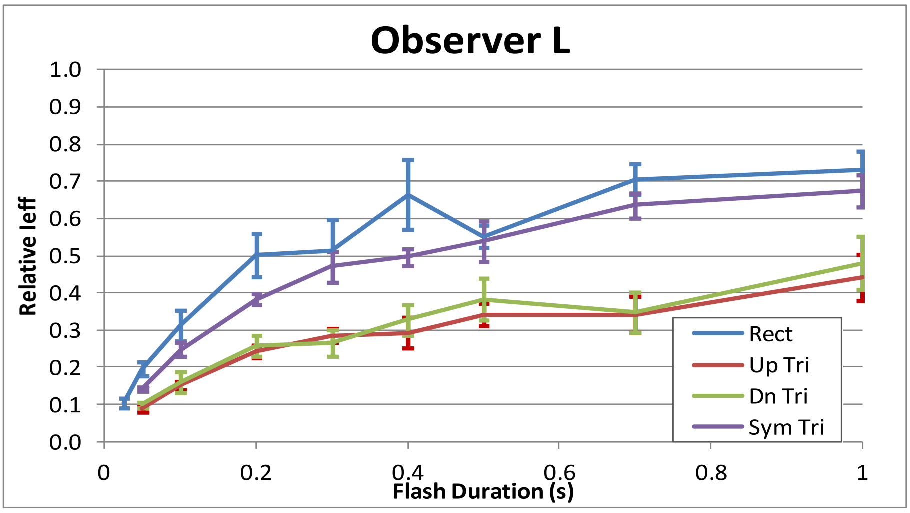


Figure 11 Average Relative Effective Intensity for Observer L

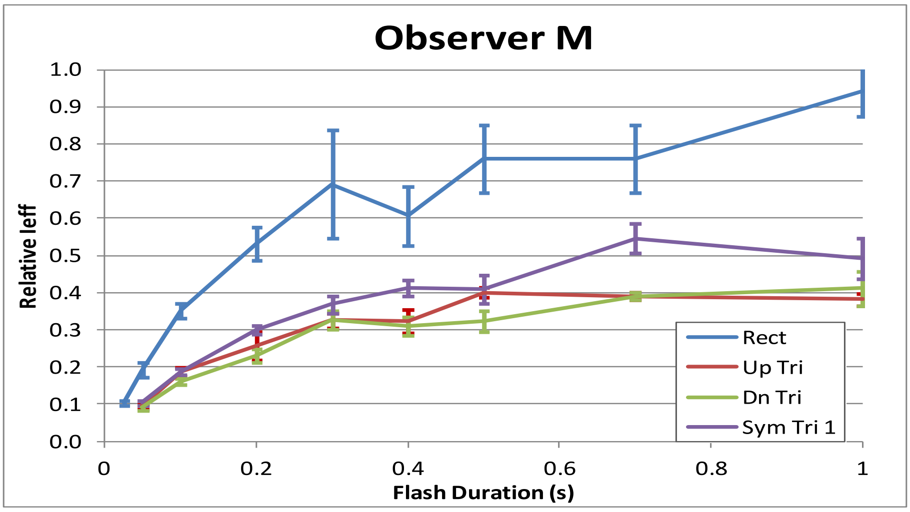


Figure 12 Average Relative Effective Intensity for Observer M

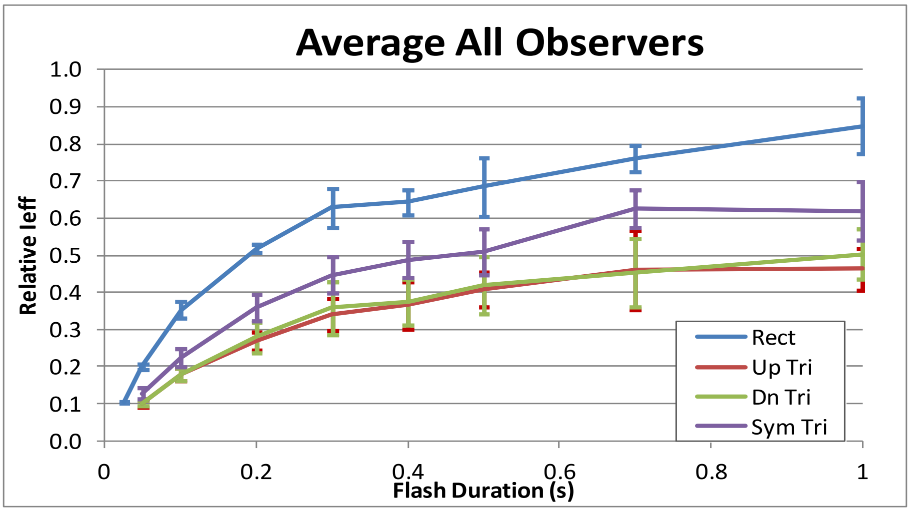


Figure 13 Average Relative Effective Intensity for All Observers

9.3 Comparison of Results to Existing Effective Intensity Models

The resultant effective intensity value, $I_{eff\ rel}$, can be compared with expected values from several effective intensity models, namely:

- Blondel-Rey[RD4];
- Schmidt-Clausen Form Factor[RD14];
- Modified Allard Method (MAM) with impulse response function $q(t) = \frac{a}{(a+t)^2}$ (Luizov)[RD13];
- Modified Allard with 'shear q3' *q(t)*[RD6 RD7].

Up to five different shear functions (q1 to q5) on the original MAM *q(t)* were developed by Dennis Couzin[RD7]. A visual time constant, *a*, of 0.2 seconds was used for all effective intensity models.

