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Trial of Conspicuity Model

A Practical Demonstration

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Executive Summary

This report covers the design, implementation and summary of the results of a conspicuity trial conducted in Harwich on the evening of 2nd February 2017. The trial is a culmination of years of research carried out by R&RNAV, and helps to build a body of evidence to support the conclusions of previous experiments.

The experiment consisted of a number of volunteers observing a number of pairs of flashing lights and deciding which of each pair seems the brighter. The flashes of light varied in intensity, shape and length, and were designed to capture a general trend towards the given perception models, including the Modified Allard Method (MAM) as currently recommended by IALA. A key element of the models is defining the visual constant, a, which describes the inertia that the human visual system exhibits when observing a flashing light. All flash intensities were at above-threshold levels of illuminance of the eye.

The results of the trial found that a trend exists that confirms the outcome of previous R&RNAV experiments. The human visual system model currently recommended by IALA can be further refined by employing the Couzin-Tutt convolution function, rather than the Luizov function. In addition, strong evidence was found for changing the visual constant from the currently recommended value of 0.2 s to 0.1 s.

The implication of this change could be that it is possible provide the same level of service with lower power consumption. Alternatively, it is possible to enhance service provision with the same level of power consumption. The impacts of such changes are discussed, and it is concluded that care must be taken if any changes to service provision are carried out on the basis of these results alone. Nevertheless, the recommendation is that these changes are made in order to refine the models used to determine maritime visual signalling provision.

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RD1 IALA Recommendation E200-4, Marine Signal Lights - Part 4: Determination and Calculation of Effective Intensity, Ed. 1, 2008

RD2 R&RNAV Technical Report RPT-07-IT-MN-14, Feasibility of Conspicuity Scale, 21/03/14

RD3 R&RNAV Technical Report RPT-04-IT-AW-16, Visual Perception of Non-rectangular Flashes at Threshold, 11/03/16

RD4 R&RNAV Technical Report RPT-06-IT-AW-16, Visual Perception of Non-rectangular Flashes at Supra-Threshold, 11/03/16

RD5 R&RNAV Technical Report RPT-11-MN-IT-15, The Apparent Intensity of a Coloured Flashing Light, 01/05/15

RD6 Couzin, D.; Basis of Allardian Ie Methods – How to Fix MAM; 25 May 2015; academia.edu

RD7 B.S.942: 1949. British Standard Formulae for Calculating the Intensities of Lighthouse Beams and Beams from Cognate Projection Apparatus. British Standards Institution. London.

1 Introduction

This report covers the design, implementation and summary of the results of a conspicuity trial conducted in Harwich on the evening of 2nd February 2017. The trial is a culmination of years of research carried out by R&RNAV, and helps to build a body of evidence to support the conclusions of previous experiments.

The experiment consisted of a number of volunteers observing a number of pairs of flashing lights and deciding which of each pair appears brighter. The flashes of light varied in intensity, shape and length. They were chosen to help in determining which perception model is correct, and the Modified Allard Method (MAM) as currently recommended by IALA [RD1] is included.

A key element of the models is defining the visual constant a, which describes the inertia that the human visual system exhibits when observing a flashing light. The system does not see the instantaneous intensity of a light immediately, but rather a lower intensity as the system reacts to the stimuli. This perceived intensity is described as the effective intensity, and a model to calculate it has been determined by observations.

The trial attempts to clarify which supra-threshold model and value of visual constant matches observations most closely.

2 Review of R&RNAV Conspicuity Scale Experiments

For a number of years, R&RNAV has undertaken the arduous task of refining the effective intensity model employed throughout the world of maritime visual signalling. The recommended models have changed over the years, based on either improved understanding of the human visual system, or on changing assumptions and techniques. Indeed, IALA Recommendation E200-4 recommends no less than four different models (Blondel-Rey, Blondel-Rey-Douglas, Schmidt-Clausen and MAM), each giving different results for non-rectangular flashes.

The IALA MAM is currently accepted as the most appropriate general model of the human visual system. In practice, the other models are employed, mainly because they make it easier to calculate the effective intensity. However, advances in computer technology since the introduction of MAM render it relatively simple to implement. At the time of writing, Commission Internationale de l'Eclairage (CIE) is on the verge of publishing a recommendation to use MAM for the calculation of effective intensity at the threshold of illuminance[1].

To further its understanding, R&RNAV has conducted a number of experiments, a selection of which are summarised below.

- Repeat of Toulmin-Smith & Green (1933) experiment of flashing white, rectangular flashes above threshold. [RD2]
- Repeat of above, but with different shapes of flash profile at threshold [RD3]
- Repeat of above, but with different shapes of flash profile above threshold [RD4]
- Repeat of above, with different coloured lights [RD5]

In [RD4], it was proposed that a new model, devised by Couzin, is used based on the work carried out by Couzin [RD6]. This work was then refined and the model verified by Tutt for R&RNAV. In this report, this new model will be referred to as the Couzin-Tutt Model.

[1] 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, where the illuminance is considered on a surface element that is normal to the incident rays at the eye. -- CIE

As a result of this body of work, two fundamental changes were proposed: a change to the model used to calculate the effective intensity so that it matches observation more closely, and a change of the visual constant from 0.2 s to 0.1 s.

These two changes are the focus of this trial, in order to appreciate whether they are reflected in environments closer to that in real life.

2.1 Overview of Models

In this trial, two visual perception models are considered: the Modified Allard Method (MAM) and the newly developed Couzin-Tutt Model. The models are broadly similar, with the same process of calculation, and they are equivalent for rectangular flashes. Indeed, they are equivalent to the Blondel-Rey model for such flashes.

Both models utilise the convolution method where the instantaneous flash profile, $I(t)$, is convolved with a function, $q(t)$, that represents the response of the human visual system. The effective intensity (I_e) of the flash is the maximum value obtained from the convolution. Thus,

$$I_e = \max_{0 \leq t \leq T} \{I(t) \otimes q(t)\}$$

where t is the instantaneous time and T is the total length of the convolution output (which should be long enough to include the peak output value).

The models differ by the definition of the visual system response function, $q(t)$. For MAM, $q(t)$ is defined by the Luizov function:

$$q(t) = \frac{a}{(a+t)^2}$$

where t is the instantaneous time and a is the visual constant (see Section 2.2).

The Couzin-Tutt model utilises a different function for $q(t)$, but is still based on the Luizov function, and they are equivalent for rectangular shapes. The function has been determined through trial-and-error, and matching the model results with those observed in practice [RD4]. As such, the mathematical model for the Couzin-Tutt is more complex, but it has been summarised in Appendix A for convenience.

Figure 1 shows the difference between the two visual system response functions. More information on the convolution method used to calculate the effective intensity can be found in IALA Recommendation E-200-4.

