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Effective Intensity of Multiple-Pulse Flashing Signal Lights

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16. Abstract

Historically, a steady light is quantified by intensity, and a flashing light is quantified by effective intensity. Experts in the lighting industry speculate that the equation specified by the Federal Aviation Administration (FAA) in Advisory Circular (AC) 150/5345-43H is not the most accurate way to determine the effective intensity of flashing lights. Flashing lights used in aviation signal applications can be characterized by the luminous intensity of a steady-burning signal light with the same visual effectiveness. Different formulas exist to calculate the effective intensity of flashing signal lights that use multiple brief pulses of light within each flash. This research effort was initiated to develop a more accurate way to compute effective intensity. In 2011, a laboratory study was conducted to test these calculation methods. The study revealed that a formula based on the Blondel-Rey effective intensity method, proposed by Douglas, was more predictive of judgments of overall visibility than the formula currently published in the FAA AC. A follow-up experiment confirmed that the current FAA equation should be updated to the Blondel-Rey-Douglas formula. In this report, different visibility aspects resulted in very different judgments, and the limitations of the effective intensity concept to characterize the visibility of flashing lights are discussed.

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LIST OF SYMBOLS AND ACRONYMS

$\int$	Integral
I	Instantaneous luminous intensity
I_e	Effective intensity
p	Statistical significance probability level
r^2	Coefficient of determination
t	Time

AC	Advisory Circular
cd	Candela
FAA	Federal Aviation Administration
Hz	Hertz
IALA	International Association of Lighthouse Authorities
IES	Illuminating Engineering Society
IRB	Institutional Review Board (at Rensselaer Polytechnic Institute)
LED	Light-emitting diode
LRC	Lighting Research Center
m	Meter
mlx	Millilux
mm	Millimeter
ms	Millisecond
RPI	Rensselaer Polytechnic Institute
s	Second

EXECUTIVE SUMMARY

Historically, a light illuminated in a steady state is quantified in terms of intensity, and a light illuminated in a flashing state is quantified in terms of effective intensity. Experts in the lighting industry speculate that the equation specified by the Federal Aviation Administration (FAA) in Advisory Circular (AC) 150/5345-43H is not the most accurate way to determine the effective intensity of flashing lights. Flashing lights used in aviation signal applications can be characterized by the luminous intensity of a steady-burning signal light with the same visual effectiveness. Different formulas exist to calculate the effective intensity of flashing signal lights that use multiple brief pulses of light within each flash. This research effort was initiated to develop a more accurate way to compute effective intensity. In 2011, a laboratory study was conducted to test these calculation methods. The study revealed that a modification of the Blondel-Rey effective intensity method, proposed by Douglas, was more predictive of judgments of overall visibility than a different formula currently published in the FAA AC. A follow-up experiment confirmed that the current equation used in the FAA AC should be updated to the Blondel-Rey-Douglas formula. In this report, different visibility aspects resulted in very different judgments, and the limitations of the effective intensity concept to characterize the visibility of flashing lights are also discussed.

1. INTRODUCTION.

Historically, a light illuminated in a steady state is quantified in terms of intensity, and a light illuminated in a flashing state is quantified in terms of effective intensity. Experts in the lighting industry speculate that the equation specified by the Federal Aviation Administration (FAA), in Advisory Circular (AC) 150/5345-43H [1] is not the most accurate way to determine the effective intensity of flashing lights. Flashing lights are used in aviation signal lighting applications, in part because flashing lights are thought to produce higher conspicuity than steady-burning signal lights. A substantial body of experimental evidence is consistent with this expectation [2 through 8]. Previous researchers have reported that very short pulses of light can appear brighter than a steady light having the same intensity as the maximum of the light pulse [9]; this is called the Broca-Sulzer effect [6]. Despite their generally higher conspicuity than steady-burning lights, flashing lights can result in three issues: (1) difficulty maintaining fixation, (2) difficulty judging the relative location or direction of the flashing signal [10 through 12], and (3) creating distractions [7]. Wienke [13] found that when the location of a flashing light signal was unknown in advance, it needed to flash about three times before it was detected.

Flashing lights are used in a variety of transportation applications including aviation, marine navigation, and road travel, each of which has its own terminologies and technical language [14]. One method that has been used extensively across transportation modes has been to quantify the visual effectiveness of flashing signal lights through the luminous intensity of a steady-burning signal light with equal effectiveness; this concept is known as effective intensity. One of the most commonly used formulas for effective intensity is based on studies conducted by Blondel and Rey [15]; this is referred to as the Blondel-Rey formula. According to the Blondel-Rey formula, the effective intensity, I_e, in candela (cd) of a flashing signal light at near-threshold viewing conditions is defined as follows:

$$I_e = \int_{t2}^{t1} I\, dt/(a + t_2 - t_1) \qquad (1)$$

where I is the instantaneous luminous intensity (in cd) at any moment between times t_1 and t_2, both represented in seconds (s); and a is a constant (in units of s) determined experimentally by Blondel and Rey [15] to have a value near 0.2.