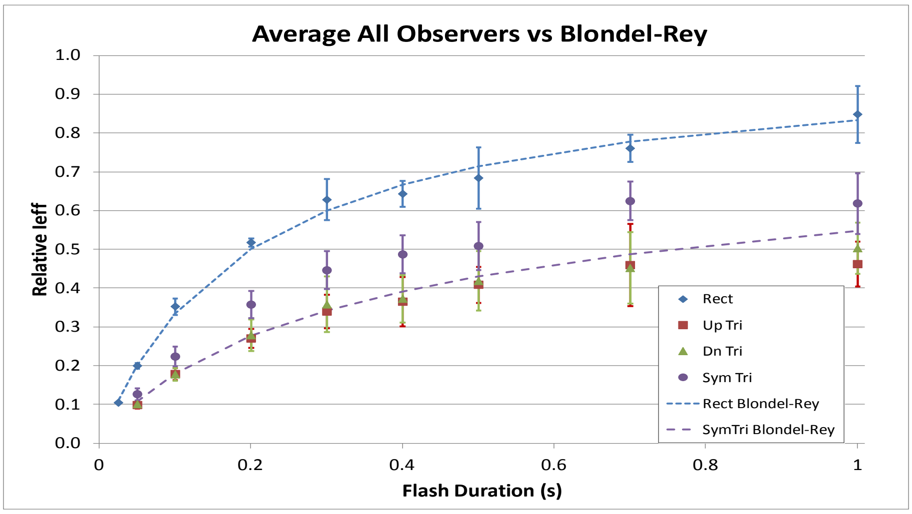


Figure 14 Average Relative Effective Intensity vs Blondel-Rey

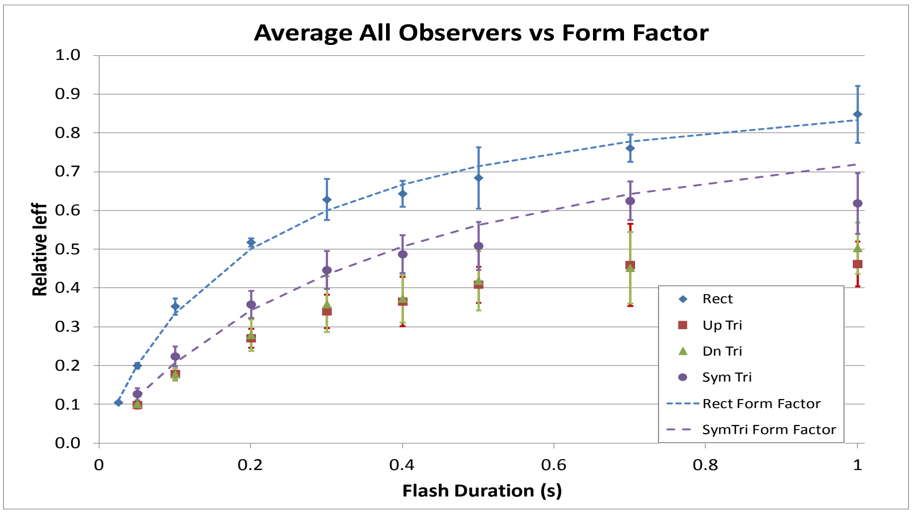


Figure 15 Average Relative Effective Intensity vs Form Factor

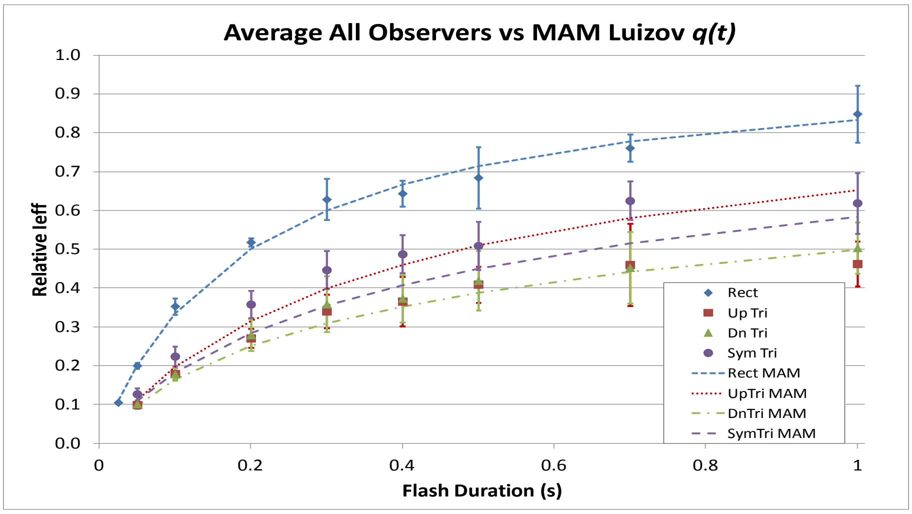


Figure 16 Average Relative Effective Intensity vs Modified Allard (Luizov q(t))

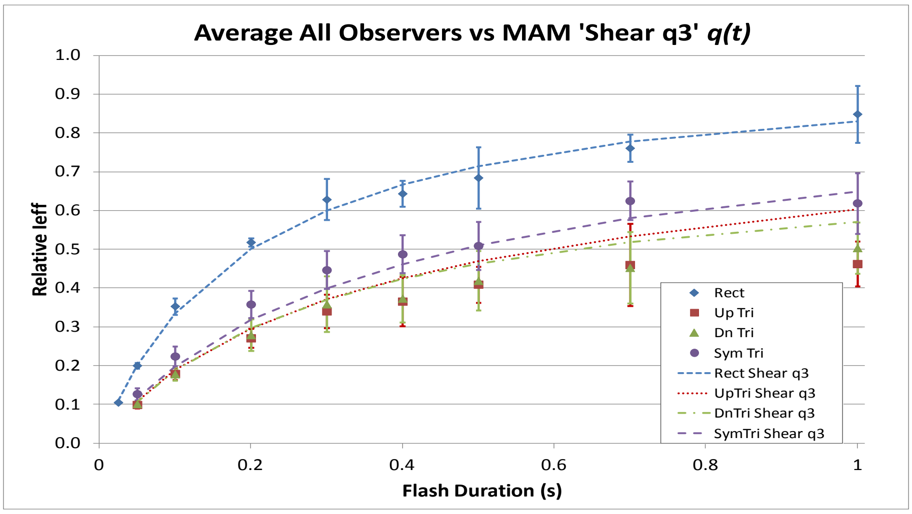


Figure 17 Average Relative Effective Intensity vs Modified Allard with 'shear q3' q(t)

Please note that for the Blondel-Rey and Schmidt-Clausen Form Factor methods the relative effective intensity of all triangular flash profiles will be the same if they have the same duration and time-integrated intensity. Therefore, for these methods, only the symmetrical triangle plot is shown.

