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Briefing Paper

Visual alarm devices – their effectiveness in warning of fire

A study of the effectiveness of Xenon and LED flashing visual alarm devices in attracting the attention of people at risk from a fire.

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Summary

Visual alarm devices (VADs) are used to warn deaf and hard of hearing people in the event of a fire. They emit pulses of flashing light to alert those that cannot hear the sounder of the fire alarm system. As Xenon and LED devices are currently used for this purpose, this study investigated their effectiveness in warning people of a fire.

The aim was to compare the responses of a group of participants to flashing Xenon and LED devices of varying pulse durations. One Xenon device, three cool white LED devices (of 40, 20 and 10 millisecond (ms) pulse durations) and two warm white LED devices (of 40 and 20ms pulse durations) were used. These devices were matched in terms of the on-axis effective luminous intensity (integrated over the pulse duration using the Blondel-Rey formula with a = 0.2 second) and the effective illumination distribution.

The flashing signals were presented individually to 96 participants who were seated in front of a screen and occupied in a written task. The devices were flashed one at a time, and from a distance of 19m were gradually brought closer to the screen until the subjects responded.

Following analysis of this data it was identified that:

- As pulse durations of LED devices shorten the attention drawing effectiveness increases.
- A comparison between the warm white LED devices and the equivalent duration cool white ones show that the responses are at similar levels.
- The Xenon was more effective than the 10ms cool white LED device in high ambient light but the LED device was more effective under low ambient light.

Based on the above results it is quite likely that a cool white LED with a pulse duration of 5ms would out-perform the Xenon in low and perhaps even in the high ambient light level condition.

One of the benefits of LED devices is that the arrangement of a single light source in a lens is more conducive to producing a uniform distribution. To match this using a Xenon tube in a complex arrangement incorporating a lens and various reflectors is a challenge. Thus LED devices can more readily be configured so that they alert people located anywhere in a protected space, rather than just highly illuminating selected areas.

The Light Research Centre has reported that the use of the constant a=0.01 second (s) in the Blondel-Rey equation gives more comparative performance for flashing devices. This was verified during this research work for LED pulse durations between 10ms and 40ms. For Xenon devices the new constant is not appropriate because the typical pulse duration of a Xenon device is significantly shorter than the constant 0.01s.

Introduction

The test standard to which all VADs in Europe must comply is EN 54-23:2010[1]. This uses the Blondel-Rey formula[2] to calculate the effective luminous intensity (I_{eff}), expressed in candela (cd), of pulses generated from Xenon and LED devices. These are then used to identify a "coverage volume" which is effectively a volume within which the effective illumination equals or exceeds a required level of 0.4 lux (lx) (see Visual alarm devices for fire[3]). The Blondel-Rey formula for I_{eff} is:

$$I_{eff} = \frac{\int_{t_1}^{t_2} I(t)\,dt}{a + (t_2 - t_1)} \qquad \text{(Formula 1)}$$

where: I(t) is the instantaneous value in candela (cd)

a = 0.2s

t2 - t1 is the pulse duration between the 10% of peak amplitude for the pulse.

According to this formula the effective luminous intensity can be the same for a Xenon device producing a high peak intensity with very short pulse duration (typically less than 1ms) and an LED device with a very low peak intensity that can produce very long pulses (up to 200ms). In effect, according to the formula, the response of human subjects to a direct presentation of such pulse signals should be the same.

The formula was based on a study of direct viewing of light sources. However, visual warnings are most often detected though indirect viewing, i.e. seeing the light in the peripheral vision. This has led many to question the suitability of this formula for fire warning devices intended to alert people. A number of studies have previously been performed, most notably by the Light Research Center[4] (LRC) and by Savage[5].

The LRC study concluded that the constant, 0.2s, used as the value for 'a' in the Blondel-Rey formula, was not a suitable metric for predicting the performance of a flashing light viewed indirectly, and proposed that a value of 0.01s was more appropriate.

The study by Savage concluded that the shorter the pulse duration, the earlier the detection and the smaller the detection variation.

Both earlier studies identified issues of concern regarding the use of the Blondel-Rey formula for visually alerting people under indirect viewing conditions. This study aimed to investigate specifically the relative responses of people to Xenon and LED flashing devices with shorter pulse durations ($\leq$ 40ms) – and in addition, the effect of the colour temperatures of LED devices by using both cool white and warm white LEDs.