Various studies on the perception of flashing lights have confirmed that the Blondel-Rey formula is reasonably predictive of the effectiveness of flashing light signals (such as visual range or relative brightness) under a wide range of conditions [16 through 21]. This is significant because different light-source technologies can produce a wide range of temporal waveforms of light output as a function of time [22]. Values for the constant a in equation 1 have been found to be different depending on factors such as the overall intensity (i.e., for suprathreshold rather than threshold conditions) [16 and 23 through 27], the color [26 and 28], and spatial configurations [26, 29, and 30] of the light.

Not all researchers have found consistent relationships between the value of a in equation 1 and the empirical determinations of effective intensity. For example, many authors have stated that the value of a decreases as the overall intensity increases [23 and 26 through 27]; however, sometimes an opposite effect [16] or no relationship [31] was found. Despite these conflicting findings, the effective intensity formula proposed by Blondel and Rey [15] remains largely accepted in a wide variety of contexts [20]; however, it may not be suitable for predicting the relative effectiveness of very complex waveforms, such as a rapidly alternating high-low sequence superimposed onto a sinusoidal temporal waveform of lower frequency [32].

Another factor that can influence the perception of a flashing light is the presence of very brief, multiple pulses within a cycle of a flashing signal light. Although sensitivity to differences in light flash onset or frequency is relatively high [33], with onset differences of 10 ms being able to be reliably detected [34], sensitivity to pulses presented in temporal sequence appears to be lower. For a series of very short flash pulses separated by dark intervals of 100 ms or less [35 through 37], the visual system will perceive only a single flash. Sometimes, the dark interval could be even larger, causing the pulses to be seen as a single flash [38]. Douglas [39] proposed and the Illuminating Engineering Society [40] accepted a formula for the effective intensity of multiple-pulse flashes that is identical to equation 1, but where t_1 is the starting time of the train of pulses, and t_2 is the ending time. There is some evidence [41 and 42] that the Douglas [39] modification of the Blondel-Rey formula for effective intensity provides good agreement with empirical data.

In comparison, the present formula for multiple-pulse flashing lights (when the frequency of the pulses is at least 50 Hz, corresponding to a dark period between pulses of approximately 0.01 s), such as those used in some obstruction lighting equipment specified by the FAA AC 150/5345-43H [1], uses a modified version of equation 1. In this version, the integration in equation 1 is performed individually for each pulse in the flash, and the effective intensities for each pulse are summed to arrive at the effective intensity, I_e, (in cd) for the entire multiple-pulse flash, as follows:

$$I_e = \int_{t1}^{ta} I\,dt/(a + t_a - t_1) + \int_{tb}^{tc} I\,dt/(a + t_c - t_b) + \int_{td}^{te} I\,dt/(a + t_e - t_d) + \ldots + \int_{tz}^{t2} I\,dt/(a + t_2 - t_z) \quad (2)$$

where I is the instantaneous luminous intensity (in cd) at any moment between times t_1 and t_2 (both represented in s); t_a is the end time for the first pulse in the flash, t_b is the start time for the second pulse, t_c is the end time for the second pulse, t_d is the start time for the third pulse, t_e is the end time for the third pulse, and so on; t_z is the start time of the last pulse, and t_2 is the end time of the last pulse (all values of t_n are in s); and a is a constant (in units of s) with a value of 0.2.

Only a single experimental investigation [43] has been identified in which the Blondel-Rey-Douglas formula was compared directly with the one specified in the FAA AC [1]. A limited field trial of various multiple-pulse flashing lights resulted in responses that appeared to be more consistent with the Blondel-Rey-Douglas method [39 and 40] than that currently used in the FAA AC [1], but there was substantial variability in the results [43]. For this reason, some authorities have proposed using the latter method to quantify the effective intensity of multiple-pulse flashing lights [44], particularly at a time when new light-source technologies (such as light-emitting diodes (LEDs), with a wide variety of onset times and possible temporal profiles) are being deployed in aviation signal light systems.

This report summarizes two laboratory experiments designed to identify the relative utility of the Blondel-Rey-Douglas [39 and 40] formula for effective intensity and the method described in the FAA AC [1] at predicting different visual effectiveness.

2. METHOD: EXPERIMENT 1.

Experiment 1 was conducted in the Levin Photometric Laboratory of the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute (RPI). Two white LED light sources were placed behind 0.6-mm-diameter pinhole apertures (figure 1) and viewed from a distance of 2 m. One source was operated on a constant current power supply, so it produced an illuminance of 15, 22, 29, 37, or 44 millilux (mlx) and a luminous intensity of 0.059, 0.089, 0.118, 0.147, or 0.177 cd, respectively. Only the leftmost and rightmost pinhole apertures were used; the central aperture was covered during the experiment.

Figure 1. Apparatus Used to Present Flashing Light Stimuli in Experiment 1

The other source was operated to produce a flash every second (at a frequency of 1 Hz) that contained three distinct, rectangular light pulses each having a duration of 0.01 s, with the pulses separated by dark periods of 0.03, 0.01, 0.003, or 0.001 s. During the light pulses, the illuminance that was produced 2 m away was 206 mlx, with an instantaneous luminous intensity of 0.825 cd. Temporal profiles of each waveform are shown in figure 2. Waveforms were verified using a fast-response photocell and an oscilloscope.

