Parameters for Indirect Viewing of Visual Signals Used in Emergency Notification

Final Report

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FOREWORD

LEDs and other innovative energy saving lighting technologies (e.g. fluorescents) are rapidly entering the marketplace and present themselves for application to emergency notification appliances. The existing requirements for the performance and application of visible notification appliances are based on relatively short duration, high peak intensity flashing lights – strobe lights. NFPA 72, *National Fire Alarm and Signaling Code*, and referenced listing standards define a method for calculating the equivalent or effective intensity of a flashing light source. The calculation method is subjective and does not produce an exact comparison and is intended only to approximate the perceived brightness for direct viewing of the light source. It has worked because all of the lights approved using the standard have all had relatively similar and short pulse durations. Thus, the peak intensities have been relatively similar.

A review of research performed for the Fire Protection Research Foundation by the RPI Lighting Research Center suggested that effective intensity may not be predictive of visual detection of signal lights when these are viewed indirectly or in the far-peripheral field of view. In particular, observers see the change in illuminance on room surfaces rather than the flashing light itself when it is not in the central field of view. Based on previous literature, the previous Foundation study suggested that a flashing light should increase the illuminance on the opposite wall by at least 7% in order for this increase to be detected reliably. For an ambient horizontal illumination level of 100 footcandles (fc) on the work plane in a space such as an office, it was estimated that the vertical illuminance on the wall should increase by at least 2 fc to be reliably detected. This estimate has not been tested empirically.

The objective of this project was to conduct a human factors laboratory study to identify whether the 7% increase in light level can be reliably detected by observers with normal vision when viewed indirectly. The results from this study provide technical basis to support the development of methods and criteria to evaluate performance of light sources used in emergency notification appliances for NFPA 72.

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Keywords: fire protection building systems, visible notification appliances

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1. Background

Visual signaling appliances used for emergency notification have commonly used xenon strobe lights that produce very brief (<1 ms), high-intensity flashes of light, and their specified performance is characterized by their *effective intensity*, which is an estimate of the luminous intensity (in candelas [cd]) of a steady-burning light that has equivalent visual effectiveness as the flashing light. Evaluations of visual signals used in a wide variety of applications have generally confirmed the utility of the effective intensity for visual signals when they are viewed within the central portion of the field of view (IALA, 2008; Bullough et al., 2013; Bullough and Skinner, 2013), regardless of the specific temporal characteristics of the flashing light. The effective intensity (I_e, in cd) is defined (IES, 1964) in terms of Equation 1:

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

where t_1 and t_2 are the start and end times (in seconds [s]) of the flash of light, respectively; $I(t)$ is the instantaneous luminous intensity (in cd) of the flash at time t; and a is a constant determined empirically (Blondel and Rey, 1912) to have a value of approximately 0.2 s. This constant is related to the temporal integration of the visual system under visual conditions similar to those under which navigational signal lights are just at the threshold for detection at night, when the visual system is dark-adapted. Even though many visual signals, including those deployed in buildings for emergency notification applications, are not viewed under dark adaptation, and are designed to be seen at well above threshold levels, the effective intensity concept has held up for on-axis and near-on-axis viewing conditions (referred in this report as "direct" viewing).

Inspection of Equation 1 suggests that the same effective intensity can be achieved with signal lights having very different temporal intensity characteristics. The duration of the flash of light and its instantaneous intensity can be traded off, so that a very brief, high-intensity flash could have the same effective intensity as a longer, lower-intensity flash of light. This has implications for visual signals using solid-state lighting technology such as light-emitting diodes (LEDs). LEDs are available with increasing efficiency and brightness, making these sources practical for visual signaling devices. Unlike the xenon sources in strobe lights, LEDs can be flashed with different durations and temporal waveforms, so that two appliances could have the same calculated effective intensity but have very different temporal flash patterns (Bullough et al., 2012a).

A review (Bullough et al., 2012b) of previous literature describing the results of studies conducted with xenon strobe light sources (UL 1991) confirmed that for indirect detection when the visual signal is in or near the field of view, an effective intensity of 15 cd provided reliable levels of detection. However, the results of the same studies showed that flashing incandescent sources used as visual signals required much higher effective intensities to be detected reliably. Incandescent flashing sources have longer flash durations that xenon strobe lights because of the inherent properties of the filament that must heat up to produce light, and cool off to stop producing light. A more recent test using LED sources varying in intensity and duration to achieve the same 15 cd effective intensity (Savage, 2011) reported that sources with longer durations tended to have lower detectability. Research studies on large field, low frequency flicker perception (Kelly, 1961) suggested that when flashing of a large field (as in indirect viewing of an emergency visual signal) occurred at a frequency near 1-2 Hz, the absolute modulation level of about 7% produced reliable detection. Based on these findings, Bullough et al. (2012b) postulated that perhaps the absolute or instantaneous intensity from a signal when viewed indirectly might be more meaningful that its effective intensity characterized using Equation 1.

To assist the Fire Protection Research Foundation (FPRF) of the National Fire Protection Association (NFPA) in identifying predictive metrics for characterizing the performance of visual signals having temporal properties different from xenon strobes, a series of human factors experiments was conducted by the Lighting Research Center (LRC); these experiments are described in the present report.

2. Methods

2.1. Experimental Laboratory

The test laboratory used for the human factors experiment was the Seminar Room at the LRC laboratory in Troy, NY. This is a large classroom space with white paint on three walls and unpainted brick on the fourth wall. Figure 1 illustrates a schematic diagram of the overall experimental set-up, showing the relative locations of the experimental subjects, the test light source and the opposite wall in the field of view (not to scale). Subjects were seated at a table facing away from the unpainted brick wall. Figure 2 shows the subjects' view of the white fall facing them.

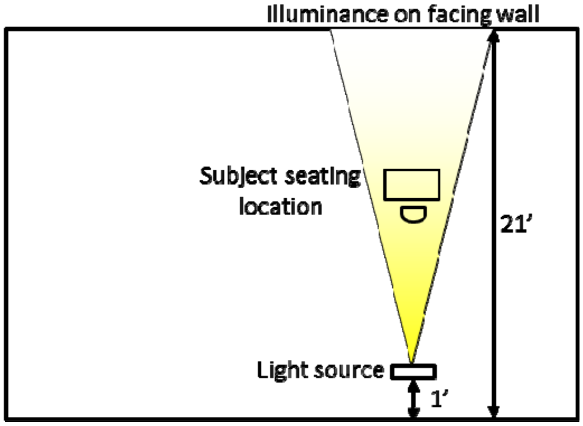


Figure 1. Schematic of experimental laboratory (position of subjects not to scale).