Test Methodology

The test subjects were seated at a desk in front of a screen. The target illumination levels, taken from the LRC report, were as follows:

- High ambient conditions were 500 lx on a table top and 200 lx on a screen.
- Low ambient conditions were 250 lx on a table top and 100 lx on a screen.

The study by LRC had found no difference in the response of subjects to flash rates of 1 and 2 Hz, so only 1Hz was used this study. Savage's method of testing subjects was used as it provided a continuous change in effective illumination, rather than discrete steps.

To identify the subjects' responses to cool white or warm white LED devices, both were used. The six devices used were:

- Xenon device
- Cool white 40ms LED device
- Warm white 40ms LED device
- Cool white 20ms LED device
- Warm white 20ms LED device
- Cool white 10ms LED device

Their use would allow the following to be established:

- how the LED devices performed in relation to the Xenon device;
- the effect of decreasing pulse duration i.e. 40, 20 and 10ms for cool white LED devices with 40 and 20ms for warm white LED devices;
- a comparison of the performance of warm white and cool white LED devices.

Spatial Conditions

Test room parameters, such as dimensions of the space, light fitting locations, reflectance levels of all surfaces etc., were fed into a DIALux program. This used a database of light fittings to identify those most suited to producing the required illumination levels and the most uniform illumination distribution on the screen and table top. The DIALux program identified four wall-washer light fittings that, using a dimmer switch, would give the closest to the required illumination levels.

A simulation from the DIALux program is shown in Figure 1, and photographs of the actual illumination levels achieved are shown in Figure 2, for the high ambient condition, and Figure 3 for the low ambient condition.

Condition	Location	Target (lx)	Average from illuminance simulation (lx)	Measured (lx)
High	Table top	500	537	570±80
	Screen	200	251	201±46
Low	Table top	250	227	227±31
	Screen	100	109	96±19

Table 1: Table of target, simulated and measured light levels in high and low ambient light levels

The values of the target, predicted and measured light levels are shown in Table 1.

The values in the 5th column are the average of the illuminance levels measured, before and after the subject trials, at a number of positions in the expected peripheral vision of human subjects (taken from the Society of Light and Lighting 2009[6]).

A non-uniform distribution of light on the screen could be a contributing factor to subject responses, if they were naturally more attuned to detecting contrasts in illumination. Using the simulation and wall-washer lighting, this variable was controlled and a relatively uniformly lit screen and table top achieved under the two different light level conditions.

The correlated colour temperature achieved from the lamps in the low and high ambient light conditions (on the screen and on the table) was 3,800K.

Figure 1: DIALux simulation of a space with four wall-washer light fittings

Figure 2: Actual illumination in high ambient light

Figure 3: Actual illumination in low ambient light

Devices Used

Four devices (shown in Figure 4) were used during the trials together with suitable control equipment that allowed the six pulse types to be generated (two of the devices could be set to deliver one of two types of pulses). All devices operated at a frequency of 1Hz.

Figure 4: Devices used for testing

The 20 and 40ms warm white LEDs had specified correlated colour temperatures of 2600K min and 3700K max.

The 20 and 40ms cool white LEDs had specified correlated colour temperatures of 5000K min and 8300K max.

The 10ms cool white LEDs had a specified average correlated colour temperature of 5700K.

The Xenon device used a reflector design compliant with UL1971[7]. The output of the Xenon was closely matched with the LED devices in terms of the on-axis effective luminous intensity levels and the effective illumination distributions. This was achieved by using the 75cd setting of the device with two filters; one frosted to even out the peak and troughs and one attenuation filter to reduce the overall light output.