9.4 Discussion

From the illuminance graphs in Figure 7 to Figure 9, it can be seen that the shapes of the curves are much as expected; the placement of the curves being dependent upon the observer's threshold sensitivity. The unexpected result is the variation in perception of different flash profiles between observers. Observer I showed similar results for all triangular flash profiles with the rectangular profile being slightly more conspicuous; Observer L showed similar results for asymmetrical triangles with the symmetrical triangle being considerably more conspicuous and quite close to the rectangular flash profile curve. Observer M showed similar conspicuity for all triangular flash profiles with the rectangular flashes being considerably more conspicuous. Despite these differences, the main observation is that all three observers showed no significant difference in perception between up triangle and down triangle flash shapes; the chirality of the triangular profile did not affect the perception of the flash.

Converting the flash peak illuminance values for each observer, E_0, to relative effective intensity by comparing to individual observer $E_{s\infty}$ eliminated the variation in individual observer thresholds. The results per observer, Figure 10 to Figure 12, could then be compared and an average of all observers taken (Figure 13).

The average relative effective intensity, $I_{eff\ rel}$, of all observers showed that there was no significant differences in perception between up and down triangle flash profiles, contrary to the prediction of the Modified Allard model. In fact the curves followed the Blondel-Rey model quite closely. The average of the symmetrical triangle flash profile was somewhat higher than the other triangular flashes, due mostly to the contribution from Observer L; although Observer I's overall triangular results were higher than predicted by Blondel-Rey. Interestingly, the average symmetrical triangle flash profile results were close to the Schmidt-Clausen Form Factor model prediction, and we know Schmidt-Clausen used a symmetrical triangle flash profile in his work[RD14]. The differences in perception of triangular flash profiles between observers gave rise to a relatively large uncertainties when an average of all observers was taken.

Rectangular flash profiles were observed as a control because many experiments have been carried out with rectangular flashes and all effective intensity models, with the exception of Allard[RD1], agree for this flash profile. The average relative effective intensity results for rectangular flashes showed close agreement with Blondel-Rey, Form Factor, Modified Allard and Modified Allard with 'shear q3' methods.

10 Considerations

Calculation of $I_{eff\ rel}$

For brightness matching (supra-threshold) investigations carried out on rectangular flashes in 2013 and 2014[RD11], where the observer matched the brightness of a rectangular flash to the brightness of a steady light at illuminance levels above threshold, the relative effective intensity ($I_{eff\ rel}$) values were calculated by dividing the average illuminance value recorded for the steady light by the average peak illuminance value for the flashing light. For brightness matching investigations, the steady light equivalence is crucial. Not so for the threshold flashes of this experiment.

The threshold for a steady light is not necessarily perceived or defined in the same way as that for a flash of light. The problem lies with the definition of effective intensity, which describes the 'fixed light equivalent of a flashing light' without adequately defining the threshold conditions. The perception at threshold of a flash, which is an event, is different from that of a steady light, which is a continuum. The mere act of increasing the illuminance of a steady light until it can be seen means that it is not steady (you are in fact observing the event of a slight increase in illuminance). And how long is a steady light viewed for? Certainly not infinity as the $E_{s\infty}$ label implies; the observation time must be finite.

Because of the disparity in flash versus steady light threshold criteria, other flash investigators, such as Blondel and Rey, Schmidt-Clausen, Mandler and Thacker, did not carry out steady light observations. They all used a calculated value of steady light illuminance ($E_{s\infty}$). Nevertheless, for this experiment, it was felt that an average of all steady light observations for each observer provided an appropriate $E_{s\infty}$ value for the determination of relative effective intensity without introducing preconditions.

Probability of Detection

The perceptual threshold for a flash is defined as the illuminance at which there is some definite probability of detection. For this experiment, observers worked with a probability of around 70%.

Frequency of Flash Repetition

There is a further variable that affects the threshold perception of a flash of light and that is the frequency at which the flash is repeated. It is known from previous experiments[RD12] that a higher repetition rate of flash presentation increases its conspicuity. The flashes in this experiment all have an eclipse time of one second. For a 0.025s flash, this means a frequency of 0.98Hz; for a one second flash, it is 0.5Hz. It is estimated that the enhancement of conspicuity due to this frequency of repetition could be between 5% and 7% when compared with a single flash. However, no correction of results have been carried out to account for any such enhancement.