Figure 2. View of facing wall from subjects' position.

The lighting system in the room is able to be controlled through a series of dimming switched. Depending upon the experiment, the illuminance in the seminar room was adjusted to produce the following conditions:

- High ambient condition: Average horizontal illuminance on table tops was 500 lx, average vertical illuminance on wall facing subjects was 200 lx

- Low ambient condition: Average horizontal illuminance on table tops was 250 lx, average vertical illuminance on wall facing subjects was 100 lx

2.2. Test Light Source

Figure 3 shows the test light source, which consists of an array of three high power white LEDs (Manufacturer: Cree, Part number: XREWHT-L1-0000) over which lenses (Manufacturer: Khatod, Part number: KEPL1127) are fitted. The lenses include three possible types of optical distributions: 40^{o}, 25^{o} or 6^{o}. (The blue films visible over the front lens apertures in Figure 3 are protective covers and are removed during testing.) The correlated color temperature (CCT) range of the white LEDs was approximately 3200 K in order to match the CCT of the fluorescent (3500 K) and halogen (2800 K) lighting in the test laboratory.

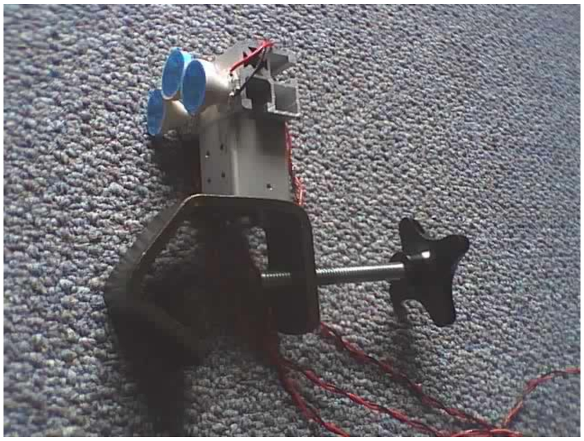


Figure 3. Test light source.

Two types of optics (Manufacturer: Khatod) were used together with the LEDs: one creates a narrow beam angle of 6° (Part number: KEPL112706) while the other creates a wide beam angle of 40° (Part number: KEPL112740). As shown in Table 1, to increase the vertical illuminance by 15 lx (an approximate 7% vertical illuminance increase) on the facing wall at height of 6 ft, it required driving current to the white LED to be 61 mA for the 6^{o} beam angle optic and 961 mA for the 40^{o} beam angle optic.

Figure 4 illustrates optical ray-tracing simulation results of different beam patterns on the wall with different beam angle optics: 6° and 40°. The LED and the optics were mounted at height of 6 ft, and they are aiming perpendicularly to the wall, which was 20 ft away from the light source. As illustrated in Figure 3, 6° optics illuminate a 2 ft by 2 ft area, while the 40° optics illuminate almost the whole 12 ft by 12 ft area. Therefore, 6°, and 40° optics were chosen in this experiment to represent narrow and wide beam types.

The light source was mounted in the ceiling behind the subjects' seating position. A plywood baffle was used to block a portion of the light from the source to avoid illuminating a shadowed portion of the wall facing the subjects, shown in Figure 5.

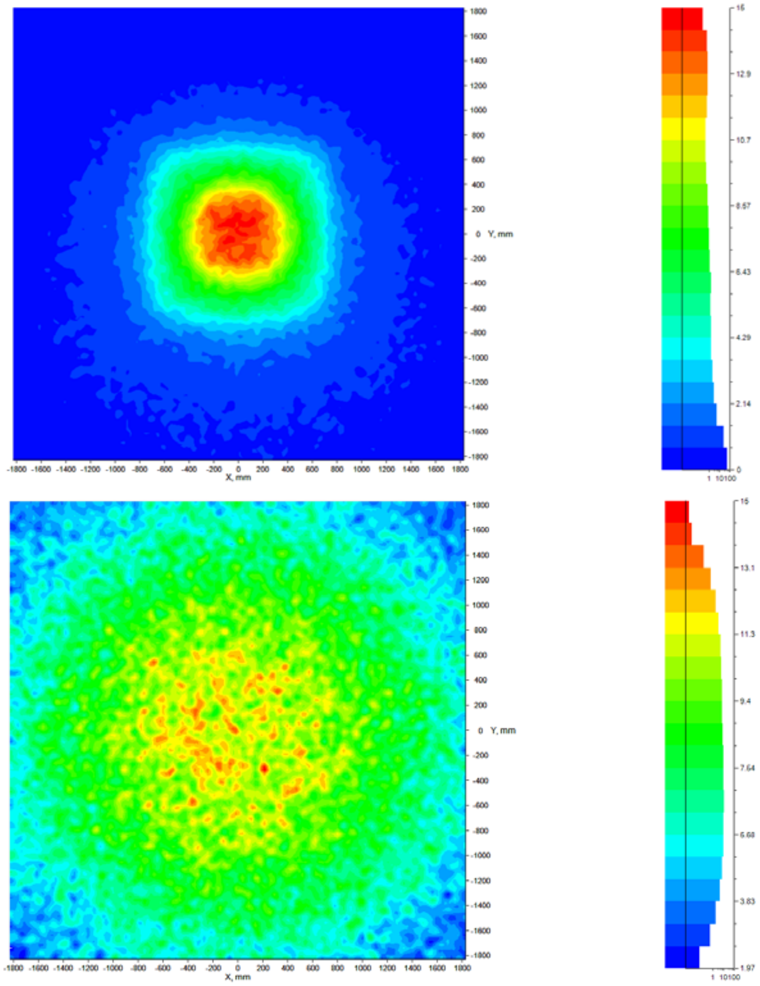


Figure 4. Optical ray-tracing simulation of vertical illuminance on the wall when using different beam angle optics (6°, top and 40°, bottom) on a 12 ft by 12 ft area with the light source aimed at the center.

Figure 5. Photograph of the baffle and light source mounted in the ceiling.