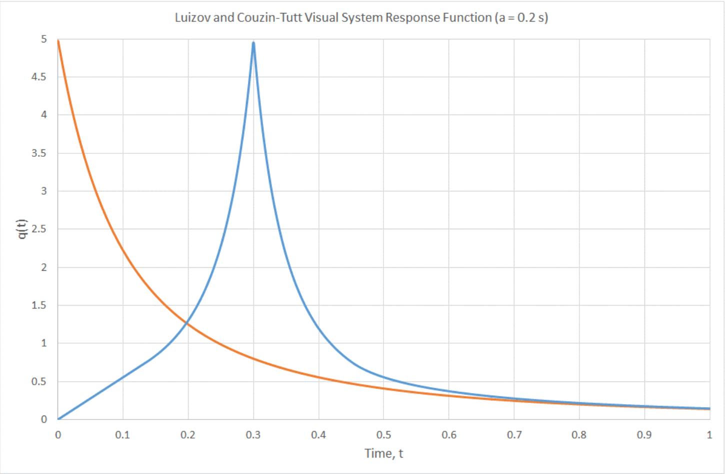

Figure 1 – Difference between the Luizov (orange) and Couzin-Tutt (blue) visual system response functions for a visual constant of 0.2 s in both cases.

2.2 Visual Constant

The other element of the effective intensity calculation under consideration is the visual constant, a, which describes the inertia that the human visual system exhibits when observing a flashing light.

The value of a has changed over time, in an effort to fit effective intensity models with observations. The current recommended value by IALA for marine applications is 0.2 s. However, recent experiments carried out by R&RNAV place the value closer to, or even less than, 0.1 s in most cases.

The visual constant applies equally to both models described above, and should be considered separately.

3 Trial Methodology

In this Section, we describe the method used in the trial. This is split into two sections covering the hardware aspect and the process used with the participants.

3.1 Hardware Overview

An overview of the hardware is shown in Figure 2. The light control hardware for the trial was based on an Arduino microcontroller board providing a controlling function to a constant current driver powering the observed LED light source. This method allowed any flash shape of any length to be produced within the limitations of the current driver and temporal resolution of the PWM used by the microcontroller. A brief outline of each functional block is given below.

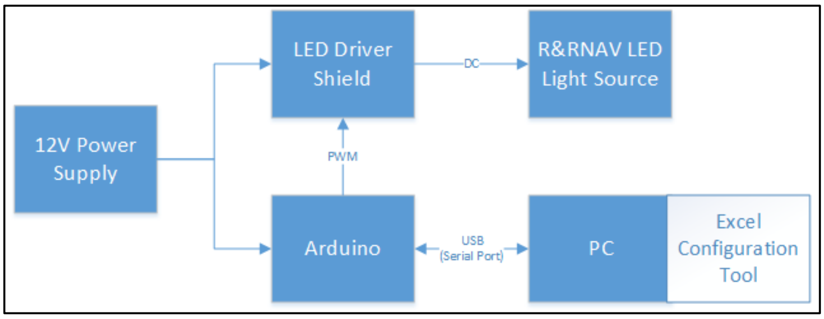

Figure 2 - Overview of the hardware used in the conspicuity trial.

3.1.1 Arduino

The Arduino project provides for an open-source hardware and software environment for building and programming AVR microcontrollers from Amtel. [2]

The Arduino controller used for this trial is an Arduino Uno[3], programmed with custom software to provide the flash shapes and the delays required for the experiment. The software relies on the built-in serial port (via the USB connection) to communicate with an external process to set up the experiment parameters. The external process can communicate via a text-based interface or, as used in the trial, a Microsoft Excel™ spreadsheet (excel) that communicates with the Arduino controller directly.

The Arduino was programmed using the Arduino IDE v1.6.11, using the C-style programming language provided by the Arduino project.

[2] https://www.arduino.cc/
[3] https://www.arduino.cc/en/Main/ArduinoBoardUno

3.1.2 LED Driver Shield

This custom-built circuit board plugs directly onto the Arduino board, and therefore provides access to the microcontroller pins in a relatively easy way. A prototype shield[4] was used to minimise time to build the board, as well as allowing the configuration to be changed quickly.

The LED constant-current driver, Recom RCD-48, was fitted to the shield and was connected directly to the external power supply. This power supply also provides power to the Arduino board with the necessary 5 V supply through a voltage regulator.

There are a number of current outputs available in the RCD-48 range[5].It was decided to use the 350 mA driver, as this has the lowest range of current and provided the highest level of stability when trimming the light intensity with its analogue dimming facility. The Arduino PWM output was connected directly to the PWM input of the LED driver. The PWM frequency is approximately 488Hz, with a duty-cycle update rate of 200 Hz.

Figure 3 shows the shield fitted to the Arduino Uno board. In this figure, the power to the boards and the LED is supplied from the left, and the power to the LED itself is on the right. The Arduino is controlled by the PC using the grey USB cable. The jumpers allowed for a different configuration of the shield, and the analogue dimming circuitry can be seen in the top-right of the board.

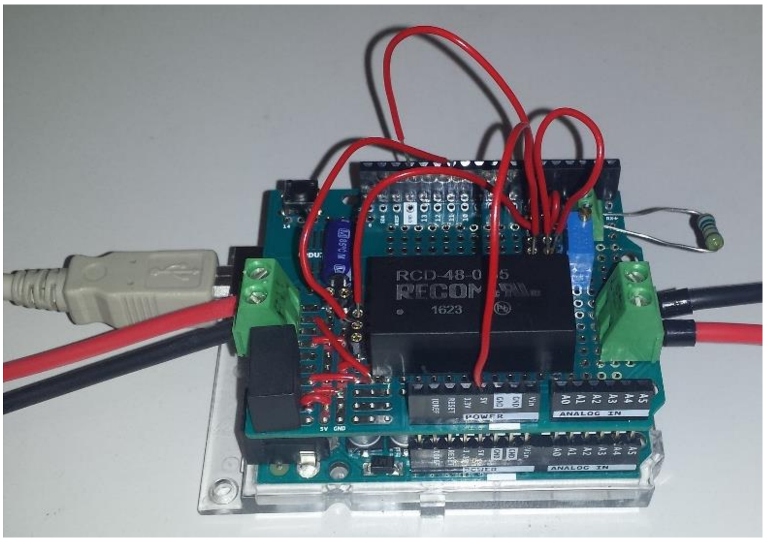

Figure 3 – Arduino Uno fitted with the custom LED Driver Shield

3.1.3 R&RNAV LED Light Source

The R&RNAV LED Light Source used in the trial is an 8-sided RLS 10-24, fitted with 24 Cree high intensity neutral white XP-L LEDs. The maximum current of the LEDs is 3 Amps, although the current is much less than this in the trial, at around 4.4 mA. It is noted that although the colour is not guaranteed at this current, it is sufficiently “white” for this trial.

The light source was installed in a black cardboard shroud, with a 20 mm hole cut at the height of the LEDs. The hole was covered with a 3mm thick white PTFE sheet to provide an even light across the hole and to attenuate the luminance of the light source.

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[4] A “shield” is an Arduino term for a circuit board that is designed for fitting directly to the Arduino range of single board microcontrollers.

[5] https://www.recom-power.com/pdf/Lightline/RCD-48.pdf

3.1.3.1 Calibration

The light source was calibrated on the R&RNAV indoor light range facility to ensure that the illuminance of the light at the observer in the experiment approaches that of visual threshold, 0.2 µlux, as defined by IALA [RD1].