According to the effective intensity formula from the FAA AC [1] and presented in equation 2, the effective intensity of each of the four waveforms shown in figure 2 is 0.118 cd. Using the Blondel-Rey-Douglas formula (based on equation 1, and setting the start [t_1] and end [t_2] times as the start and end times for the entire train of pulses), the calculated effective intensities are as follows:

- 0.03 s dark interval: 0.085 cd
- 0.01 s dark interval: 0.099 cd
- 0.003 s dark interval: 0.105 cd
- 0.001 s dark interval: 0.107 cd

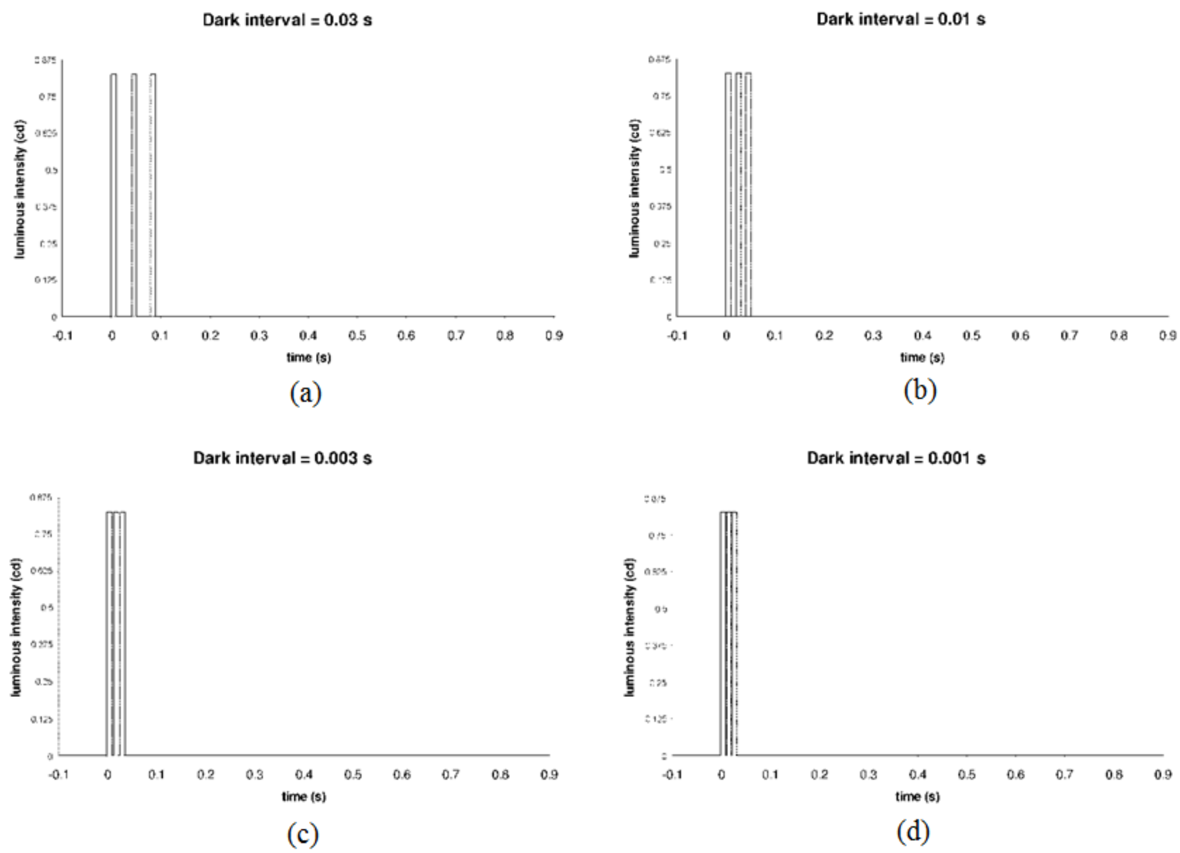


Figure 2. Temporal Waveforms of the Multiple-Pulse Flashing Light Conditions (Intervals between pulses were (a) 0.03 s, (b) 0.01 s, (c) 0.003 s, and (d) 0.001 s.)

The luminous intensities of the steady-burning light signals were centered at approximately 0.118 cd, which was the calculated effective intensity of the flashing light signals according to the FAA AC [1]. The other four luminous intensity values for the steady-burning light signal were 50%, 75%, 125%, and 150% of this value. They also included values lower and higher than the range of calculated effective intensity values based on the Blondel-Rey-Douglas [39 and 40] formula. Each flashing light signal could be presented simultaneously with 1 of the 5 steady-burning light signals, for a total of 20 experimental conditions.

Ten subjects (5 male and 5 female, aged 23 to 62 years, mean age 38) participated in the experiment. After signing a consent form approved by RPI's Institutional Review Board (IRB), the subjects were seated in position, and the height of the signal light apparatus was adjusted to the eye height of each subject. First, an experimenter read the following instructions to each subject:

> *In this experiment, you will be asked to compare pairs of simulated signal lights viewed side by side. One will be a flashing light and one will be a steady light. First, you will be asked to judge which one would be more likely to capture your attention if you were not looking directly at it. Second, you will be asked to judge the relative average brightness of the two lights. By average brightness, we*

mean: over the duration of several cycles of the flashing light, which one looks like it produces more total light? Finally, you will be asked to judge the relative overall visibility of the lights. Visibility may be a combination of how easy it is to detect, identify, and locate a signal light. Taking all of these factors into account, which light do you think is more visible? Try to keep your method of judging each pair of lights the same for each pair of lights you will see. If you need these instructions repeated during the experiment, just let the experimenter know.