2.3. Experimental Conditions

The light sources were controlled using a custom Labview (National Instruments) program hat could produce flashes of light varying in intensity (in terms of the illuminance increment on the wall facing the subjects' seating position) and duration, with flash rates from 1 Hz (one flash per second) to 2 Hz (one flash per half-second). In some experiments, subjects were requested to look directly ahead at the wall facing them, and in others, subjects performed a numerical verification task (NVT) placed on the table in front of them and would have detected the flashing in their peripheral vision. The numerical verification task consisted of printed columns of nearly matching 5-digit numbers, with 3% of the digits not matching. Subjects were instructed to place a check mark near non-matching 5-digit numbers and to report whether they saw flashing while performing this task. In the final experiment, subjects unaware of the purpose of the experiment performed the task and then answered whether they noticed the flashing after an experimental condition was displayed.

Table 1. Preliminary measurement results of the illuminance level ("I" represents driving current)

Height (ft)	Vertical Illuminance (lx)		
	Ambient light on wall	6° optics (I=61mA)	40° optics (I=961mA)
8	117		
7	206		
6	219	15	15
5	208		
4	198		

The source was calibrated and adjusted to produce the following experimental conditions in each of the seven experiments that were conducted:

- Experiment 1: Ambient illuminance 500 lx; Beam angle 40°; Duration 1, 10, 100 ms; Illuminance increment 1%, 2%, 4%, 8%; Frequency 1 Hz; Subjects looking at wall
- Experiment 2: Ambient illuminance 500 lx; Beam angle 40°; Duration 10, 25, 50, 100 ms; Illuminance increment 1%, 2%, 4%, 8%; Frequency 2 Hz; Subjects looking at wall
- Experiment 3: Ambient illuminance 250 lx; Beam angle 40°; Duration 10, 25, 50, 100 ms; Illuminance increment 2%, 4%, 8%, 16%; Frequency 1 Hz; Subjects looking at wall
- Experiment 4: Ambient illuminance 500 lx; Beam angle 40°; Duration 10, 25, 50, 100 ms; Illuminance increment 1%, 2%, 4%, 8%; Frequency 1 Hz; Subjects performing NVT
- Experiment 5: Ambient illuminance 250 lx; Beam angle 40°; Duration 10, 25, 50, 100 ms; Illuminance increment 2%, 4%, 8%; 16%; Frequency 1 Hz; Subjects performing NVT
- Experiment 6: Ambient illuminance 250 lx; Beam angle 6°; Duration 10, 25, 50, 100 ms; Illuminance increment 2%, 4%, 8%, 16%; Frequency 1 Hz; Subjects performing NVT
- Experiment 7: Ambient illuminance 250 lx; Beam angle 40°; Duration 50 ms; Illuminance increment 4%, 16%; Frequency 1 Hz; Subjects performing NVT

In Experiments 4 and 5 a commercially available emergency notification visual signal was also included. The signal had an adjustable effective intensity setting, which was set during both experiments to the nominal 15 cd setting. Based on intensity profile data provided by the manufacturer, an estimated value of 40 cd for the effective intensity (when calculated using Equation 1) was used for subsequent analysis. During the experiments in which this signal was used, it was fitted with a baffle to produce a distribution similar to that of the LED test source when equipped with the 40° lens optics.

2.4. Subjects and Procedure

Ten subjects participated in each experiment. In Experiments 1 through 6, subjects were exposed to each of the experimental conditions in a random order for 10 s after which they were asked whether they detected the flashing light. Three null condition trials with no flashing present were also presented in each of these six experiments to measure responses when no signal was present. In Experiment 7, subjects were shown one condition (4% or 16% illuminance increment) only; half saw each condition.

In Experiments 1 through 7, subjects also rated the ease/difficulty of detection using the following scale (if they did not detect the flashing, a value of -3 was assigned as the response to this question):

+2	Very easy
+1	Somewhat easy
0	Neither easy nor difficult
-1	Somewhat difficult
-2	Very difficult

In Experiments 2 through 7, subjects also rated the perceived urgency of detection using the following scale (if they did not detect the flashing, a value of -1 was assigned as the response to this question):

3	Very urgent
2	Somewhat urgent
1	Slightly urgent
0	Not at all urgent

3. Results

The results of each experiment are included in this section, with the detection percentages, ease/difficulty ratings, and urgency ratings for each condition plotted as a function of the effective intensity for each condition calculated using Equation 1.

For the null-condition trials in all of the experiments, the “false positive” detection rates in all of the experiments ranged from 0% to 3%. These rates were low enough to feel confident that subjects were only very rarely responding that they detected something when no flashing condition was presented, and that the detection percentages reported here are representative of the likelihood that a signal light would be detected.

3.1. Experiment 1

Figure 6a shows the detection percentages and ease/difficulty ratings for Experiment 1.

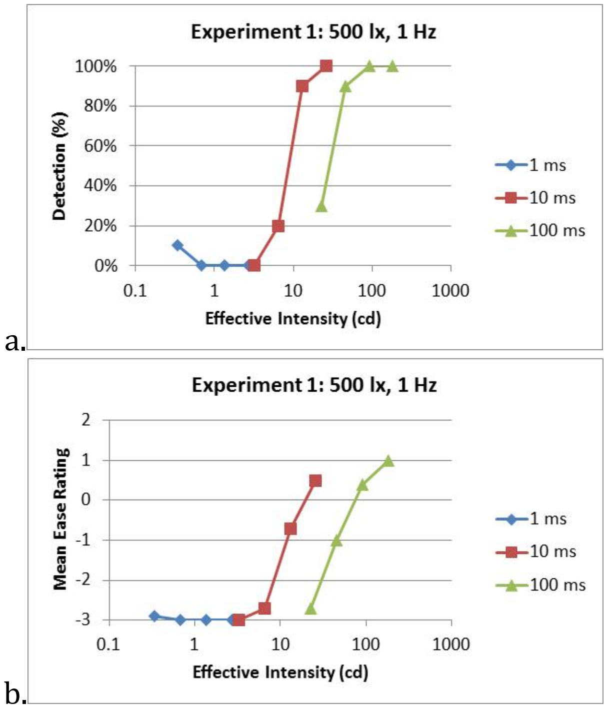


Figure 6. a: Detection percentages for Experiment 1; b: Ease ratings for Experiment 1.

It can be seen in Figure 6 that the ability to see the flashing signals indirectly was not well predicted by their effective intensity based on Equation 1. Nor was the absolute illuminance increment predictive of performance. For example, in Figure 6a, the 10 ms flash with a 2% illuminance increment yielded only 20% detection, but the 100 ms flash with the same illuminance increment was detected 90% of the time. The 1 ms signals were hardly ever detected.