Accuracy of Generated Flashes

The triangular flash profiles generated by the programmable flasher, PF1, should have ideally had the same time-integrated intensity; since the area of a triangle equals half the base times the height. However, due to the stepping program used to generate the flashes, there were slight differences. To investigate these differences, each flash was measured photometrically and the time-integrated intensities of each flash profile compared. The time-integrated intensities agreed within 1% with the exception of the shortest flash where measurement uncertainty was somewhat higher. Despite a combined measurement uncertainty of 5%, the time-integrated intensities of 0.05s flashes still agreed to within 3.5%. Differences in time-integrated intensity between the generated flash shapes were therefore considered insignificant.

Observer Fatigue and Visual Noise

From an observer viewpoint, two factors that affect observation results are fatigue and visual noise. Both can vary significantly over relatively short periods of time and longer periods; both can affect the threshold of perception and cause large variations in the recorded threshold value. Fatigue can affect reaction time and sustained fatigue can lower the trajectory of the resultant effective intensity curve.

11 Conclusions

Although the conspicuity of rectangular flash profiles was similar for all observers, there were significant differences between observers in the perception of triangular flash profiles.

All three observers perceived little difference in relative effective intensity between chirally opposite triangular flash profiles (up triangle and down triangle). This is contrary to the results from the Modified Allard Method (MAM), which predicted a difference of up to 30%. It is concluded therefore that MAM, with the Luizov $q(t)$ of $a/(a+t)^2$ is not suitable for complex flash profiles. The average of all observers for these chirally opposite triangular flash profiles was close to the curve predicted by the Blondel-Rey method.

For two observers, the symmetrical triangle flash profile was slightly more conspicuous than the asymmetrical triangle flash profiles but for one observer, the conspicuity of the symmetrical triangle was significantly higher. The average of all observers showed that the trajectory of the symmetrical triangle flash profile was close to that predicted by the Schmidt-Clausen Form Factor model.

The Modified Allard Method with 'shear q3' $q(t)$ predicted similar effective intensity values for up triangle and down triangle flash profiles with slightly enhanced values for the symmetrical triangle flash profile. This model is more in line with experimental results but the trajectories of the asymmetrical triangle flash profiles predicted by the 'shear q3' model are somewhat higher than the observer averages.

Due to the large differences in observer perception of triangular flash profiles at threshold, the average results have large standard errors. There is a need for more observations with a much larger number of observers to reduce these errors and obtain a more meaningful representation of human perception of non-rectangular flash profiles.

12 Recommendations

The findings of this report should be presented to CIE Technical Committee TC2-49 and to the IALA Engineering Committee, as it may have an impact on IALA Recommendations[RD10].

Further experiments into the perception of triangular flash profiles at threshold should be undertaken. However, formal experiments with large numbers of observers can be costly and time consuming, consequently many organisations will be reluctant to carry them out. Smaller scale experiments, each with a few experienced observers, should be encouraged but there needs to be a system for disseminating the aims and methods of such experiments, as well as collating the results, in order to ensure consistency.

The results of this experiment should be compared to results of the same flash profiles at supra-threshold levels in the forthcoming brightness matching experiments due to be undertaken by R&RNAV.

Annex 1 Threshold Illuminance Values in microlux

Observer I

Flash	Rectangle				Up Triangle				Down Triangle				Symmetrical Triangle 1				Symmetrical Triangle 2			
Duration (s)	fwd1	fwd2	rev1	rev2	fwd1	fwd2	rev1	rev2	fwd1	fwd2	rev1	rev2	fwd 1	fwd 2	rev1	rev2	fwd3	fwd5	rev3	rev4
0.025	0.57	0.47	0.69	0.55																
0.05	0.28	0.26	0.29	0.30	0.50	0.49	0.49	0.64	0.46	0.50	0.66	0.51	0.33	0.40	0.49	0.43	0.43	0.46	0.56	0.51
0.1	0.16	0.16	0.15	0.15	0.30	0.27	0.29	0.37	0.27	0.24	0.31	0.38	0.23	0.23	0.27	0.29	0.24	0.30	0.34	0.23
0.2	0.12	0.13	0.15	0.09	0.19	0.16	0.23	0.20	0.17	0.15	0.18	0.20	0.13	0.14	0.19	0.16	0.15	0.15	0.16	0.16
0.3	0.10	0.09	0.10	0.08	0.12	0.14	0.19	0.15	0.13	0.11	0.11	0.17	0.11	0.13	0.11	0.12	0.15	0.17	0.12	0.11
0.4	0.09	0.10	0.10	0.09	0.12	0.14	0.13	0.12	0.14	0.12	0.11	0.14	0.10	0.11	0.09	0.12	0.12	0.13	0.10	0.11
0.5	0.07	0.07	0.09	0.10	0.14	0.13	0.12	0.11	0.10	0.10	0.13	0.12	0.09	0.12	0.10	0.10	0.17	0.11	0.10	0.11
0.7	0.07	0.09	0.08	0.06	0.11	0.11	0.10	0.07	0.09	0.09	0.09	0.14	0.07	0.09	0.10	0.07	0.12	0.10	0.08	0.09
1	0.08	0.08	0.06	0.06	0.12	0.14	0.10	0.09	0.10	0.11	0.10	0.09	0.08	0.11	0.08	0.09	0.09	0.11	0.08	0.08
steady	0.08	0.06	0.08	0.05	0.06	0.05	0.09	0.08	0.02	0.06	0.07	0.04	0.03	0.05	0.07	0.05	0.08	0.05	0.06	0.06