Then, the room lights were switched off. In a randomized order, each pair of steady-burning and flashing light signals was presented to each subject twice, and subjects were instructed to respond on a laptop computer (with a screen luminance of 2 cd/m^2) to each of the three questions described in the instructions:

- Which light is more attention-getting?
- Which light has a higher average brightness?
- Which light is more visible overall?

After subjects entered their responses, the next signal light pair was presented until they had completed 40 trials (2 repetitions of the 20 conditions). The sessions took about 20 minutes for each subject to complete.

3. RESULTS: EXPERIMENT 1.

3.1 ATTENTION-GETTING PROPERTIES.

Figure 3 shows, for each of the four flashing light waveforms (each with a different dark interval), the proportion of responses that the steady-burning light was judged more attention-getting than the flashing light, as a function of the luminous intensity of the steady-burning light. Each panel of figure 3 shows five data points, representing the five steady-burning luminous intensities compared to each flashing signal light.

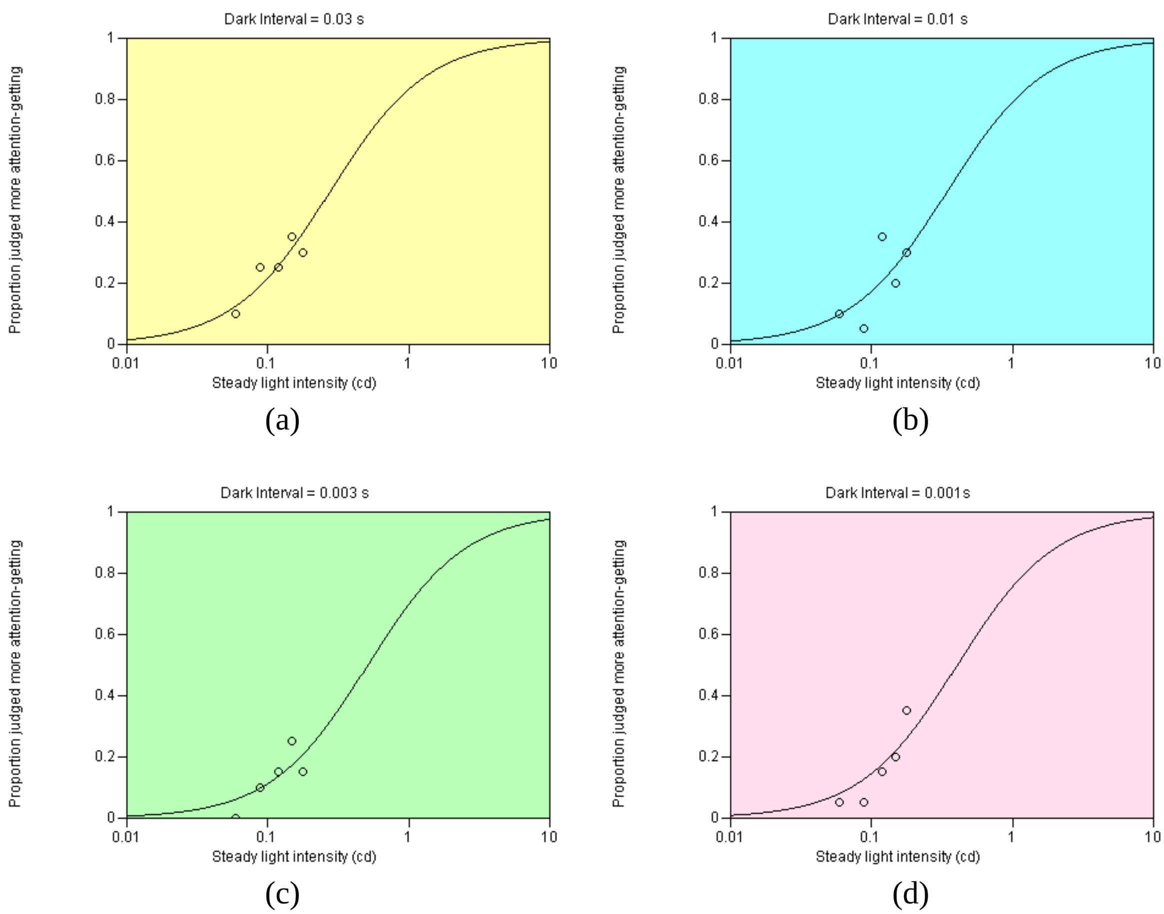


Figure 3. Proportion of Times Subjects Judged the Steady-Burning Signal Light as More Attention-Getting Than Each Flashing Light Signal (Goodness-of-fit (coefficient of determination: r^2) values are (a) r^2=0.73, (b) r^2=0.47, (c) r^2=0.59, and (d) r^2=0.74.)

Also shown in figure 3 are the best-fitting sigmoid functions to the data in each panel, having the form:

$$y = (a - c)/[1 + (x/b)^d] + c \tag{3}$$

where *a* and *c* are the minimum and maximum values of the function (fixed at 0 and 1, respectively, representing the minimum and maximum proportions of times the steady light could be chosen); *b* is the luminous intensity (in cd) where the proportion would be 0.5; and *d* is the relative slope of the functions.