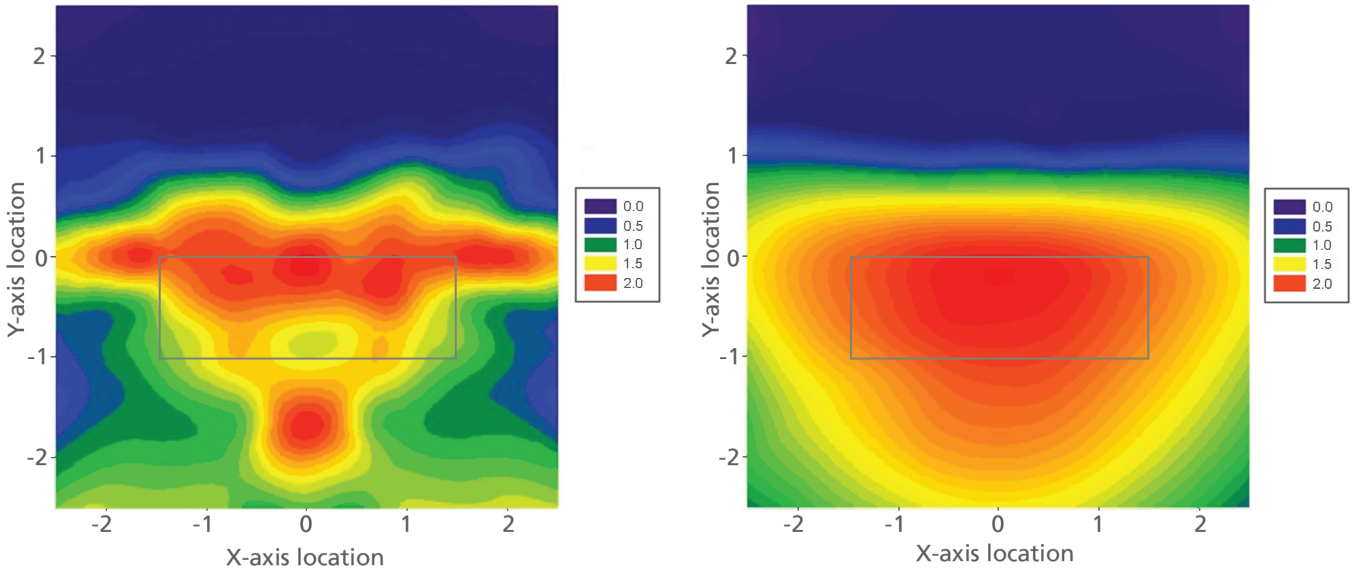
The devices were individually removed from the housing shown in Figure 4 and placed on the BRE VADER light measurement equipment used to conduct the coverage volume test from EN 54-23:2010. A coverage volume test was conducted using the >17m range (see Annex A of EN 54-23:2010), between the alpha angles of 90˚ (on axis) and 60˚ (30˚ off axis). All measurements for the effective luminous intensities were made using the Blondel-Rey formula with a = 0.2s.

The pulse durations and effective luminous intensity levels from the six devices are shown in Table 2. The pulse profiles for all 6 devices can be found in Appendix A

Device	Type	Pulse duration (ms)	Ieff at 90° α (cd)
1	Xenon (with 2 filters)	0.21	48.6
2	Cool white 40ms	37.8	49.5
3	Cool white 20ms	18.7	48.4
4	Warm white 40ms	38.4	47.6
5	Warm white 20ms	18.9	49.6
6	Cool white 10ms	9.3	46.6

Table 2: Pulse durations and effective luminous intensity levels from the six devices

The results from the coverage volume test for all devices were plotted on a colour contrast chart to give a visual representation on a screen opposite the device (at 5m) of the effective light contrast and effective illumination distribution. Two of these are shown in Figure 5 for the Xenon device (left) and the cool white 10ms LED device (right).



Peak illumination at (0,0) = 1.94 lux

Peak illumination at (0,0) = 1.86 lux

Figure 5: Effective illumination distribution (lx) of Xenon (L) and CW 10ms LED (R) devices

The distributions are similar in terms of the peak effective illuminations at (0,0) and the effective illumination distributions.

Even though the above distributions from the two devices appear to be very different their effective illumination in the area of interest, i.e. peripheral vision of the subjects, are closely matched. The effective illumination distributions shown above are at 5m and 94.6% of all subject responses occurred at distances greater than this which means subjects were observing the distributions within the grey boxed area which were centred around point (0,0).

Further information, particularly on the comparative responses of Xenon and LED devices, can be inferred by plotting the raw data from all devices (shown in Figure 6). The plot shows the Ieff (cd) output of the devices at measurement positions that are increasingly off axis. The first measurement is directly opposite the device, and an increasing number of measurements are taken in each rotational plane at fixed incremented divisions as they get further from the normal axis i.e. at 85˚, 80˚, 75˚ etc.