The light intensity to produce the required level of illuminance is below the measurement sensitivity of the light range and therefore a ratio method is used to determine the actual intensity used in the experiment. Without the analogue dimming, the full intensity of the LED light is 52.04 cd. When fitted with the shroud, the same light source has an intensity of 0.122 cd. This means that the diffuser reduces the light intensity by a factor 427. When the analogue dimming circuitry was employed, we get a light intensity of 2.72 cd without the shroud. When fitted with the shroud, the diffuser attenuation factor should be the same, meaning that the actual peak light intensity used in the experiment is 6.4 mcd.

At a distance of 64 m, as used in the experiment, this equates to an illuminance of 1.56 µlux at the observers. With the microcontroller software, it was possible to change the peak intensity by steps of 10%. The lowest peak intensity used in the experiment is 20%, equating to a peak illuminance of 0.31 µlux. This is sufficient for this experiment.

3.1.4 PC and Excel Software

The Arduino board is configured via a virtual serial port on the PC, and an Excel sheet was created to communicate the required flash shapes, lengths and intensity to the controller. The Excel sheet is designed keep an accurate record of all the experiments that were carried out, as well as making it very easy to control the operation of the experiment.

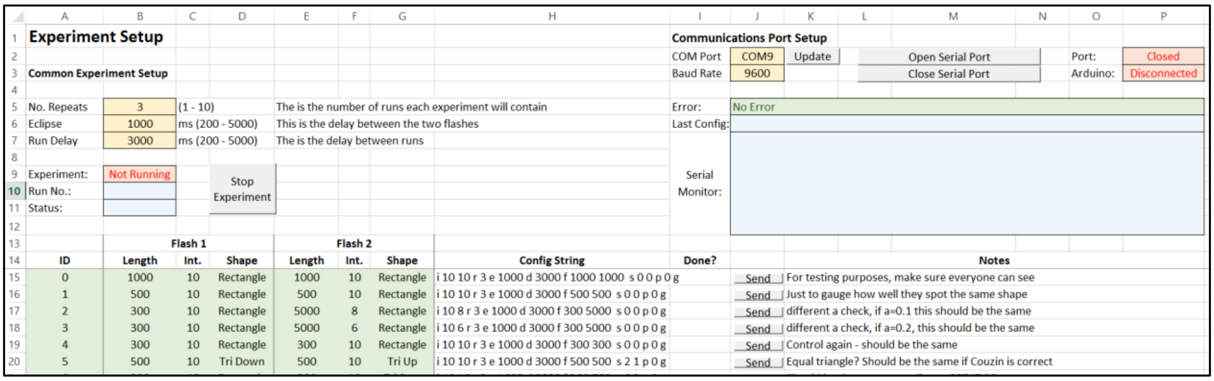

Figure 4 - Experiment control software in Excel

3.2 Process

The basic principle of the experiment was for observers to compare two flashes, and to rate the apparent brightness of one against the other.

The experiment took place inside the R&RNAV Outdoor Light range (ODLR), situated in Harwich. This long, enclosed tunnel allows R&RNAV to accurate measure large light sources using calibrated photometric equipment and a goniometer. For the purposes of this experiment, the ODLR is used to provide a comfortable long-range viewing facility in near complete darkness. The observers are sat some 64m away from the light source, meaning that the 20mm diameter hole cut into the light source shroud subtends an angle of just over 1 minute of arc at the observer's eye. Figure 5 shows the set up used at the light source end of the trial.

The light source was controlled by an operator in the ODLR control room, using the software described above, away from the experiment area.

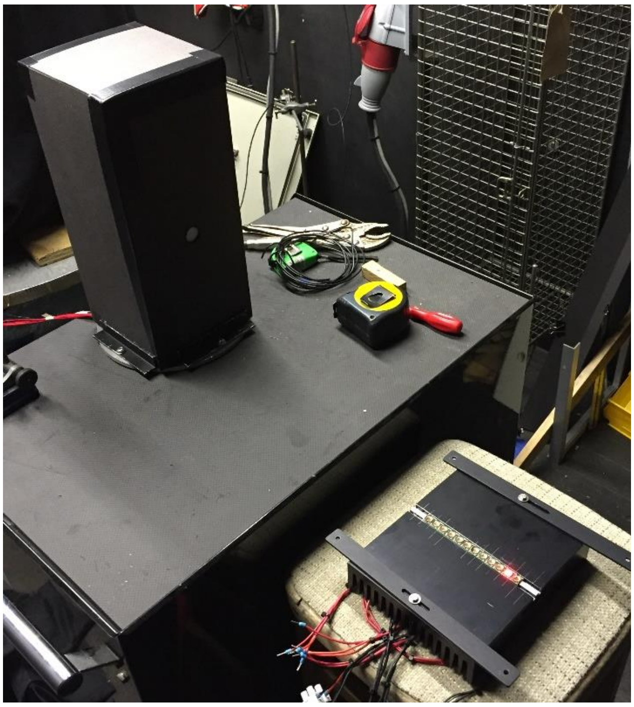

Figure 5 – Light Source used during the trial. Note the red fixation light in the lower right.

The observers were allowed time before beginning the experiment to become adapted to the dark for approximately 10-15 minutes. A low-level red light was provided behind the observers to allow them to see and mark the recording sheets.

The observers were asked to judge two flashes on their apparent brightness, and not (necessarily) which is the more conspicuous. A delay of 1 second was inserted between flash 1 and flash 2. The 2 flashes were shown consecutively 3 times with a 3 second delay between each set of flashes (see Figure 6). Then the observers were asked to write down their judgement. The choices were: flash 1 was much brighter; flash 1 was somewhat brighter; both flashes are the same; flash 2 was somewhat brighter; and, flash 2 was much brighter. Absolutely no discussion of the flashes was allowed during the experiment to minimise inadvertent bias in the results.

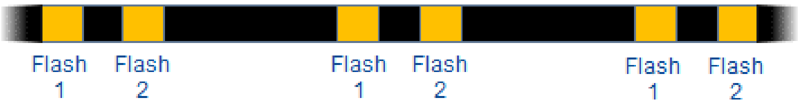

Figure 6 – Flash sequence used in the trial.

At the end of the experiment, the record sheets were collected and analysed.

A list of the flash runs conducted in the experiment are shown in Appendix B, and a summary of the flash shapes is shown in Figure 7.

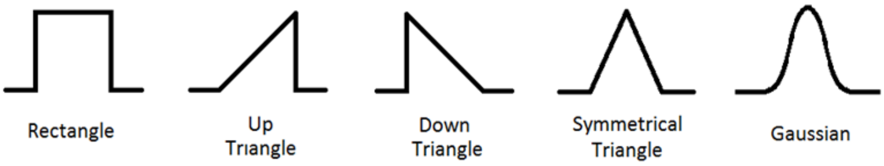

Figure 7 – Flash shapes used during the trial

3.3 Observers

For this trial, six observers from all three GLA were involved. All observers were male, with ages varying from 29 to 63. Where necessary, the observers wore their normal eyewear that would enable them to view the light source in focus. The observers were in good health and alert. Three of the observers were ex-mariners.