Based on these results, the 1 ms conditions were eliminated from future experiments, and in order to provide more resolution between 10 and 100 ms, flash durations of 25 and 50 ms were included. Approximately, the flash durations for each duration increment doubled except for the step between 10 and 25 increment, a factor of 2.5 increase.

3.2. Experiment 2

Figure 7a shows the detection percentages, Figure 7b the ease/difficulty ratings, and Figure 7c the urgency ratings for Experiment 2.

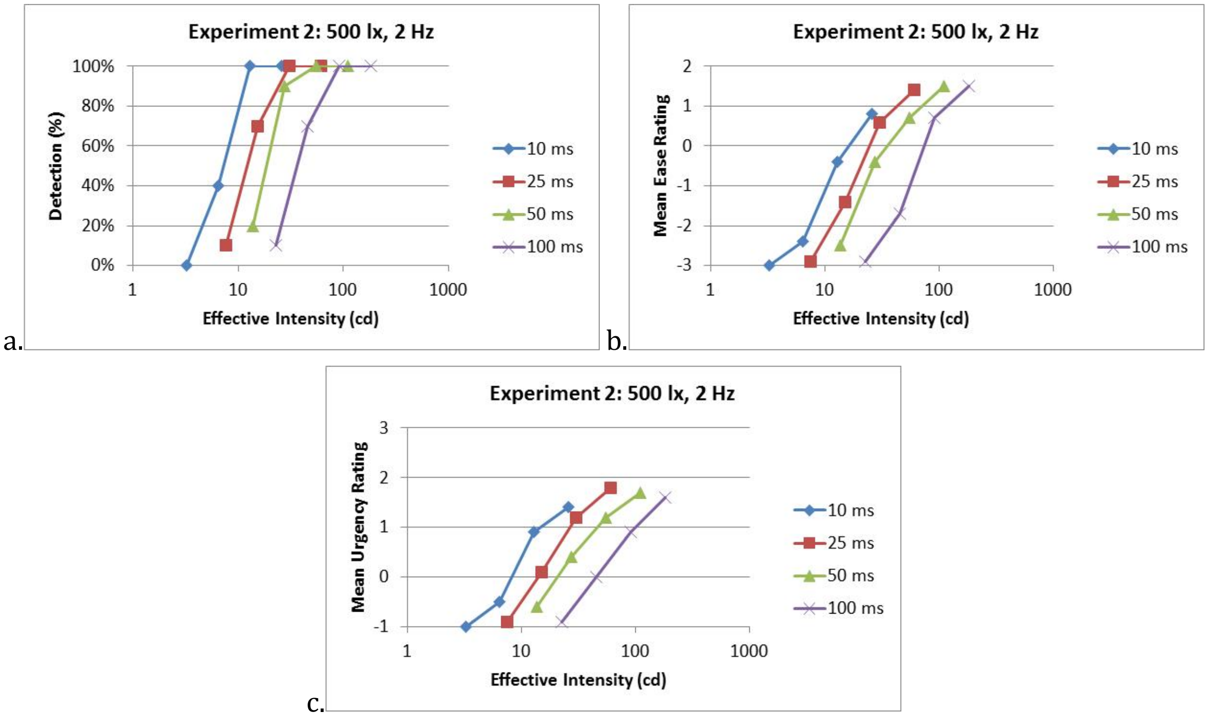


Figure 7. a: Detection percentages for Experiment 2; b: Ease ratings for Experiment 2; c: Urgency ratings for Experiment 2.

As with Experiment 1, neither effective intensity nor the absolute illuminance increment was predictive of performance for the conditions in Experiment 2. In addition, although the flash frequency between Experiments 1 and 2 differed (1 Hz in Experiment 1 and 2 Hz in Experiment 2), the detection performance and rated ease/difficulty for the conditions common to both experiments (10 and 100 ms, for each illuminance increment) were highly correlated to each other (r^2=0.90 for detection, and r^2=0.96 for ease/difficulty) and very similar in magnitude. Based on this correlation, all subsequent experiments used a flash rate of 1 Hz, since there does not appear to be an effect of frequency between 1 and 2 Hz.

3.3. Experiment 3

Figure 8a shows the detection percentages, Figure 8b the ease/difficulty ratings, and Figure 8c the urgency ratings for Experiment 3.