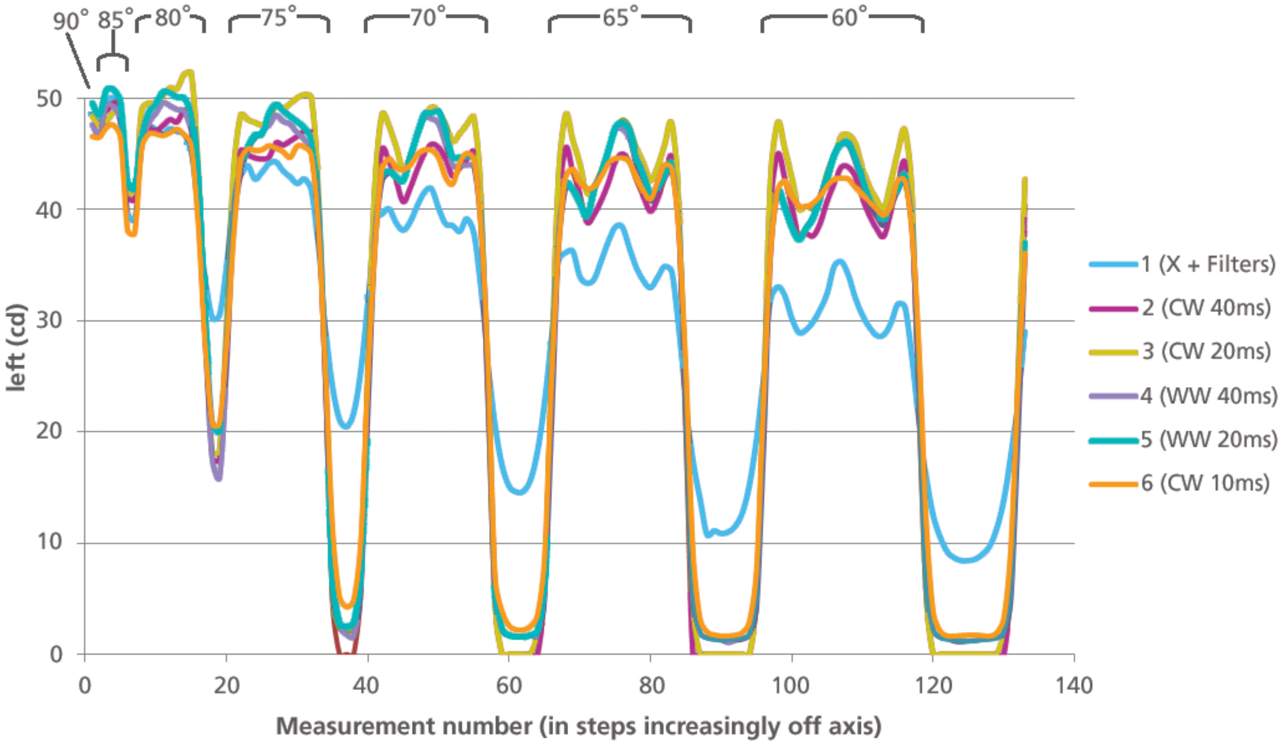


Figure 6: **Ieff results for the six samples**

Initially the Xenon device was used with a 15cd output setting and, even though the on-axis measurement matched the LED devices quite closely, it dropped off rapidly when increasingly off-axis. The Xenon device setting was thus increased to 75cd output and, using two filters, a more comparative response with the LED devices was achieved (as can be seen in Figure 6).

Pulse profiles generated from the original 15cd output and the modified 75cd are shown in Figure A1 (in Appendix A). As can be seen from the graphs in Appendix A, the peak output from the Xenon device used was around a hundred times greater than the highest peak of the LED devices (10ms cool white).

Subject Selection

The three main variables identified that could affect subject responses were gender, age and whether the participant wore glasses. The selection of subjects was such that a complete set comprised 12 people - taking account of gender (M/F), glasses (Y/N) and age group (<40, 40-60, >60). It was established that eight sets would be required to have sufficient statistical data, totalling 96 participants.

Volunteers matching the demographic profiles were contacted using the BRE research project volunteers' database. They were told that the work was part of an office environment research project that was investigating how well people were able to concentrate under different light and sound conditions, whilst performing a written arithmetic and comprehension test.

The volunteers were informed that there was a chance of winning £100 for scoring the highest in the tests. This was done to introduce a competitive element to the exercise, to focus their attention during the trials and to try to prevent them from looking out for the flash.

Subject Test Procedure

Subjects were seated at a desk in front of the screen (see Figure 7) and were given two written exercises to work through. They were instructed to raise their hand if they became aware of a flashing light and then continue with the test.