4 Results

The results were recorded by the observers on paper sheets, and transferred to Excel for further processing. One observer missed the result for run 2, and another observer marked run 5 with two different results with nothing for run 4. Since it was not possible to determine what the intended response for run 5 is, the results were removed.

The 5 possible responses for each run were given a value, ranging from -2 for flash 1 being much more bright, 0 for both flashes being the same, through to 2 for flash 2 being much brighter. This produces a sliding scale to understand any bias towards which flash seems brighter. The raw results are shown in Appendix B.

However, it should be made clear that a value of 2 does not mean that flash 2 brightness was double that if the value was 1. This is an artificial scale to provide guidance to observer perception. It is not possible to use this as an absolute scale to calculate the apparent intensity directly. This must be borne in mind when interpreting the results given below.

4.1 Control Runs

Throughout the experiment, a number of runs consisted of identical flashes to determine the ability of the observers to identify flashes of genuinely identical apparent intensity. A total of 8 runs (13% of total) were used for this purpose. The results of the control runs are shown in Table 1.

Run	Flashes 1 and 2			Observer Results						Average
	Length	Int.	Shape	P1	P2	P3	P4	P5	P6	
1	500	10	Rectangle	-1	0	0	0	0	0	-0.2
4	300	10	Rectangle	0	-1	1	-	0	0	0.0
7	500	10	Tri Up	0	-1	1	0	1	0	0.2
20	500	10	Tri Down	0	0	0	0	0	0	0.0
36	500	10	Tri Sym	-1	0	0	0	-1	0	-0.3
48	500	10	Gauss	0	0	1	0	-1	0	0.0
59	200	5	Rectangle	0	-1	0	0	0	0	-0.2
60	500	10	Rectangle	1	0	-1	0	0	0	0.0
			Average	-0.13	-0.38	0.25	0.00	-0.13	0.00	**-0.063**
			Observer Age	52	29	58	51	63	60	

Table 1 – Results from the control runs during the trial

Overall, the observers were able to identify identical flashes throughout the entire trial, resulting in an average very close to zero, as expected. This reassuring result is also true for the different flash shapes and lengths. It also indicates that the observers were not experiencing issues related to fatigue towards the end of the experiment.

At the beginning of the trial, the observers were asked to note their ages on the top of the recording sheets (no other identifiable information was taken). It has been noted in the past that older observers tend to have more consistency in their responses. In this small sample, there does seem to be some element of truth in this, with the highest average deviation from zero being obtained by the youngest participant in the trial. However, there is not enough data to derive any firm conclusions, particularly since the participant with the next highest average deviation from zero also had the highest number of deviations from zero. Much more data would need to be collected before any further conclusions can be obtained on this.

4.2 Comparison against Models

The original plan for analysing the data was to review the individual runs to determine if there is any bias towards a particular model or visual constant value. This would be achieved by setting the flash intensities so that they would produce equal brightness according to the different models being tested; the highest number of equal brightness matches per model would indicate which model is more correct. However, it became apparent in post-processing that more subtle effects could be seen in the results that indicated that the trial needed more granularity in the intensity of the flashes. Good examples of this are runs number 25 and 32. Both runs compared a 200 ms Triangular Up shape with an intensity of 10 against a 5-second rectangular flash with an intensity of 4. While intended to be of equal brightness, there was insufficient granularity to achieve this and the results shown in [RD4] suggest that the triangular flash would be very slightly brighter. The observers agreed with this in both runs, which suggests that the “equal brightness count” method would not work effectively.

However, by calculating the actual differences between the flashes using the two effective intensity models considered here, IALA MAM and the Couzin-Tutt Model, it will be possible to get an understanding of which model the observers more closely agree with.

The relative effective intensity using both models was calculated for each flash using its shape, length and intensity setting. For each run, the relative effective intensities were compared to determine the ratio of flash 1 to flash 2. This returns a value comparable to the average values used for the observations: a negative value implies flash 1 was brighter, a positive value implies flash 2 was brighter, and 0 meaning they were exactly the same.

The results of this calculation are shown in Appendix C.

It noted that such a comparison between observations and the models is somewhat limited due to the subjective nature of the observations, and the coarse marking scheme used to record the observations. However, the general trend should be visible by calculating the correlation co-efficient between the observed results and the two models.

4.2.1 Pearson Product Moment Correlation Coefficient

The Pearson product moment correlation coefficient, r, is a measure of the linear dependence between two data sets. It has a value ranging from -1 to 1 inclusive to indicate the nature of the correlation; -1 indicates a total negative linear correlation, 0 is no linear correlation, and 1 is total positive linear correlation.

Mathematically, it is calculated using the following equation:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$$

where x and y are the data of the two data sets respectively, and $\bar{x}$ and $\bar{y}$ are their sample means.

4.2.2 Comparison of the Models

We calculate the Pearson product moment correlation coefficient by using the Observed Averages as the first data set. The second data set will be the effective intensity ratio calculated for one of the models. By comparing this way, it is possible to determine which model fits the observed data the best.

The observed results were compared with MAM and the Couzin-Tutt Model, both with the visual constant equal to 0.1 s and 0.2 s. The results are shown in Table 2. The comparison between the models and observations is shown visually in Figure 8, with the red lines representing the trend between the data sets.

	Modified Allard Method	**Couzin-Tutt Model**
a = 0.1 s	0.555	0.618
a = 0.2 s	0.166	0.235

Table 2 – Pearson product moment correlation coefficient, r, between the observation averages and the prediction models.

The results shown in the table above provide evidence that in all cases, there is some positive linear correlation between the averaged observations and the outcome predicted by the models. However, it is evidently clear that there is much stronger correlation with both models using a visual constant value of 0.1 s than a value of 0.2 s. This is also seen clearly in Figure 8 where the scatter of data when a = 0.2 s (plots on the right) is greater than that at a = 0.1 s (plots on the left).