For the data in figure 3, the average value of the slopes when this was a free parameter was 1.262; therefore this was fixed as the value of *d* for the curve fitting, and the value of *b* was the only free parameter. For each dark-interval duration, the value of *b* leading to the best-fitting sigmoid function was:

- 0.03 s dark interval: *b*=0.277 cd
- 0.01 s dark interval: *b*=0.345 cd

- 0.003 s dark interval: *b*=0.512 cd
- 0.001 s dark interval: *b*=0.406 cd

In each case, there was at least a moderate correlation [45] between the observed data and the best-fitting function. The values of *b* listed above correspond to the steady-burning luminous intensity that would be predicted to be judged as equally attention-getting as each of the four flashing light conditions.

<u>3.2 AVERAGE BRIGHTNESS</u>.

Figure 4 shows the proportion of responses that the steady-burning light was judged as having higher average brightness than the flashing light, as a function of the luminous intensity of the steady-burning light. Also shown in figure 4 are the best-fitting sigmoid functions to the data in each panel, having the same form as equation 3. The slope (*d* in equation 3) was constrained to the average slope (*d*=1.559) of the best-fitting functions when this was a free parameter for each set of data. The values of *b* resulting in the best-fitting sigmoid functions for each flashing light condition were:

- 0.03 s dark interval: *b*=0.046 cd
- 0.01 s dark interval: *b*=0.066 cd
- 0.003 s dark interval: *b*=0.091 cd
- 0.001 s dark interval: *b*=0.085 cd

Except for the dark interval of 0.003 s, where the goodness of fit could not be determined to be better than a straight line of zero slope, there was always a strong correlation [45] between the observed data and the best-fitting function. The values of *b* listed above correspond to the steady-burning luminous intensity that would be predicted to be judged as having equal average brightness as each of the four flashing light conditions.

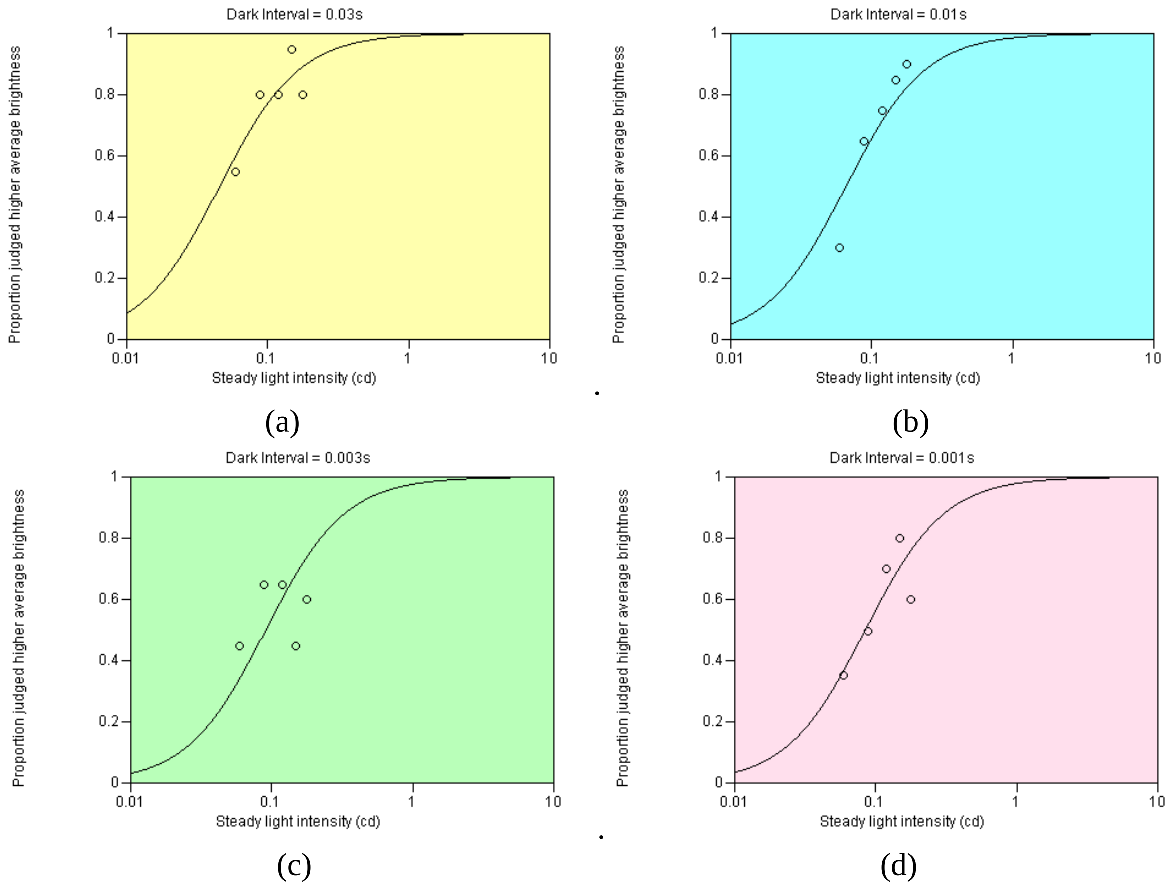


Figure 4. Proportion of Times Subjects Judged the Steady-Burning Signal Light as Having Higher Average Brightness Than Each Flashing Light Signal (Goodness-of-fit values are (a) r^2=0.73, (b) r^2=0.83, (c) r^2=undefined, and (d) r^2=0.67.)