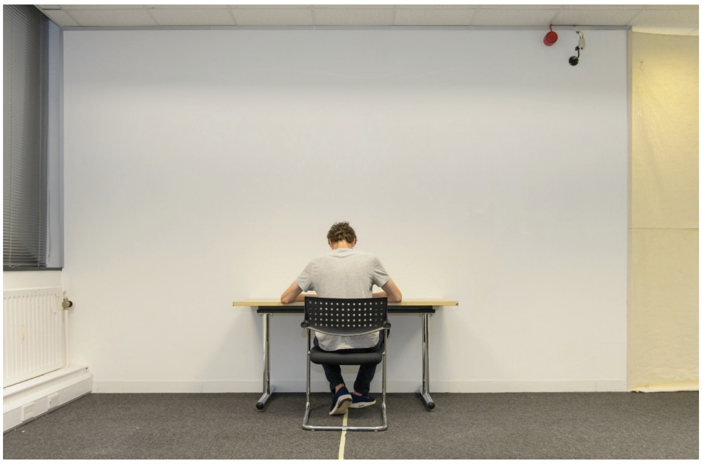


Figure 7: Subject seated in front of the screen and working on test papers

Following the test a short, simple examination of peripheral vision was conducted for every subject to check for any unusual responses (due to visual impairments) that could skew the data. Advice from an optometrist was taken about how to perform a basic peripheral vision test (see Figure 8).

Figure 8: Basic peripheral vision test being performed on a subject

Test Methodology

Presentations of the effective illumination levels from the different flashing devices were performed by switching on one device (mounted 2m from the floor) at a distance of 19.0m from the screen (see Figure 9). The devices were aligned such that the normal axis was in line directly above the test subject's head and 2m from the ground.

Figure 9: Photo of wheeled trolley with devices facing the screen

After a few seconds in this position the trolley was moved towards the screen at a speed of around 0.3m/s, until it was 7.5m from the screen and then the pace was reduced to 0.1m/s. This ensured that the effective illumination levels on the screen were increasing at a linear rather than a geometric rate.

Two looped sound files of a typical office environment were played in the background at a level of 45±5 dB. These were of different durations (91 and 106 seconds each) so that the background sounds were always changing, but were at a level representative of an office environment. This served to cover sounds from the popping Xenon, switches being changed on the control box, and the wheels of the trolley on which the devices were mounted.

At the start of the day the tester was provided with a randomisation table detailing the devices to be used and the order of their presentations to the subject (see Table 3). The background light levels in the room were set more than two minutes before the arrival of the first subject, which enabled all the ambient lights to warm up and produce the required illumination.

Subject number	Ambient light level	Presentation order					
1	Low	3	4	5	1	2	6
	High	4	2	1	6	3	5
2	Low	6	1	2	5	3	4
	High	5	1	3	6	2	4
3	High	1	3	2	6	4	5
	Low	6	5	1	4	3	2
4	Low	3	5	6	2	1	4
	High	2	5	6	3	1	4

Table 3: Example of randomisation order presented to the tester

Once the subject was sat down at the desk he/she was instructed to start the first written exercise. After a period of at least two minutes the first presentation was conducted with periods of 1-5 minutes between subsequent presentations. When the subject raised his/her hand the device was switched off and the distance (in metres) of the device from the screen (determined using a laser tape measure) was noted.

The light level would then be changed and the subject would be asked to start the second written exercise. After a period of at least two minutes (for stabilisation) the first presentation from the second order would be conducted with periods of 1-5 minutes between subsequent presentations.

After the final presentation the ambient light level was changed to that required for the next subject. The subject being tested was told to stop the second exercise and was then taken for the peripheral vision test.

Results

The mean (μ), standard deviation (SD), maximum, minimum and median response distances (in m) from the 96 people are shown in Table 4 (see Table 2 for device details).

Further data was gathered on the effective illumination levels on the screen at distances of 3, 6, 9, 12, 15 and 18m for all devices. From these a formula was used to convert the distance measurements to values of the effective illumination (lx) for each device.

	Low light level (m)					
Device no.	**1**	**2**	**3**	**4**	**5**	**6**
μ	15.1	10.6	13.1	10.6	13.5	14.9
SD	3.1	3.0	3.5	3.0	3.3	3.1
Minimum	6.2	2.0	3.9	3.7	3.0	6.8
Maximum	18.1	17.7	18.7	18.5	18.8	19.0
Median	16.2	10.7	13.1	10.9	13.7	15.3
Variation (%)*	20.6	27.8	26.5	28.4	24.6	20.7

* A measure of the variation was taken (SD/μ as a %) to check Savage's claim that the shorter pulse durations had smaller detection variations.