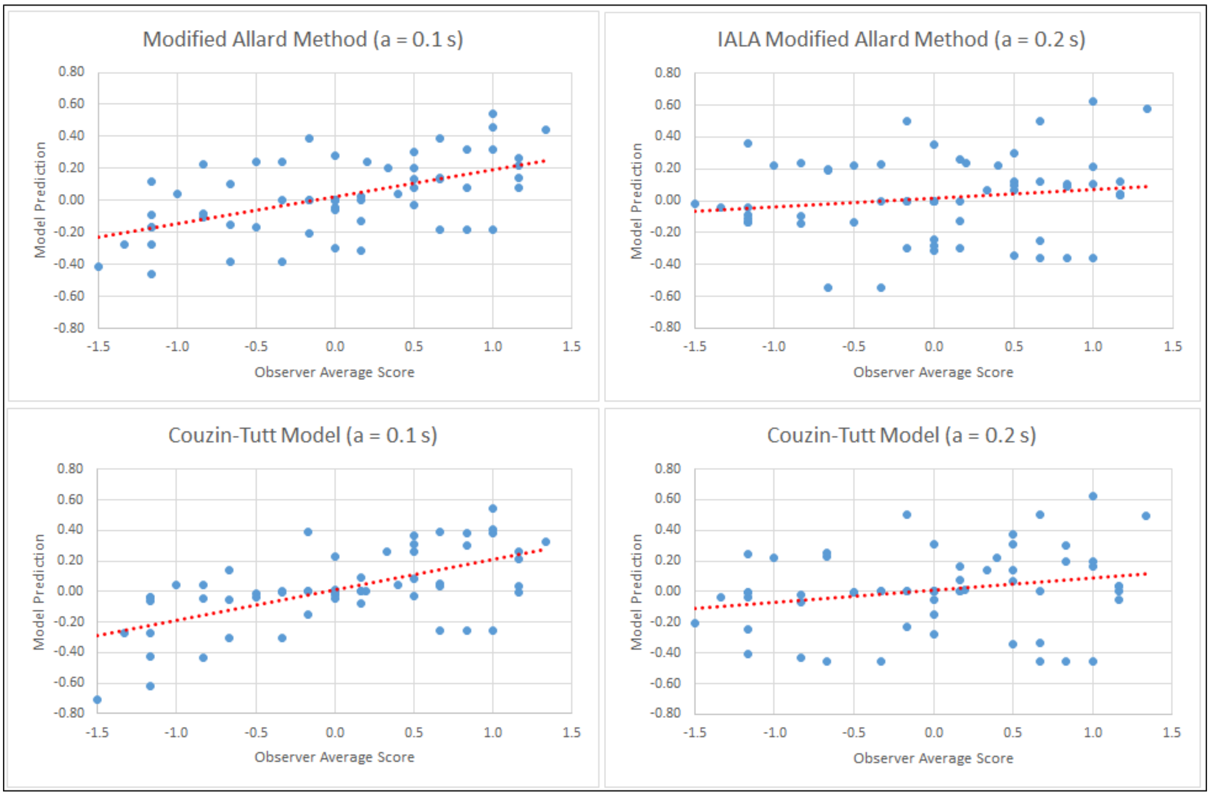

Figure 8 – Summary of the comparison between observations and the models. The red line represents the trend in the comparison.

The difference between MAM and the Couzin-Tutt Model is somewhat subtler, with the correlation indicating that the Couzin-Tutt Model fitting with observed averages better than MAM. This will be due to the influence of how the models treat the flash *shapes*. This is unsurprising, since the Couzin-Tutt Model has been fitted to more precise measurements than was capable during this experiment and showed that the human visual system does not quite respond as MAM predicts. Again, this can been seen in Figure 8 where the scatter of data points for the Couzin-Tutt Model with a = 0.1 s (bottom left) is less than that for the MAM with a = 0.1 s (top left).

4.3 Supplementary Post-Experiment Discussion

As an aside, and due to the experiment finishing earlier than expected, it was decided to run a selection of the flashes again, to obtain feedback from the observers and promote discussion. Some observers said they changed their minds several time during some of the runs. Given some of the subtle differences in the flashes: this is, perhaps, to be expected. Curiously, some observers felt they were able to make decisions quite conclusively and quickly.

The way the experiment was conducted required the use of short-term visual memory of the first flash in order to compare it to the second flash. It is speculated that when the “changing of minds” situation occurs, doubt was cast on the memory of the first flash, making the decision more uncertain. This was the reason the flashes were repeated 3 times, and that the observers were asked not to overthink the decision (the longer it takes to make a decision, the worse the memory of the flashes and the more uncertain the decision becomes).

A quick test was carried out to, effectively, compare two rectangular shapes, but with different intensities. These intensities would indicate whether a = 0.1 s or a = 0.2 s is more appropriate by comparing it to a very long rectangular flash. There was a unanimous verdict that when a is 0.2 s, the flash appears significantly brighter than MAM suggests. When a flash peak intensity was set to that which fits with a = 0.1 s, the verdict was much towards being the same intensity.

5 Conclusions

The purpose of the experiment was to collect more data on conspicuity models and trials that have been conducted by R&RNAV over the years.

The results of the trial show that the MAM with a visual constant of 0.2 s, as currently recommended by IALA, seems to underestimate the effective intensity for white light. This has been confirmed by this experiment, and by others performed in the past.

There is an indication in the results of this “in-the-field” experiment that the Couzin-Tutt Model does indeed follow observations more closely than IALA MAM. The differences are much more subtle than the impact of changing the value of the visual constant, as we would expect, but a difference does seem to be there.

The following discussion relies on the results from all of R&RNAV results, not just the trial described in this report.

5.1 Implications of Changing the Visual Constant

The results of the R&RNAV trials indicate that the currently recommended effective intensity model is underestimating the effective intensity of flashing light by some margin.

The biggest impact is the change of the visual constant, a, from 0.2 s to 0.1 s. There is a precedence for a lower value – the British Standard BS942 recommended the value of 0.15 s for revolving beams and 0.1 s for eclipsed light in 1949 [RD7]. IALA chose a value of 0.2 s, presumably to err on the side of caution, but this cannot be verified.

However, the author feels that manipulating the visual constant to be cautious in this way is misleading and confuses the intention of such changes. If a certain illuminance of the eye is required in order to correctly detect and identify a flashing visual signal, then the threshold of illuminance should be selected to provide the required level of confidence. The model used to calculate the effective intensity of flashing lights should, as much as possible, reflect the actual human response to such stimuli.

The current threshold of illuminance for maritime applications, as recommended by IALA, is 0.2 µlux. This, already, is some margin above the threshold of foveal vision, which is determined to be approximately 0.06 µlux [RD3]. If there were sufficient concern regarding the perception of visual signals at night, then a debate would be needed to determine whether the IALA recommended threshold of illuminance is sufficiently high. If not, it would be more appropriate to increase it to meet the levels required rather than using an inaccurate value of a in the effective intensity model to compensate for a lower than required threshold value. This, however, is beyond the scope of this report and trial.

5.1.1 Reduced Power

The obvious implication in changing the value of the visual constant downwards, assuming all else remains equal, is that a luminous range of a flashing light can be achieved with a lower intensity light, and therefore lower electrical power. This would be seen as advantageous by both service providers and manufacturers since it would be possible to maintain existing nominal ranges for lower cost.

This is certainly appealing; however, one should not decide to reduce the light intensity in isolation. In many areas, reducing the intensity may not be acceptable, in which case the increased range option should be considered, see below.

5.1.2 Increased Range

Another way to consider the downward change in the visual constant is that the nominal range increases for the same flashing light intensity. A number of viewing trials may have determined that the observed light intensity is what is necessary for the visual signal in question, due to, say, conflicting background illumination. This light intensity, once certain assumptions and threshold are applied, is determined to have some nominal range. However, the key metric here is the observed light intensity – the nominal range is simply a crude means to describe that intensity. Where the required intensity of a light is based on observed performance rather than a purely numerical assessment, the light intensity should not be reduced, rather the published range updated based on the result of the new model In this scenario, the performance of the light does not change; only the figure that is published based on that performance.