Observer L

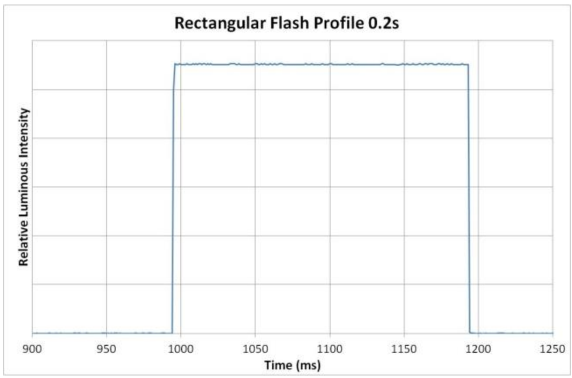
Flash	Rectangle				Up Triangle				Down Triangle				Symmetrical Triangle 1				Symmetrical Triangle 2			
Duration (s)	fwd1	fwd2	rev1	rev2	fwd1	fwd2	rev1	rev2	fwd1	fwd2	rev1	rev2	fwd 1	fwd 2	rev1	rev2	fwd3	fwd5	rev3	rev4
0.025	0.45	0.45	0.67	0.63																
0.05	0.26	0.27	0.27	0.36	0.6	0.81	0.6	0.55	0.53	0.68	0.56	0.52	0.41	0.44	0.34	0.39	0.47	0.34	0.36	0.44
0.1	0.16	0.15	0.17	0.24	0.4	0.42	0.34	0.33	0.31	0.49	0.36	0.25	0.2	0.22	0.15	0.28	0.26	0.2	0.26	0.25
0.2	0.12	0.08	0.12	0.13	0.21	0.27	0.24	0.21	0.21	0.27	0.23	0.17	0.17	0.15	0.15	0.12	0.14	0.14	0.15	0.16
0.3	0.09	0.12	0.08	0.15	0.19	0.22	0.17	0.21	0.18	0.25	0.26	0.16	0.12	0.15	0.09	0.15	0.15	0.11	0.11	0.08
0.4	0.09	0.08	0.06	0.11	0.19	0.19	0.25	0.14	0.17	0.22	0.17	0.13	0.13	0.12	0.1	0.12	0.13	0.11	0.11	0.09
0.5	0.11	0.1	0.09	0.11	0.2	0.14	0.15	0.17	0.12	0.2	0.15	0.12	0.14	0.11	0.08	0.13	0.14	0.08	0.08	0.08
0.7	0.09	0.08	0.08	0.07	0.22	0.16	0.16	0.12	0.17	0.22	0.14	0.12	0.09	0.09	0.08	0.09	0.11	0.1	0.08	0.07
1	0.07	0.07	0.08	0.09	0.17	0.13	0.11	0.1	0.11	0.16	0.11	0.09	0.07	0.09	0.08	0.1	0.08	0.09	0.1	0.06
steady	0.05	0.05	0.08	0.06	0.09	0.03	0.06	0.06	0.07	0.07	0.06	0.06	0.05	0.06	0.04	0.05	0.04	0.06	0.04	0.05