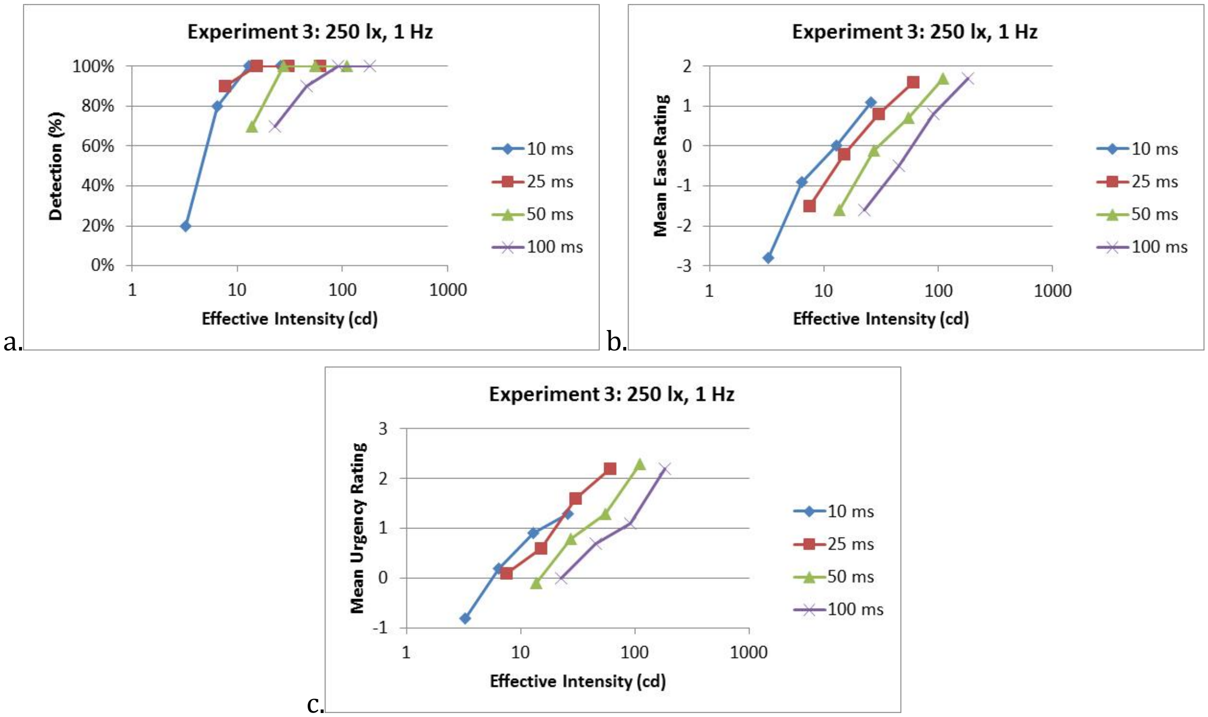


Figure 8. a: Detection percentages for Experiment 3; b: Ease ratings for Experiment 3; c: Urgency ratings for Experiment 3.

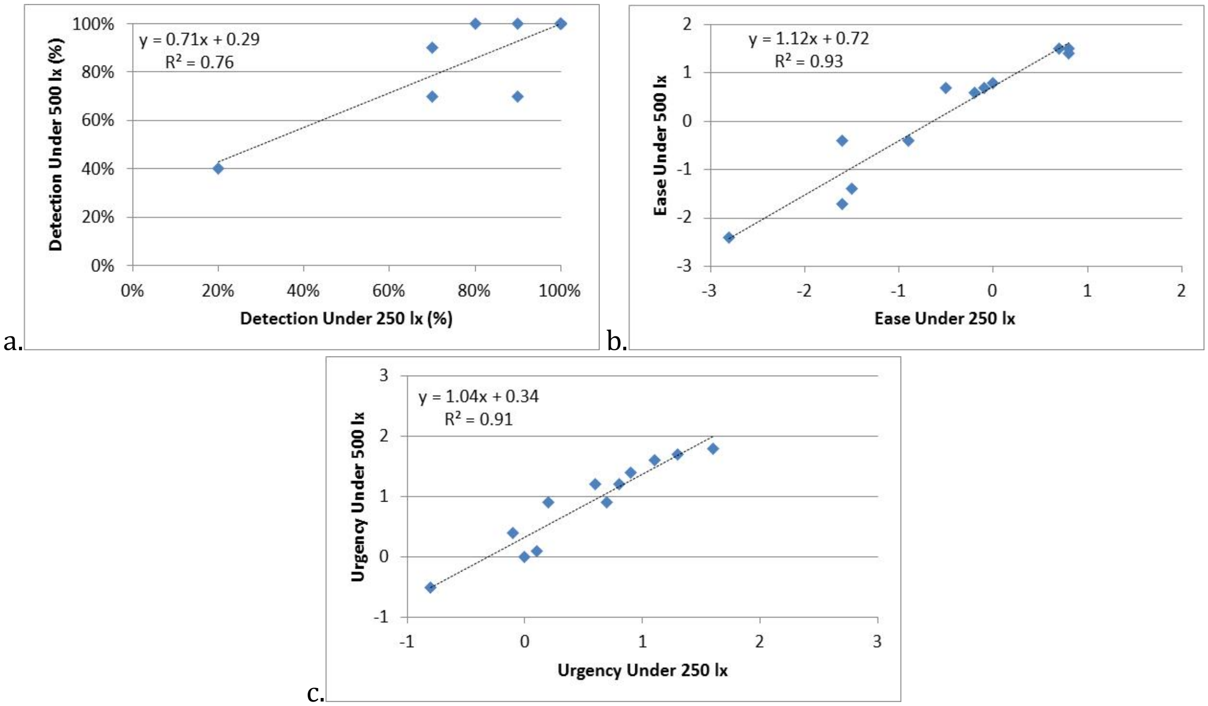


Figure 9. Correlation of detection (a), ease/difficulty (b), and urgency (c) for corresponding conditions in Experiments 2 and 3.

As expected, since the ambient light level in Experiment 3 was lower than in Experiments 1 and 2, the performance and subjective ratings were higher. Comparing the conditions for which the flash duration and the relative illuminance increment (2%, 4% and 8%) were common to both experiments, the results of these experiments were very similar and strongly correlated with each other (Figure 9). This suggests that the relative illuminance increment rather than the absolute increment is more important for the performance of a signal light when viewed indirectly. Nonetheless, the positive y-intercepts of the best-fitting linear functions in Figure 9 suggest that performance was slightly improved under the higher ambient level, for the same duration and relative illuminance increment.

3.4. Experiment 4

Figure 10a shows the detection percentages, Figure 10b the ease/difficulty ratings, and Figure 10c the urgency ratings for Experiment 4.