5.1.3 Higher Resilience to Service Conditions

A higher effective intensity for a given power means that the nominal range is increased, as discussed above. However, by keeping the published nominal range as is, it allows more scope to deal with the service conditions. IALA currently recommend applying a service condition factor of 25% when designing a visual signal. However, experiments carried out by R&RNAV during its field measurement campaigns have shown that, in some cases, this factor is not sufficient.

By changing the model as discussed above, the scope for existing lights to deal with higher service condition factors is increased, and therefore improving the service provision.

Again, one should be careful in interpreting the implications in this way, and this should not replace what is good practice – a good maintenance regime is always needed.

5.2 Implications of Changing Effective Intensity Model

The differences between MAM and the Couzin-Tutt Model are more difficult to quantify from the results in the trial reported here. However, previous experiments by R&RNAV have shown that there is indeed a difference to how the human visual system responds to flash shapes than to what MAM predicts. This is particularly highlighted with MAM predicting a significant difference between the Up Triangle and the Down Triangle flash shapes; a difference that is not perceived by observers. The Couzin-Tutt Model seeks to correct for this anomaly and ensure that it fits with observations more closely.

In the real world with non-ideal flash shapes, the impact of changing the model is hard to characterise. As a rule, for a given visual constant value, the Couzin-Tutt Model tends to result in a slightly higher effective intensity than MAM. However, the key point of the Couzin-Tutt Model is that it should reflect the human visual system more accurately than MAM, and for that reason alone, it should be seriously considered as a replacement for MAM, regardless of the decision regarding the value of the visual constant.

5.3 Impact of Colour Light

One should briefly consider the impact of colour on the results described above. This experiment, and most of the others carried out by R&RNAV, have used white light. This is reasonable since the majority of lights in marine visual signalling are white.

Research carried out by R&RNAV, and highlighted in [RD5], found that there is no variation between white, and the other IALA preferred colours in terms of the visual constant. However, the exception to this was blue light. It was found that the human visual system does indeed seem to respond to blue light more slowly than other colours, and that a visual constant of 0.2 s is more applicable.

Whilst blue is important for emergency wreck marking, it is not used elsewhere in the IALA maritime buoyage system. Nevertheless, it is recommended that for blue light only, the visual constant should remain at a value of 0.2 s, regardless of the whether the MAM or the Couzin-Tutt Model is used.

5.4 Further Work

Despite the extensive amount of work carried out by R&RNAV over the years, more data would be valuable in further confirming the models and the value of the visual constant. This could include repeat runs of the trial described in this report, or more precise measurement as carried out by R&RNAV in the past.

One area that would require further understanding is the effect of background luminance on perceiving a visual signal. This can be considered in two stages. Firstly, the impact of rival point sources near the required visual signal. Does this have an effect on its conspicuity? Secondly, the effect of daytime, or constant background luminance, on the perception of the flashes. This will be an interesting experiment, particularly because the perception will depend on a different level of dark adaptation.

6 Recommendations

Following the results of this trial, and those that precede it, it is recommended that IALA consider revising:

- the visual constant, a, from 0.2 s to 0.1 s; and,
- the model for calculating the effective intensity from the Modified Allard Method to the Couzin-Tutt Model.

It is also recommended that if the internationally agreed method of calculating effective intensity is changed, that the threshold of illuminance is reviewed to ensure that it does meet the requirements for marine signalling with a lower value of a for flashing lights.

It should be noted that the implications of any changes to the international recommendations on calculating effective intensity based on the above should be carefully considered by service providers and manufacturers alike.

Appendix A Couzin-Tutt Model Convolution Function

The Couzin-Tutt convolution function is the Luizov convolution function that has initially been modified by "shear mapping" and further adjusted to better match empirical data. The resulting function peaks at a non-zero positive value of t, unlike the Luizov function, where the peak occurs at zero. The function is made to have exactly the same horizontal distance between two points with the same value of $q(t)$ as that for the Luizov function [RD6].

Due to the more complex nature of the function, it is formed of four segments. The total function is a combination of all four segments as seen in Figure 9.

In order to calculate the function, three constants must be defined. These are:

a is the visual constant, set to 0.1 s or 0.2 s.

T is the time at which the peak of the impulse occurs, and has a value of 0.3 s.

m is the "rise ratio" and has a value of 0.918.

These values have been determined through trial and error, and fitting the model results to observations.

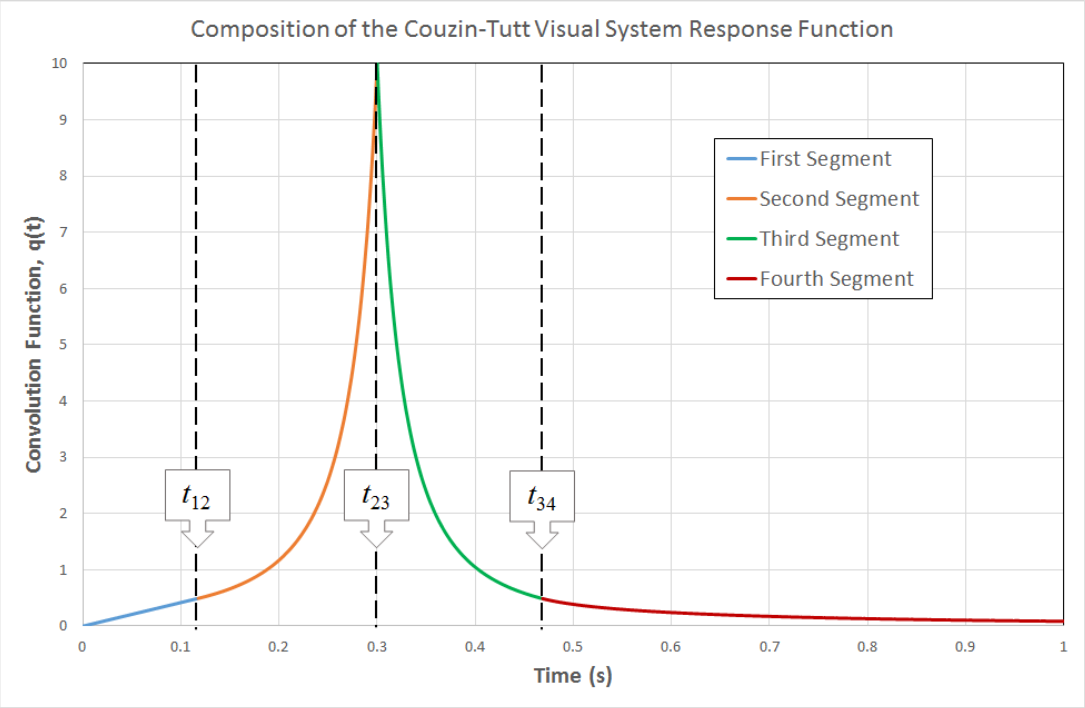

Figure 9 – Composition of the Couzin-Tutt Convolution Function

We must first determine the locations of the segments. These are defined as follows.