3.3 OVERALL VISIBILITY.

Figure 5 shows the proportion of responses that the steady-burning light was judged as having greater overall visibility than the flashing light, as a function of the luminous intensity of the steady-burning light. Also shown in figure 5 are the best-fitting sigmoid functions to the data in each panel, having the same form as equation 3. The slope (*d* in equation 3) was constrained to the average slope (*d*=1.559) of the best-fitting functions when this was a free parameter for each set of data. The values of *b* resulting in the best-fitting sigmoid functions for each flashing light condition were:

- 0.03 s dark interval: *b*=0.069 cd
- 0.01 s dark interval: *b*=0.072 cd
- 0.003 s dark interval: *b*=0.081 cd
- 0.001 s dark interval: *b*=0.093 cd

In each case, there was at least a strong correlation [45] between the observed data and the best-fitting function. The values of *b* listed above correspond to the steady-burning luminous intensity that would be judged as having equal overall visibility as each of the four flashing light conditions.

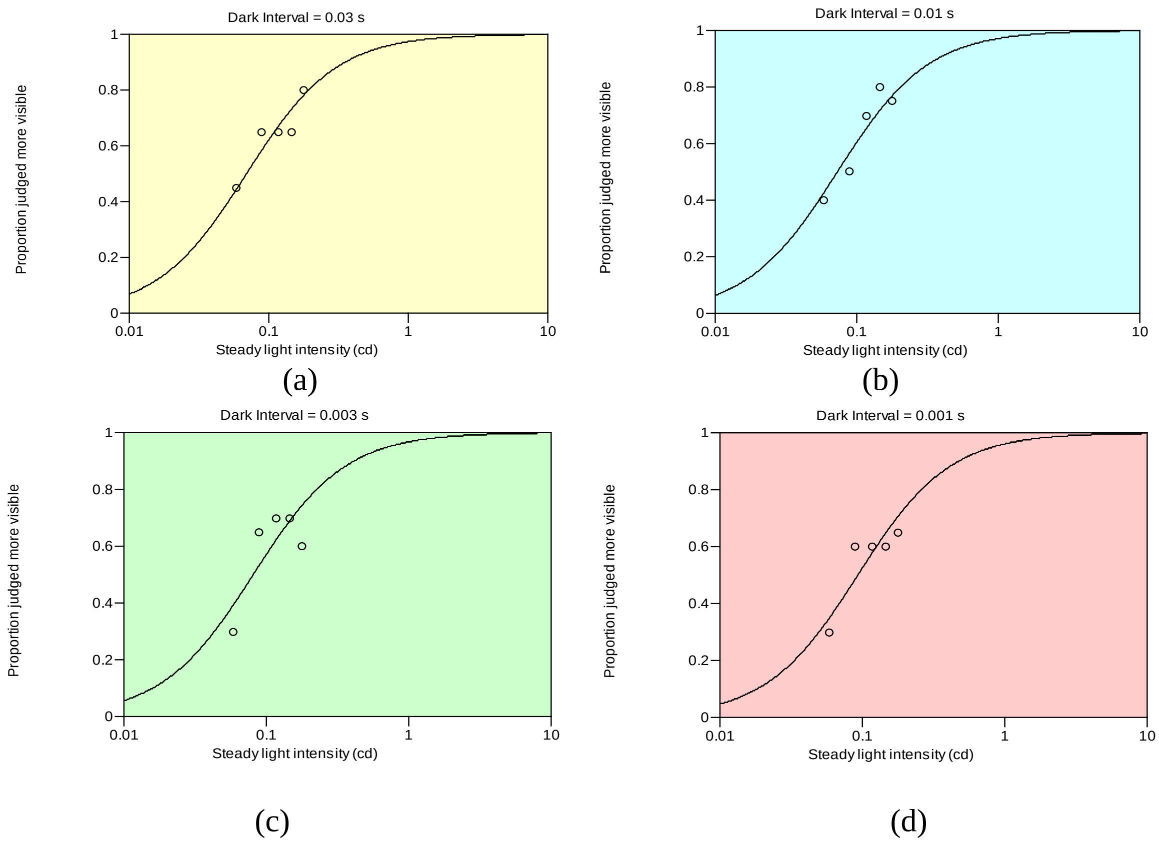


Figure 5. Proportion of Times Subjects Judged the Steady-Burning Signal Light as Having Higher Overall Visibility Than Each Flashing Light Signal (Goodness-of-fit values are (a) r^2=0.80, (b) r^2=0.89, (c) r^2=0.56, and (d) r^2=0.72.)

4. METHOD: EXPERIMENT 2.

Experiment 2 was conducted in the same laboratory with the same apparatus as experiment 1, except only the four flashing light conditions illustrated in figure 2 were used. Ten subjects (7 male and 3 female, aged 23 to 61 years, mean age 37) participated in the experiment.