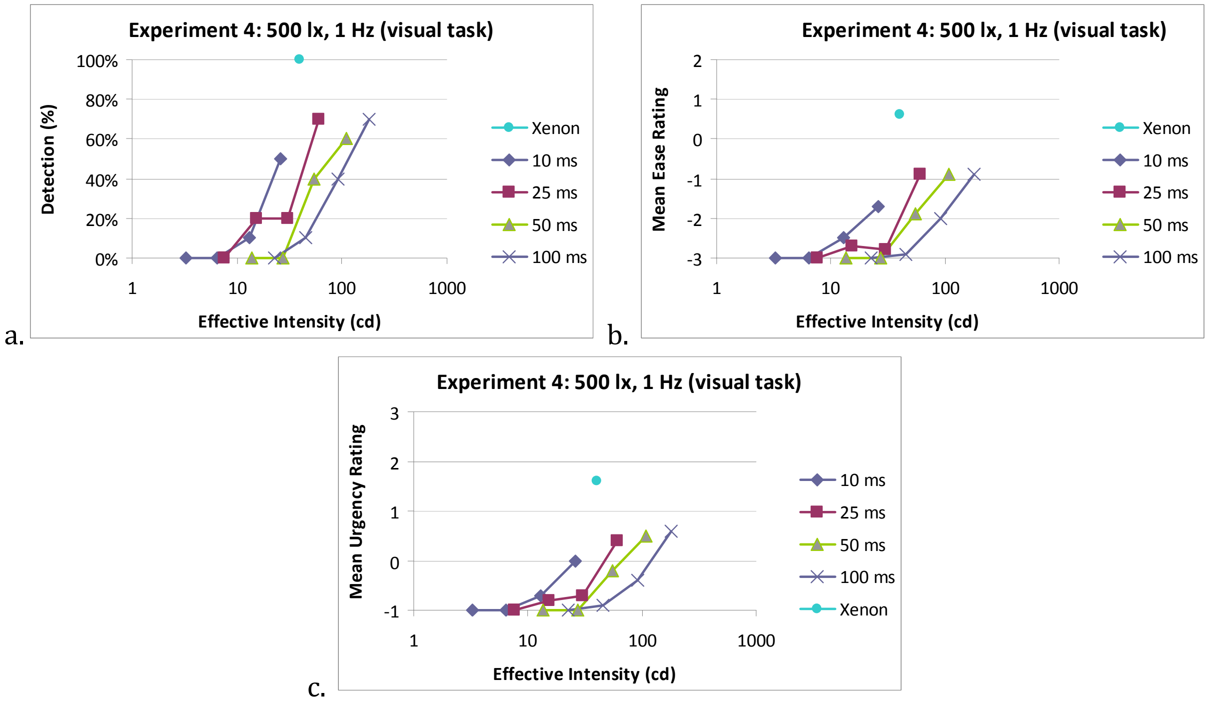


Figure 10. a: Detection percentages for Experiment 4; b: Ease ratings for Experiment 4; c: Urgency ratings for Experiment 4.

The detection performance is lower for this experiment, in which subjects performed the NVT during the study, than for Experiment 2, in which subjects were permitted to look directly at the wall. It can also be seen that the detection and ratings for the xenon signal were higher than for any of the other conditions.

3.5. Experiment 5

Figure 11a shows the detection percentages, Figure 11b the ease/difficulty ratings, and Figure 11c the urgency ratings for Experiment 5.

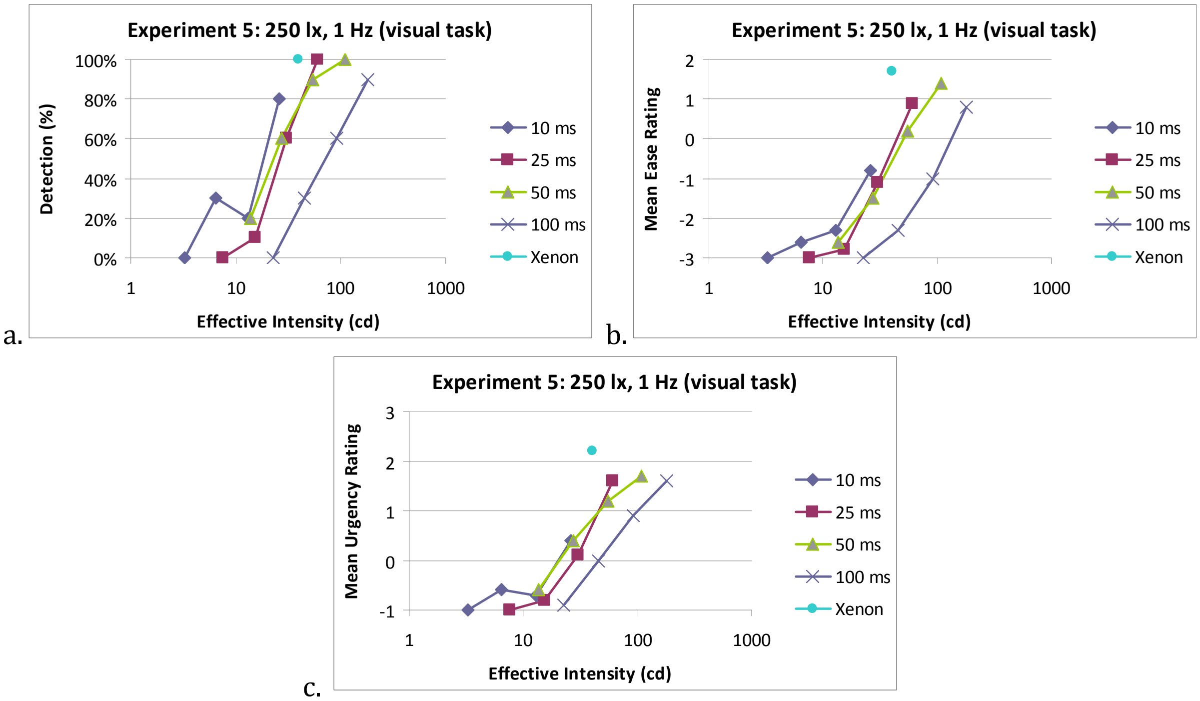


Figure 11. a: Detection percentages for Experiment 5; b: Ease ratings for Experiment 5; c: Urgency ratings for Experiment 5.