The point where the first and second segment join occurs at

$$t_{12} = \frac{\left(\frac{a}{1+m} + T\right)}{3}$$

The point where the second and third segments join occurs at

$$t_{23} = T$$

The point where the third and fourth segments join occurs at

$$t_{34} = T + m(T - t_{12})$$

We can now calculate the value of the $q(t)$ function for each segment.

The first segment is a straight line:

$$q_1(t) = \frac{q_2(t_{12})}{t_{12}}t$$

The second segment is calculated as follows

$$q_2(t) = \frac{a}{[a + (1 + m)(T - t)]^2}$$

The third segment is calculated as follows

$$q_3(t) = \frac{a}{\left[a + \left(1 + \frac{1}{m}\right)(t - T)\right]^2}$$

The fourth segment is more complex, and is calculated by solving for the roots of the following cubic equation:

$$Y^3 - 2s(a + t)Y^2 + s^2(a + t)^2Y - as^2 = 0$$

where the smallest real root is $q_4(t)$ and $s = \frac{q_2(t_{12})}{t_{12}}$ (this is the slope of the linear first section).

Note that the real root values are only valid for $t \geq t_{34}$.

Determining the roots for the final section is algebraically difficult, but it can be achieved numerically, relatively easily using helper functions in a mathematics application or in Excel. One can consider using Matlab or Octave, and simply using the roots function to calculate the required value:

```
min(roots([1 -2*s*(a + t) s^2*(a + t)^2 -a*s^2]));
```

No such function exists in Excel, and it is entirely possible to write a sheet to calculate the roots as necessary. However, it is also possible to obtain functions that will calculate the real roots as required. An example of this can be seen at this website:

https://newtonexcelbach.wordpress.com/2010/08/04/solving-cubic-and-quartic-equations-with-excel/.

Finally, we combine all the segments to produce the final complete Couzin-Tutt convolution function. Thus,

$q(t) = q_1(t)$	for $0 \leq t < t_{12}$
$q(t) = q_2(t)$	for $t_{12} \leq t < t_{23}$
$q(t) = q_3(t)$	for $t_{23} \leq t < t_{34}$
$q(t) = q_4(t)$	for $t_{34} \leq t$

Appendix B Flash Configurations and Raw Results for Trial

Below is the list of flash profiles used during the trial. The rows highlighted in yellow are the control experiments containing two identical flashes. The observer results have been converted to a score, indicating whether flash 1 was much brighter (-2) through to flash 2 being much brighter (2). A value of 0 means that the two flashes appeared to be of identical brightness.

Run	Flash 1			Flash 2			Observer Results					
	Length	Int.	Shape	Length	Int.	Shape	P1	P2	P3	P4	P5	P6
1	500	10	Rectangle	500	10	Rectangle	-1	0	0	0	0	0
2	300	10	Rectangle	5000	8	Rectangle	1	1	0	0	0	
3	300	10	Rectangle	5000	6	Rectangle	-1	-1	-1	-1	-1	-2
4	300	10	Rectangle	300	10	Rectangle	0	-1	1		0	0
5	500	10	Tri Down	500	10	Tri Up	1	0	-1		1	0
6	200	10	Rectangle	500	10	Tri Sym	-1	-2	-2	1	-1	-2
7	500	10	Tri Up	500	10	Tri Up	0	-1	1	0	1	0
8	700	7	Rectangle	700	7	Gauss	0	-2	0	-1	-1	-1
9	500	7	Tri Sym	700	7	Gauss	0	1	-1	0	0	0
10	300	8	Tri Down	5000	6	Rectangle	0	2	2	0	2	2
11	200	10	Tri Down	5000	4	Rectangle	-1	-1	-2	-1	-1	-1
12	200	8	Tri Down	5000	2	Rectangle	-1	-2	-2	0	-2	-2
13	700	10	Gauss	200	10	Rectangle	0	1	1	0	1	1
14	5000	6	Rectangle	500	10	Gauss	0	1	1	0	0	1
15	5000	8	Rectangle	500	10	Gauss	0	0	0	0	0	0
16	5000	5	Rectangle	200	10	Rectangle	1	2	1	0	2	1
17	5000	7	Rectangle	200	10	Rectangle	0	1	2	-1	0	1
18	300	5	Tri Down	300	5	Tri Up	0	0	-1	-1	-1	0
19	400	7	Tri Up	400	7	Tri Down	0	-1	1	1	0	0
20	500	10	Tri Down	500	10	Tri Down	0	0	0	0	0	0
21	400	10	Tri Down	400	7	Tri Up	-1	-2	-1	0	-1	0
22	1000	10	Gauss	1000	10	Tri Sym	0	0	0	-1	0	0
23	500	7	Tri Sym	200	7	Rectangle	1	1	1	2	1	1
24	5000	2	Rectangle	200	8	Tri Up	1	2	-2	2	1	2
25	5000	4	Rectangle	200	10	Tri Up	1	2	1	0	0	0
26	750	10	Tri Up	750	10	Tri Down	-1	1	0	-1	0	1
27	300	7	Tri Down	300	7	Tri Sym	1	1	1	0	0	0
28	5000	4	Rectangle	200	10	Gauss	1	2	1	0	1	1
29	200	10	Gauss	5000	6	Rectangle	0	1	-1	1	1	-1
30	500	10	Tri Down	500	7	Tri Up	-1	-1	-1	-1	-2	-1
31	300	10	Rectangle	1000	10	Gauss	-1	1	-2	0	-1	-1
32	200	10	Tri Up	5000	4	Rectangle	-1	-1	-1	-1	-1	1
33	700	10	Gauss	500	10	Tri Sym	0	-1	-1	-2	0	0
34	200	7	Rectangle	500	7	Tri Sym	0	-1	-1	0	0	-1

Run	Flash 1			Flash 2			Observer Results					
	Length	Int.	Shape	Length	Int.	Shape	P1	P2	P3	P4	P5	P6
35	1000	10	Tri Sym	300	10	Rectangle	1	1	2	1	2	0
36	500	10	Tri Sym	500	10	Tri Sym	-1	0	0	0	-1	0
37	5000	6	Rectangle	500	10	Gauss	1	1	0	-1	0	1
38	1000	5	Tri Down	1000	5	Tri Up	-1	-1	-1	0	-1	-1
39	200	10	Rectangle	500	10	Tri Sym	-2	-2	0	-1	-2	0
40	200	10	Gauss	5000	4	Rectangle	-1	-2	-1	-2	0	-1
41	200	6	Rectangle	200	10	Gauss	1	1	1	0	0	0
42	300	6	Rectangle	5000	10	Rectangle	1	2	1	0	0	2
43	300	8	Rectangle	5000	10	Rectangle	-1	1	0	2	1	1
44	300	7	Tri Up	300	10	Tri Down	0	1	1	0	1	0
45	300	7	Tri Up	300	7	Tri Sym	0	0	0	0	1	0
46	700	7	Gauss	500	7	Tri Sym	-1	0	0	0	-1	0
47	500	10	Tri Sym	200	10	Rectangle	1	1	1	0	1	0
48	500	10	Gauss	500	10	Gauss	0	0	1	0	-1	0
49	700	10	Gauss	200	10	Rectangle	1	1	2	1	0	1
50	400	5	Tri Down	400	5	Tri Up	0	0	0	0	-1	-1
51	300	5	Rectangle	5000	3	Rectangle	-1	-2	-1	-2	-1	-1
52	300	5	Rectangle	5000	4	Rectangle	-1	-1	-1	-1	-1	-1
53	700	7	Gauss	200	7	Rectangle	1	1	1	0	1	1
54	5000	6	Rectangle	300	10	Rectangle	1	2	2	1	0	1
55	5000	4	Rectangle	200	10	Gauss	1	1	1	0	1	1
56	400	7	Tri Up	400	10	Tri Down	0	2	1	0	2	0
57	5000	4	Rectangle	300	5	Rectangle	0	0	0	-1	0	1
58	300	8	Rectangle	5000	10	Rectangle	1	-1	-1	0	1	-1
59	200	5	Rectangle	200	5	Rectangle	0	-1	0	0	0	0
60	500	10	Rectangle	500	10	Rectangle	1	0	-1	0	0	0