	High light level (m)					
Device no.	**1**	**2**	**3**	**4**	**5**	**6**
μ	11.0	7.2	9.4	7.2	9.0	10.5
SD	3.2	2.2	2.8	2.0	2.7	3.3
Minimum	3.4	2.6	3.0	2.6	3.0	3.3
Maximum	17.9	11.8	16.3	11.9	16.6	17.4
Median	11.4	7.3	9.6	7.1	8.7	10.3
Variation (%)*	29.3	30.9	29.6	27.6	30.4	31.3

* A measure of the variation was taken (SD/μ as a %) to check Savage's claim that the shorter pulse durations had smaller detection variations.

Table 4: The mean, SD, min, max, median and response distances for all presentations

Analysis and Conclusions

Using the average distance measurements in Table 4, together with the conversion formula the effective illumination levels at the peak performance for each device were calculated. These are plotted in Figure 10 for both the high and low ambient light level conditions. Low levels of effective illumination indicate that less light was required to alert subjects to the flashing lights (i.e. they were seen from a greater distance and were thus more effective).

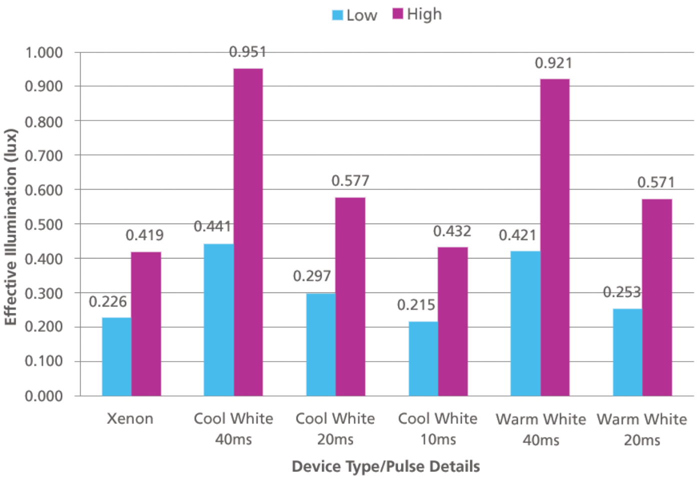


Figure 10: The peak performance responses for all devices under both light levels conditions

This demonstrates that the Blondel-Rey formula does not lead to similar effective illumination levels, in terms of the response of human subjects, for different pulse types and durations. If it had done then all of the values under the low ambient condition would have been at the same level, as would all of those under high ambient conditions.

The following conclusions can be drawn from these results:

- As pulse durations of LED devices shorten the attention drawing effectiveness increases (this is true for both warm and cool white light in both ambient light level conditions).
- The Xenon and 10ms cool white LED devices were more effective at alerting people than the 20ms cool white and warm white LED devices which were more effective than the 40ms cool white and warm white LED devices.
- A comparison between the warm white LED devices and the equivalent duration cool white ones shows that the responses are at similar levels.
- The Xenon was more effective than the 10ms cool white LED device in the high ambient condition (3.3%), but the LED device was more effective under low ambient light (4.9%).

The last point suggests that under the low ambient light level illumination the 10ms LED device outperforms the Xenon device. On closer examination of the distribution detailing the subject response frequency against distance for all devices, it becomes apparent that there was a skew in the data for the Xenon and 10ms cool white LED device under the low ambient level condition.

This skew was because the light outputs from these devices were very high, which led to a quicker response in the low light level condition. This meant that soon after the test was started, as the device was moving towards the screen, the subjects responded almost immediately, resulting in a greater frequency of responses at the higher distances.

Comparison with findings of Savage

One of the findings from the study by Savage was that the shorter the pulse durations the smaller the detection variations. This was validated for the low ambient light level condition, but for the high light level condition there was no correlation.

Comparison with findings of LRC

The study by LRC had reported that using a constant value of 0.2s in the denominator of the Blondel-Rey formula was not a suitable metric for predicting the performance of a signal light viewed indirectly. LRC claimed that a smaller value for the constant needs to be used and proposed a=0.01s, saying that this allowed the data for flashes of light of different durations to be superimposed on each other.

This claim was investigated by comparing the results from all devices. A multiplying factor was then used to convert the effective illumination levels recorded for each of the six device types under the low and high ambient light level conditions (see Figure 10,) to those shown in Figure 11.

This data shows that the peak performance responses for the different devices are in much closer agreement for all LED devices in both low and high ambient light level conditions. However, this is not the case for the Xenon device.