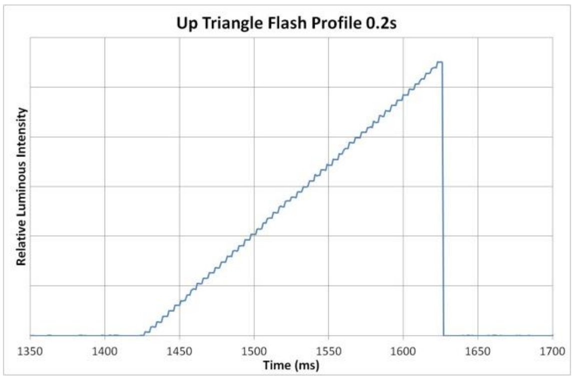
Observer M

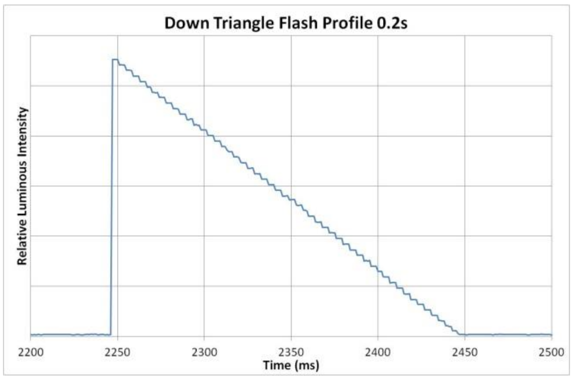
Flash	Rectangle				Up Triangle				Down Triangle				Symmetrical Triangle 1				Symmetrical Triangle 2			
Duration (s)	fwd1	fwd2	rev1	rev2	fwd1	fwd2	rev1	rev2	fwd1	fwd2	rev1	rev2	fwd 1	fwd 2	rev1	rev2	fwd3	fwd5	rev3	rev4
0.025	0.37	0.38	0.44	0.45																
0.05	0.22	0.17	0.24	0.27	0.4	0.43	0.46	0.52	0.42	0.43	0.53	0.49	0.42	0.37	0.46	0.39				
0.1	0.11	0.11	0.13	0.13	0.2	0.22	0.22	0.26	0.25	0.29	0.24	0.27	0.21	0.22	0.22	0.25				
0.2	0.07	0.07	0.09	0.09	0.11	0.18	0.18	0.23	0.21	0.15	0.19	0.19	0.13	0.15	0.14	0.14				
0.3	0.04	0.05	0.09	0.1	0.13	0.12	0.12	0.15	0.15	0.13	0.11	0.13	0.12	0.11	0.1	0.13				
0.4	0.05	0.07	0.08	0.09	0.16	0.11	0.14	0.12	0.15	0.11	0.15	0.14	0.09	0.1	0.11	0.11				
0.5	0.04	0.06	0.06	0.07	0.11	0.1	0.1	0.11	0.13	0.11	0.16	0.13	0.11	0.08	0.11	0.12				
0.7	0.04	0.06	0.06	0.07	0.11	0.11	0.1	0.11	0.11	0.11	0.11	0.1	0.09	0.07	0.07	0.08				
1	0.05	0.04	0.05	0.04	0.11	0.12	0.11	0.1	0.08	0.11	0.13	0.1	0.11	0.09	0.08	0.07				
steady	0.04	0.03	0.04	0.04	0.05	0.04	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.05	0.04	0.04				

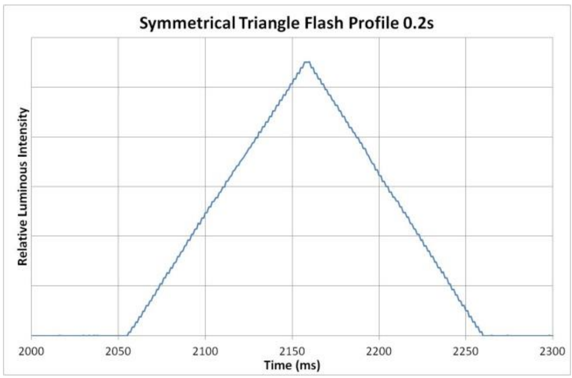
Annex 2 Examples of Flash Profiles Generated

The following flash profiles were measured by a photometer and digitally recorded at 1000 samples per second. The photometer slew rate was around 100 microseconds.









Annex 3 Examples of Impulse Functions (*q(t)s*)

For a convolution, or Allardian, method of determining effective intensity, an Impulse Function, *q(t)*, is convolved with the flash profile. The peak value of the resultant convolution is taken as the effective intensity value. Three impulse functions are shown below along with a graph of the resultant convolution of a rectangular flash profile with the Luizov *q(t)*.