After the subjects entered the laboratory, signed a consent form approved by RPI's IRB, and sat in their position, the apparatus was adjusted to match each subject's eye height. An experimenter read the following instructions:

> *In this experiment, you will be asked to compare pairs of flashing signal lights viewed one after another. You will be asked to judge the relative overall visibility of the lights. Visibility may be a combination of how easy it is to detect, identify, and locate a signal light. Taking all of these factors into account, which light do you think is more visible? Try to keep your method of judging each pair of lights*

the same for each pair of lights you will see. If you need these instructions repeated during the experiment, just let the experimenter know.

After the instructions were read, the room lights were extinguished, and subjects were presented each combination of signal lights in sequential pairs, one after another. The first in the pair was called A, and the second was called B. Subjects were given the opportunity to view each pair of lights as often as needed to make their judgments before stating which pair they believed was more visible. Each pair was viewed twice in a randomized order, and the lights in each pair were presented in opposite order for each trial featuring a given pair of lights. An experimenter recorded each subject's response during each trial. Each experimental session was completed in approximately 15 minutes.

5. RESULTS: EXPERIMENT 2.

Table 1 shows the number of times each condition was judged as more visible in experiment 2. Figure 6 shows the number of times each condition was chosen as a percentage.

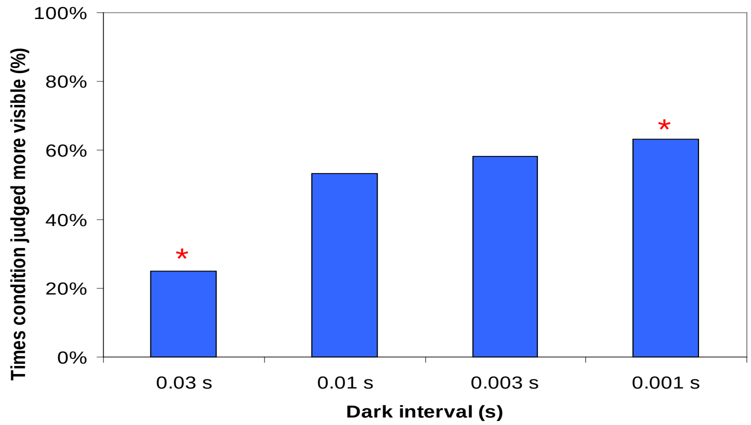
For each pair of conditions in table 1, the rightmost column also indicates whether the proportion of times a given condition was judged as more visible is statistically significant ($p<0.05$) based on a chi-square test, and assuming a 0.5 probability of being chosen under chance conditions. Of the three pairs of conditions in table 1 that resulted in statistically significant differences, the direction of the difference always favored the condition with the shorter dark interval between multiple pulses.

Table 1. Summary of Visibility Responses for Experiment 2

Conditions in Each Pair	Condition Judged More Visible Most Frequently	Number of Times Condition was Judged More Visible (out of 20)
Dark interval=0.03 s and Dark interval=0.01 s	Dark interval=0.01 s	15/20 ($p<0.05$)
Dark interval=0.03 s and Dark interval=0.003 s	Dark interval=0.003 s	16/20 ($p<0.01$)
Dark interval=0.03 s and Dark interval=0.001 s	Dark interval=0.001 s	14/20 (n.s., $p>0.05$)
Dark interval=0.01 s and Dark interval=0.003 s	Dark interval=0.01 s	12/20 (n.s., $p>0.05$)
Dark interval=0.01 s and Dark interval=0.001 s	Dark interval=0.001 s	15/20 ($p<0.05$)
Dark interval=0.003 s and Dark interval=0.001 s	Dark interval=0.003 s	11/20 (n.s., $p>0.05$)

n.s. = not significant

In figure 6, the percentages of time each flashing light condition was judged as more visible (out of the total number of times it was presented) increase monotonically as the dark interval between the pulses in each flash decrease. For the dark intervals of 0.03 s and 0.001 s, chi-square tests revealed that the percentages were statistically significantly different from chance. The condition with the dark interval of 0.03 s was judged more visible reliably fewer than half the time, whereas the condition with the dark interval of 0.001 s was judged more visible reliably more than half the time.



* Percentages that differ reliably (p<0.05) from chance

Figure 6. Percentage of Times Each Flashing Light was Judged More Visible

6. DISCUSSION.

6.1 DIFFERENCES AMONG RESPONSE TYPES IN EXPERIMENT 1.

Observing the data in figures 3 through 5 indicates that the three responses elicited in experiment 1 were very different. Figure 3 shows the relative attention-getting characteristics of the steady-burning lights relative to the flashing lights. All proportions in figure 3 are less than 0.5, which suggests that, on average, the flashing lights were all judged to be more attention-getting than the steady-burning lights used in the study.

This finding is consistent with previously published studies on the conspicuity of flashing lights [2 through 8]. It also suggests that neither the Blondel-Rey-Douglas formula [39 and 40] for effective intensity nor the one used in the FAA AC [1] are very predictive of the conspicuity characteristics of flashing lights.

In figure 4, most proportions are greater than 0.5, suggesting that people judged the steady-burning lights to have higher time-averaged brightness than the flashing lights overall. This is a much different response from those on attention-getting characteristics, and the steady-burning luminous intensities. Of the three response types, the data for overall visibility in figure 5 are most balanced in terms of the number of proportions greater than or lower than 0.5. These differences underscore the importance of understanding the different responses needed in detecting, identifying, and locating flashing signal lights. A flashing light that is more conspicuous than a particular steady-burning light may not be judged as having greater average brightness or as being more visible than the same steady-burning light.