The use of the constant a=0.01s in the Blondel-Rey formula appears more appropriate for LED devices than the existing value of 0.2s, and has been verified for LED pulse durations between 10ms and 40ms for single LEDs driven with a steady current for a fixed duration.

For Xenon devices the new constant is not appropriate because the pulse duration of a Xenon device (typically <1ms) is significantly shorter than the constant 0.01s. Effectively the pulse duration of the Xenon device plays no or little part in the denominator that forms part of the Blondel-Rey equation when using the 0.01s constant. Further work is required on Xenon devices with different pulse durations and peak intensities to identify a suitable formula that would equate their responses to those of LED devices.

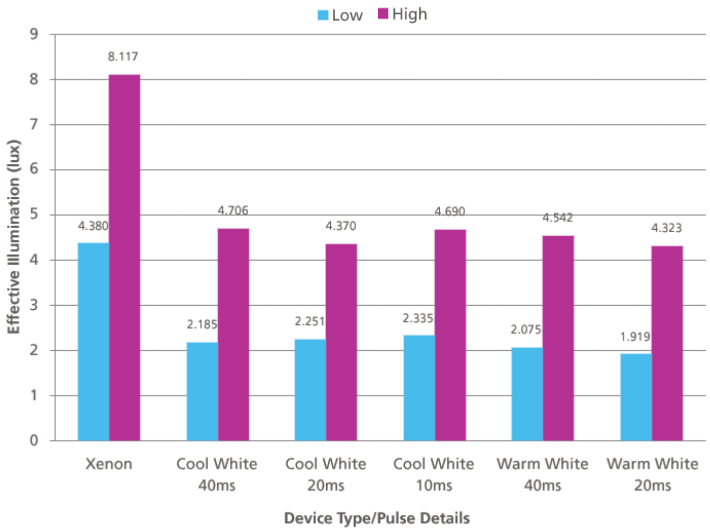


Figure 11: Required effective illumination levels for all devices using the constant a=0.01s in the Blondel-Rey formula

Analysis of sample numbers

An analysis of sample numbers was conducted by reviewing the average responses for the six devices (under both light level conditions) after 24, 48 and 96 subjects. This was performed to identify whether a smaller sample size would give the same results.

Under the low ambient light levels the relative response order remained the same after 24, 48 and 96 subjects’ data were reviewed. Under the high ambient light levels the relative response order changed with subject size, but either device 1 or 6 was always performed best.

This suggests that one can use smaller sample sizes with confidence in a low ambient light level condition if the aim is to determine the relative responses of different devices.

Analysis of demographic subsets

A basic analysis of the demographic subsets was performed by comparing the sum of all 12 distance averages in that set, with another set.

When comparing the responses of gender, females scored 132.1m and males scored 131.9m indicating no real difference in performance as a result of one’s gender.

Those with glasses scored 130.1m and those without scored 133.8m indicating a slightly better performance for those not wearing glasses.

The data regarding age was more difficult to review due to difficulties in obtaining some of the demographic profiles, such as males and females over 60 not wearing glasses. This resulted in 32 people in each of the specific age ranges 20-33, 34-46 and 47-76. The responses from these were 137.2m, 143.2m and 115.6m respectively, suggesting that those in their middle ages generally had the best response!

Most importantly, this exercise demonstrated that no matter which subset was picked for comparison with another, the order of best to worst performing devices was always maintained in low, and generally maintained in high ambient light.

Recommendations for Further Work

The following recommendations are made:

- Further work with LED devices of 5ms, 10ms and 200ms pulse durations to identify whether shorter pulse durations of LED devices can outperform Xenon device/s. This would also demonstrate quantitatively that much longer LED pulse durations are increasingly ineffective at alerting people.
- Further work with equivalent red LED devices would identify the response characteristics of subjects to effective illumination with red light.
- Further work with Xenon devices of differing peak pulse intensities and pulse durations, but the same effective intensities, would provide data from which a suitable relationship could be established to standardise Xenon pulses with different characteristics.