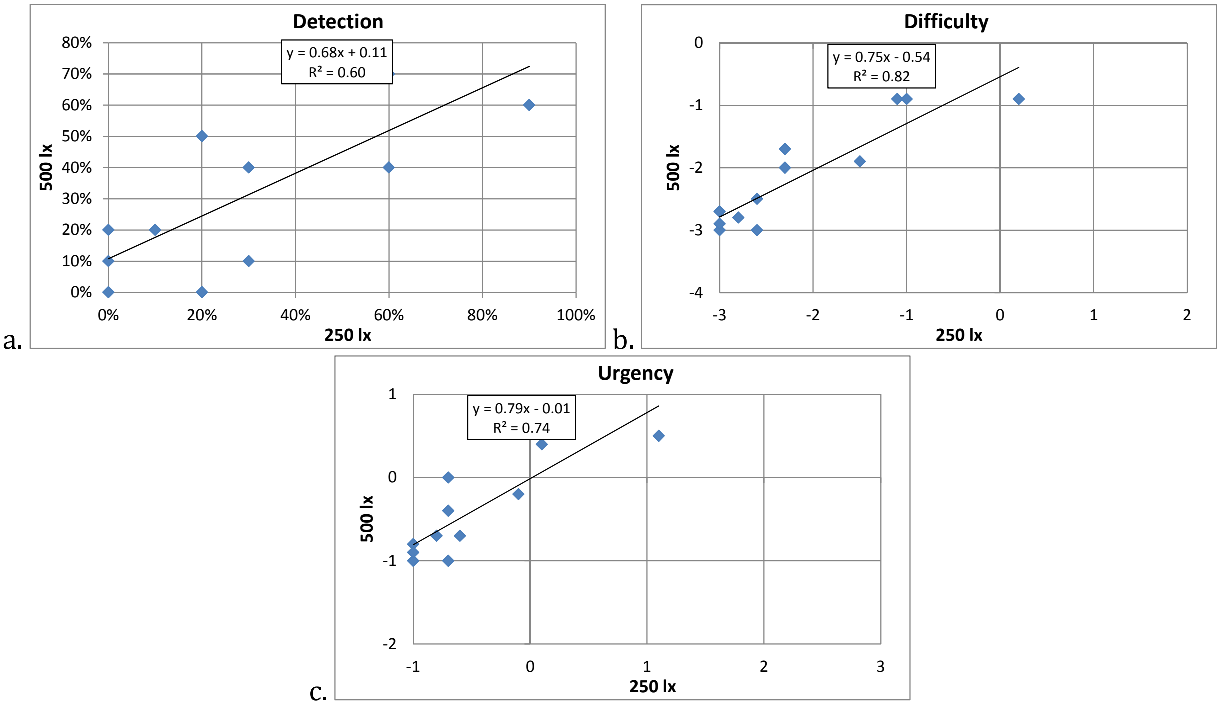


Figure 12. Correlation of detection (a), ease/difficulty (b), and urgency (c) for corresponding conditions in Experiments 4 and 5.

The performance in Experiment 5 was higher than for Experiment 4, which used a higher ambient light level. However, when compared for the same duration and the same relative illuminance increments common to both experiments (2%, 4%, 8%), the results were similar and reasonably correlated with each other (Figure 12). The positive y-intercepts in Figure 12 suggest, as in Figure 10, that performance was slightly improved under the higher ambient level for the same relative illuminance increment.

3.6. Experiment 6

Figure 13a shows the detection percentages, Figure 13b the ease/difficulty ratings, and Figure 13c the urgency ratings for Experiment 6.

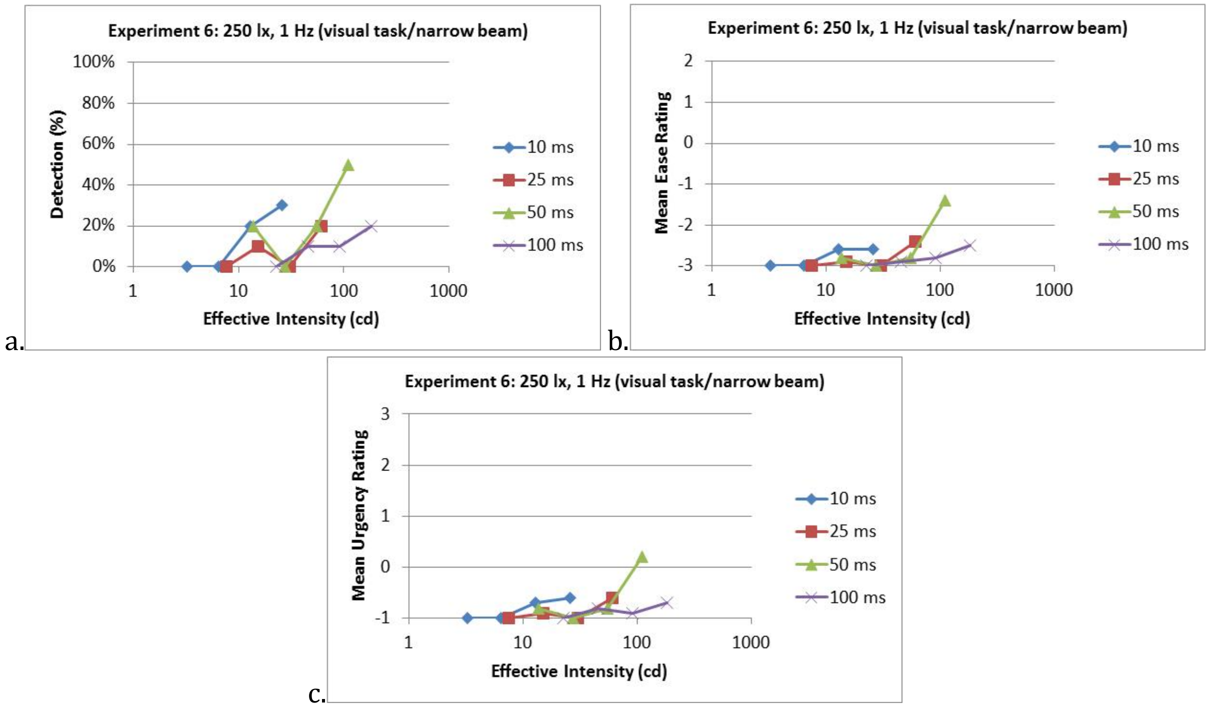


Figure 13. a: Detection percentages for Experiment 6; b: Ease ratings for Experiment 6; c: Urgency ratings for Experiment 6.

It can be seen that using the narrow beam light source in Experiment 6 resulted in generally low detection performance and low ratings of ease/difficulty and urgency. Only the highest illuminance increment (16%) for a duration of 50 ms was detected at least 50% of the time.

3.7. Experiment 7

Figure 14a shows the detection percentages, Figure 14b the ease/difficulty ratings, and Figure 14c the urgency ratings for Experiment 7.