It is worth noting that, in general, the steady-burning luminous intensities predicted to produce equivalent attention-getting, average brightness, and overall visibility characteristics seem to increase as the dark interval decreases from 0.03 s to 0.001 s. This is more consistent with the Blondel-Rey-Douglas [39 and 40] formula than with the one used in the FAA AC [1], which would predict the same effective intensity for all four conditions.

6.2 AGREEMENT BETWEEN EXPERIMENTS.

The results of both experiments were consistent. Based on the overall visibility response data in figure 5, the steady-burning luminous intensities predicted to have equivalent visibility as each flashing light were (see section 3.3):

- 0.03 s dark interval: 0.069 cd
- 0.01 s dark interval: 0.072 cd
- 0.003 s dark interval: 0.081 cd
- 0.001 s dark interval: 0.093 cd

In comparison, the overall percentages of time that each flashing light was judged as more visible were:

- 0.03 s dark interval: 25.0%
- 0.01 s dark interval: 53.3%
- 0.003 s dark interval: 58.3%
- 0.001 s dark interval: 63.3%

Both sets of data indicate that the visual effectiveness for the four flashing light conditions was highest when the dark interval between pulses of light in the flash was shortest.

Since the effective intensity formula used in the FAA AC [1] predicts each of these conditions to have the same effective intensity, the results from these experiments call into question the use of equation 2 as a means to compare multiple-pulse flashing lights.

Based on equation 1, the predicted effective intensity values using the Blondel-Rey-Douglas formula [39 and 40] for the four experimental conditions are (see section 2):

- 0.03 s dark interval: 0.085 cd
- 0.01 s dark interval: 0.099 cd
- 0.003 s dark interval: 0.105 cd
- 0.001 s dark interval: 0.107 cd

These calculated values exhibit reasonably strong correlations [45] with the estimated equivalent intensities for overall visibility in experiment 1 (r^2=0.68) and the overall visibility percentages listed above from experiment 2 (r^2=0.98). However, only the data from experiment 1 can be used to make absolute comparisons between the Blondel-Rey-Douglas [39 and 40] predictions and measured visibility assessments. When this is done, it is clear that, on average, the equivalent steady-burning intensities for equal overall visibility are about 20% lower than the predictions using the Blondel-Rey-Douglas formula [39 and 40] for multiple-pulse flashing lights.

Although a 20% difference is rather small, the agreement can be lessened by using a slightly different value of *a* in equation 1. If the value of *a* is 0.25 rather than 0.2, the calculated effective intensity for each condition is:

- 0.03 s dark interval: 0.073 cd
- 0.01 s dark interval: 0.083 cd
- 0.003 s dark interval: 0.087 cd
- 0.001 s dark interval: 0.088 cd

As reported in section 1, Neeland et al. [16] suggested that for suprathreshold conditions, the value of *a* increases as the overall intensity increases. However, this finding has not been consistent in the literature, as other authors [23, 26, and 25] came to the opposite conclusion.

7. SUMMARY AND RECOMMENDATIONS.

In general, the results of both experiments summarized in this report agree with the notion than the formula for effective intensity of multiple-pulse flashing lights, currently used in the FAA AC [1], which is based on the sum of the effective intensity values for each pulse, will not predict the relative visual effectiveness of those lights. Using different flashing light conditions in which three pulse flashes were presented with different dark intervals between pulses, the modification of the 1912 Blondel-Rey formula [15] (recommended by Douglas in 1957 [39] and published by the Illuminating Engineering Society in 1964 [40]) appears to be more appropriate for estimating the relative effectiveness of multiple-pulse flashing lights for the range of pulse intervals used in the present study.

The use of different response measures in experiment 1 of this study, and the very different steady-burning light intensities found to provide equivalence according to each of those criteria, serve to emphasize several important limitations of the effective intensity concept. It should be recalled that, as initially defined by Blondel and Rey [15], the effective intensity was used to determine the relative visibility of lights when viewed at threshold conditions when the light is barely visible, such as at very long-range viewing distances. It could be argued that flashing lights used in aviation applications, such as obstruction lighting, are designed to be seen well above threshold, more similar to the conditions employed in the present experiments. A 2008 study by the International Association of Lighthouse Authorities (IALA [20] revealed that, although effective intensity values are not applicable to suprathreshold viewing conditions, there is presently no alternative to using effective intensity formulas based on threshold conditions. Therefore, the IALA recommends effective intensity to evaluate signal lights even when viewed above threshold conditions. Certainly, the relative effectiveness seems to be characterized reasonably by the effective intensity concept, provided the issue of multiple-pulse flashes of light is handled accordingly.

Although the absolute values of the equivalent steady-burning intensity data in this study were more closely predicted when the Blondel-Rey-Douglas formula [39 and 40] was modified to use a different value of the constant *a* in equation 1, it is not recommended at this time to use a value of *a* different from 0.2, because previously reported values of *a* have ranged from 0.08 to 0.35 [25]. Projector [17] states that the inherent imprecision of effective or equivalent intensity measurements and judgments limits the precision of specifying the value of *a* in such formulas. Therefore, it is recommended that the current equation used in the FAA AC [1] should be updated to the Blondel-Rey-Douglas formula [39 and 40].

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