Reference

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Appendix A: Pulse Profiles of all Devices

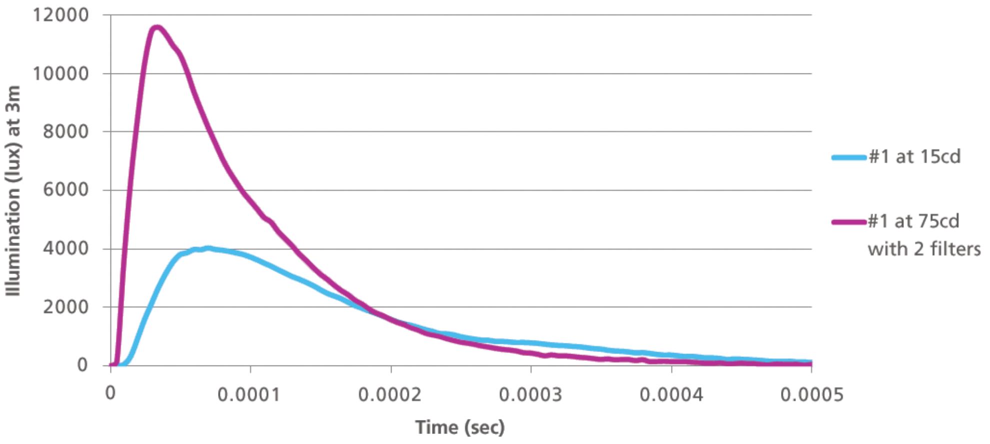

Figure A1: Pulse profile of Xenon device before and after modification

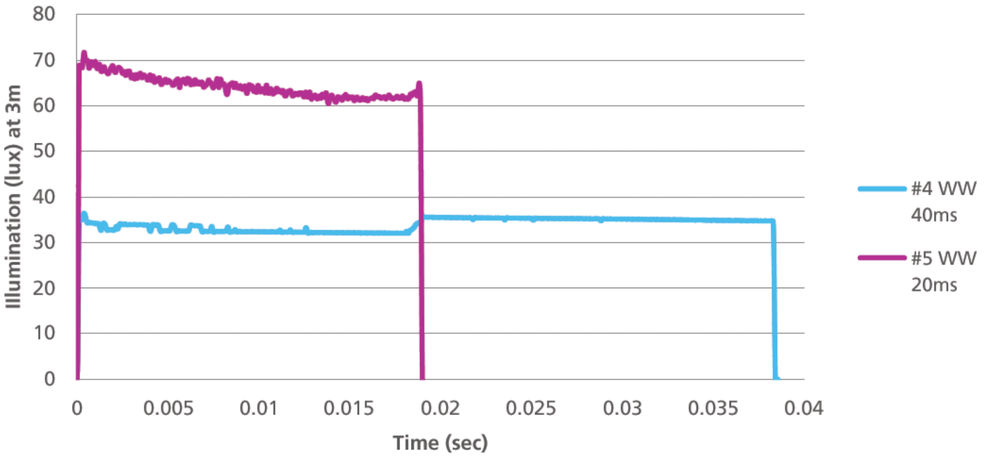

Figure A2: Pulse profiles of the warm white LED devices (pulse durations of 20 & 40ms)

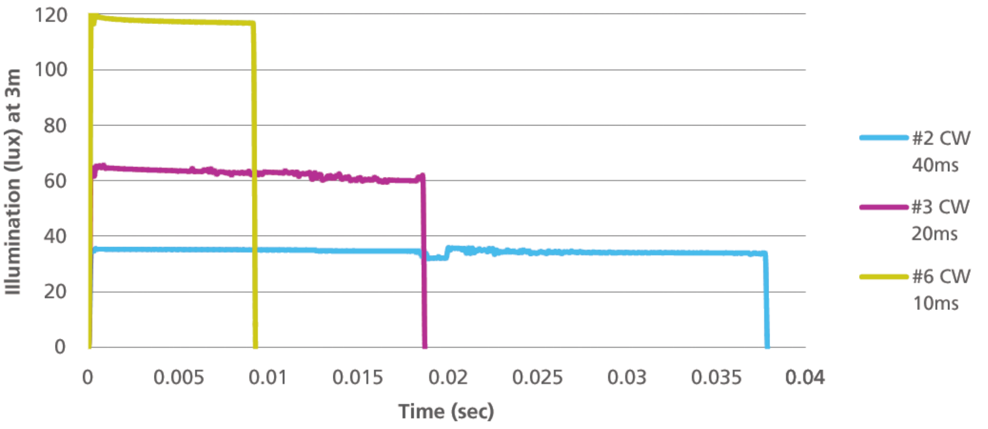

Figure A3: Pulse profiles of the cool white LED devices (pulse durations of 10, 20 & 40ms)

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- Gary Timmins- Head of Acoustics, Building Technology Group
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