Appendix C Results of Observations and Models

The table below summarises the average of the observed difference between the two flashes in each run, and the predicted ratio between the two flashes according to IALA MAM and the Couzin-Tutt Model. The ratios are calculated so that a negative value implies that flash 1 is brighter, and a positive value implies that flash 2 is brighter. The observed averages are simply an average of the values allocated to the responses shown in Appendix B. Whilst it is understood that these values are based on subjective decisions, it does indicate the trend of the observer group.

Run	Flash 1			Flash 2			Observed Average	IALA MAM	Couzin-Tutt Model
	Length	Int.	Shape	Length	Int.	Shape			
1	500	10	Rectangle	500	10	Rectangle	-0.2	0.00	0.00
2	300	10	Rectangle	5000	8	Rectangle	0.4	0.22	0.04
3	300	10	Rectangle	5000	6	Rectangle	-1.2	-0.04	-0.28
4	300	10	Rectangle	300	10	Rectangle	0.0	0.00	0.00
5	500	10	Tri Down	500	10	Tri Up	0.2	0.24	0.00
6	200	10	Rectangle	500	10	Tri Sym	-1.2	-0.14	-0.04
7	500	10	Tri Up	500	10	Tri Up	0.2	0.00	0.00
8	700	7	Rectangle	700	7	Gauss	-0.8	-0.14	-0.05
9	500	7	Tri Sym	700	7	Gauss	0.0	0.35	0.23
10	300	8	Tri Down	5000	6	Rectangle	1.3	0.58	0.33
11	200	10	Tri Down	5000	4	Rectangle	-1.2	0.36	-0.07
12	200	8	Tri Down	5000	2	Rectangle	-1.5	-0.02	-0.71
13	700	10	Gauss	200	10	Rectangle	0.7	-0.36	-0.25
14	5000	6	Rectangle	500	10	Gauss	0.5	0.06	0.26
15	5000	8	Rectangle	500	10	Gauss	0.0	-0.25	0.01
16	5000	5	Rectangle	200	10	Rectangle	1.2	0.04	0.26
17	5000	7	Rectangle	200	10	Rectangle	0.5	-0.35	-0.03
18	300	5	Tri Down	300	5	Tri Up	-0.5	0.22	-0.01
19	400	7	Tri Up	400	7	Tri Down	0.2	-0.30	0.00
20	500	10	Tri Down	500	10	Tri Down	0.0	0.00	0.00
21	400	10	Tri Down	400	7	Tri Up	-0.8	-0.10	-0.43
22	1000	10	Gauss	1000	10	Tri Sym	-0.2	-0.30	-0.15
23	500	7	Tri Sym	200	7	Rectangle	1.2	0.12	0.04
24	5000	2	Rectangle	200	8	Tri Up	1.0	0.22	0.41
25	5000	4	Rectangle	200	10	Tri Up	0.7	-0.25	0.05
26	750	10	Tri Up	750	10	Tri Down	0.0	-0.32	-0.03
27	300	7	Tri Down	300	7	Tri Sym	0.5	0.12	0.08
28	5000	4	Rectangle	200	10	Gauss	1.0	0.10	0.38
29	200	10	Gauss	5000	6	Rectangle	0.2	0.26	-0.08
30	500	10	Tri Down	500	7	Tri Up	-1.2	-0.09	-0.42
31	300	10	Rectangle	1000	10	Gauss	-0.7	0.19	0.14
32	200	10	Tri Up	5000	4	Rectangle	-0.7	0.20	-0.06
33	700	10	Gauss	500	10	Tri Sym	-0.7	-0.55	-0.30
34	200	7	Rectangle	500	7	Tri Sym	-0.5	-0.14	-0.04

Run	Flash 1			Flash 2			Observed Average	IALA MAM	Couzin-Tutt Model
	Length	Int.	Shape	Length	Int.	Shape			
35	1000	10	Tri Sym	300	10	Rectangle	1.2	0.05	0.00
36	500	10	Tri Sym	500	10	Tri Sym	-0.3	0.00	0.00
37	5000	6	Rectangle	500	10	Gauss	0.3	0.06	0.26
38	1000	5	Tri Down	1000	5	Tri Up	-0.8	0.24	0.04
39	200	10	Rectangle	500	10	Tri Sym	-1.2	-0.14	-0.04
40	200	10	Gauss	5000	4	Rectangle	-1.2	-0.12	-0.62
41	200	6	Rectangle	200	10	Gauss	0.5	0.30	0.37
42	300	6	Rectangle	5000	10	Rectangle	1.0	0.63	0.54
43	300	8	Rectangle	5000	10	Rectangle	0.7	0.50	0.39
44	300	7	Tri Up	300	10	Tri Down	0.5	0.10	0.31
45	300	7	Tri Up	300	7	Tri Sym	0.2	-0.13	0.09
46	700	7	Gauss	500	7	Tri Sym	-0.3	-0.55	-0.30
47	500	10	Tri Sym	200	10	Rectangle	0.7	0.12	0.04
48	500	10	Gauss	500	10	Gauss	0.0	0.00	0.00
49	700	10	Gauss	200	10	Rectangle	1.0	-0.36	-0.25
50	400	5	Tri Down	400	5	Tri Up	-0.3	0.23	0.00
51	300	5	Rectangle	5000	3	Rectangle	-1.3	-0.04	-0.28
52	300	5	Rectangle	5000	4	Rectangle	-1.0	0.22	0.04
53	700	7	Gauss	200	7	Rectangle	0.8	-0.36	-0.25
54	5000	6	Rectangle	300	10	Rectangle	1.2	0.04	0.22
55	5000	4	Rectangle	200	10	Gauss	0.8	0.10	0.38
56	400	7	Tri Up	400	10	Tri Down	0.8	0.09	0.30
57	5000	4	Rectangle	300	5	Rectangle	0.0	-0.28	-0.05
58	300	8	Rectangle	5000	10	Rectangle	-0.2	0.50	0.39
59	200	5	Rectangle	200	5	Rectangle	-0.2	0.00	0.00
60	500	10	Rectangle	500	10	Rectangle	0.0	0.00	0.00