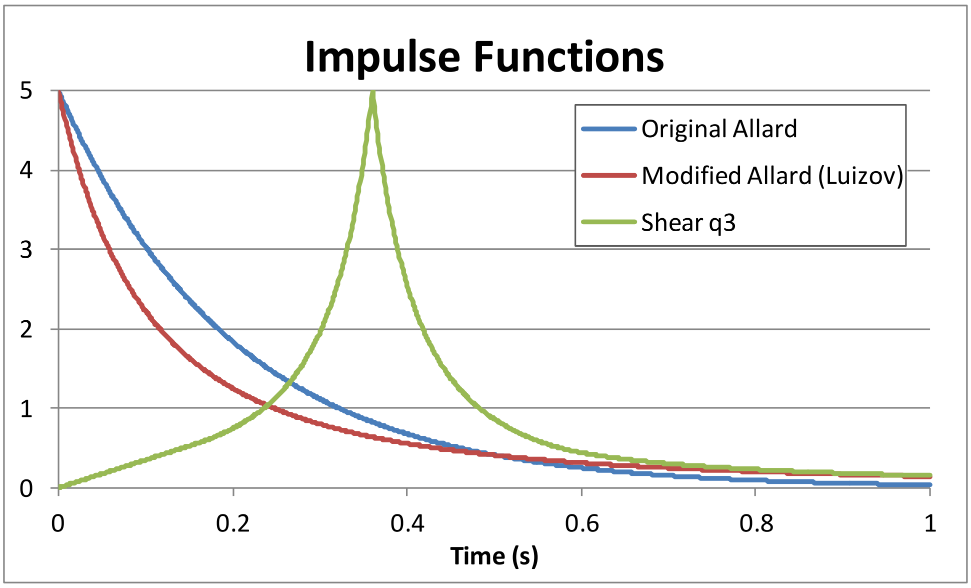


Figure 18 Three impulse functions

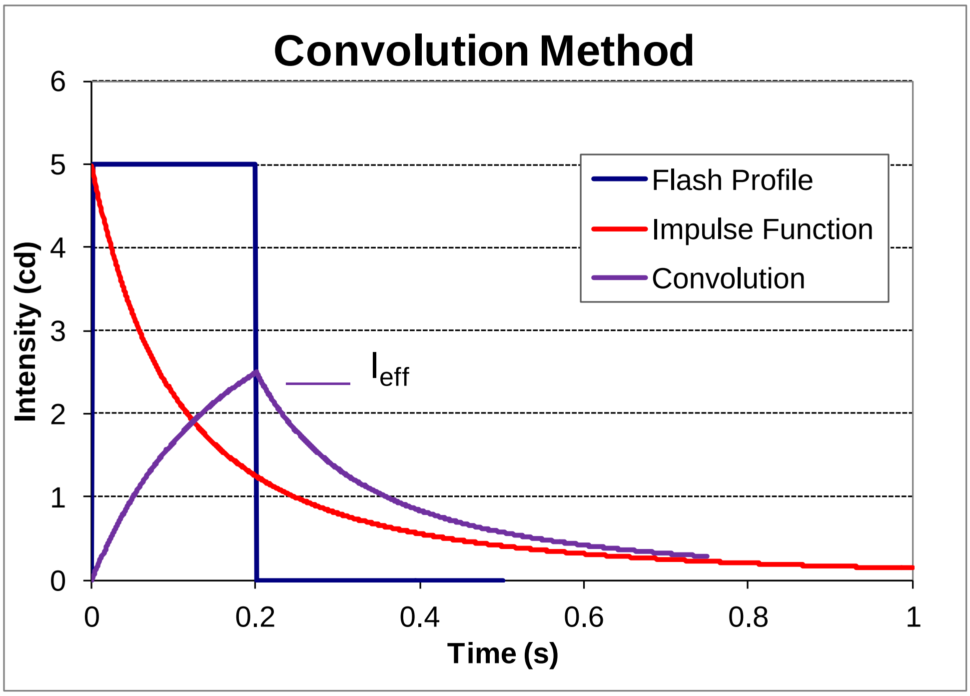


Figure 19 Graph of Convolution Method