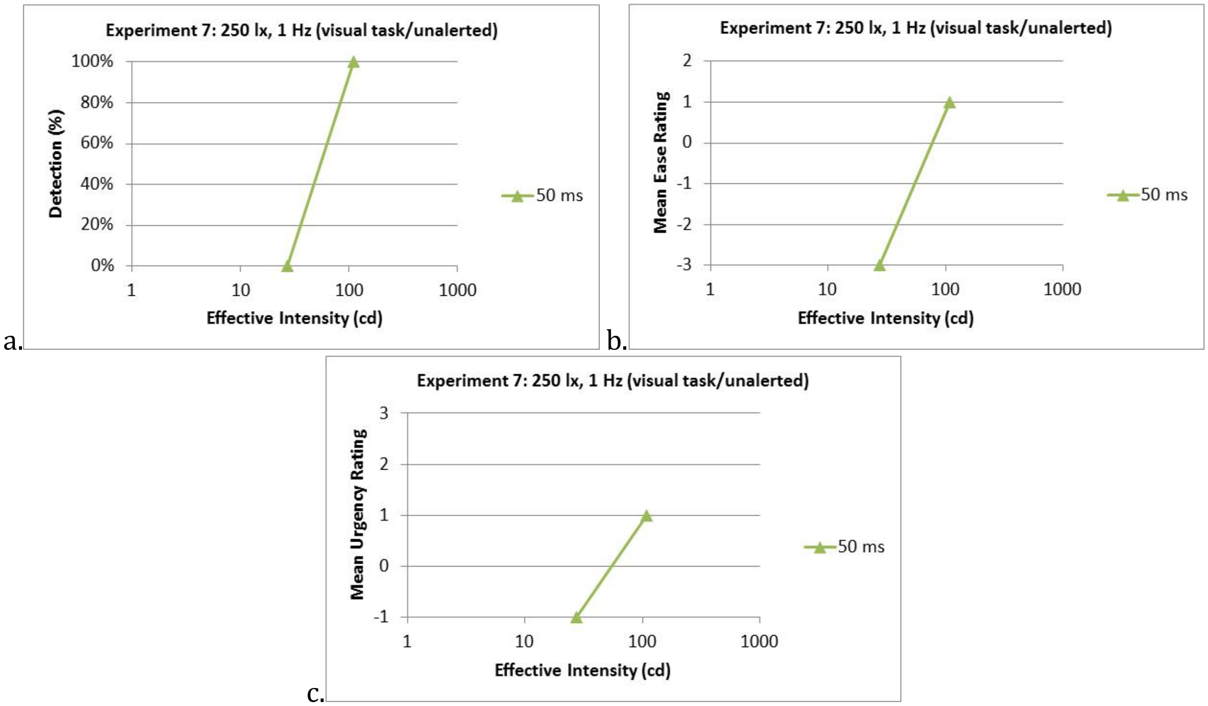


Figure 14. a: Detection percentages for Experiment 7; b: Ease ratings for Experiment 7; c: Urgency ratings for Experiment 7.

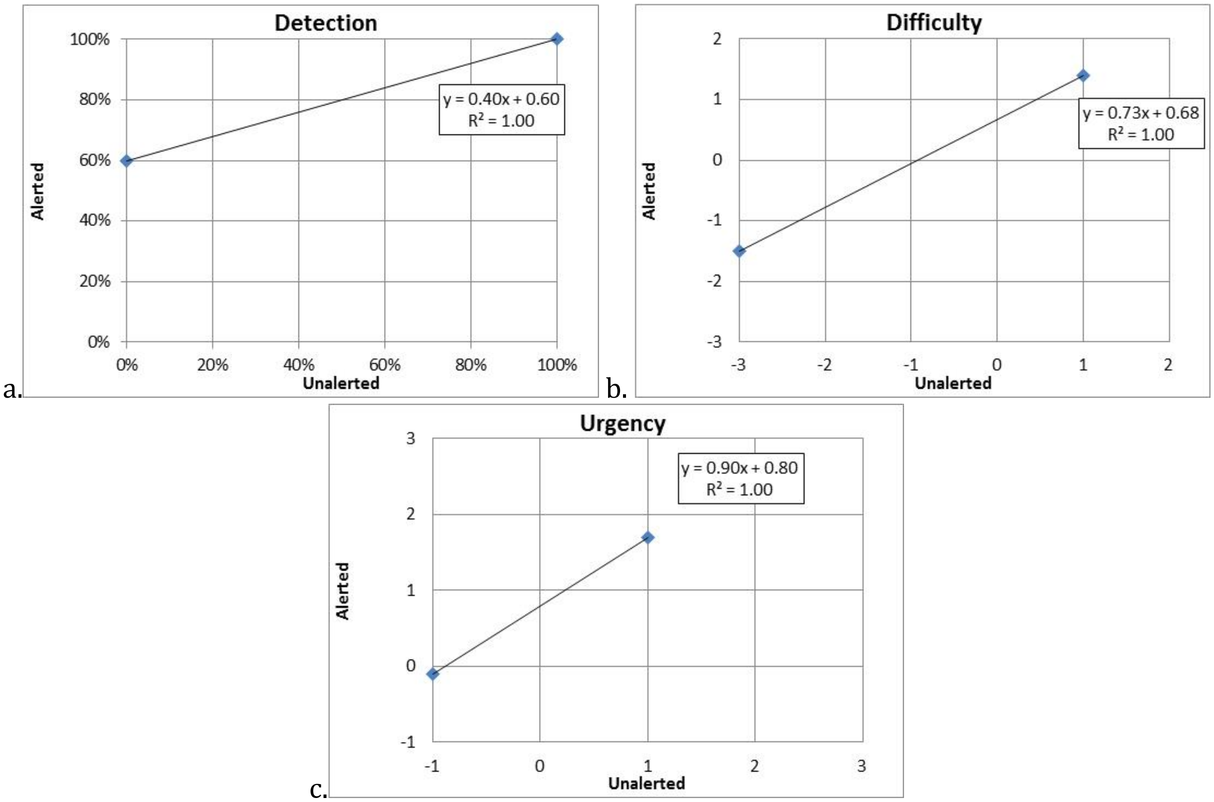


Figure 15. Correlation of detection (a), ease/difficulty (b), and urgency (c) for corresponding conditions in Experiments 5 and 7.

Fewer conditions were used in Experiment 7 than in Experiment 5, which used corresponding conditions. This is because subjects in Experiment 7 only viewed a single condition in order to identify the responses of unalerted subjects unaware of the purpose of the experiment; once subjects were asked whether they detected the first condition they saw, they would be aware of the nature of the experiment for any subsequent presentations. To compare the implications of unalerted, unaware subjects, the data in Experiments 5 and 7 were compared for corresponding conditions in Figure 15.

Similar to the comparisons between ambient light levels, the performance and responses of the unalerted subjects who were unaware of the purpose of the experiment, was generally lower than for subjects who were aware of the purpose of the experiment, and the y-intercept values of the best-fitting functions in Figure 15 are positive. The exception to this pattern was for the 16% increment condition, which was detected 100% of the time in both experiments, although this condition was rated as more difficult and less urgent by the unalerted subjects.

4. Discussion

As described in the results section, the effective intensity (as defined in Equation 1) was not a useful predictive metric for the performance of visual signals having different durations. Nor was the relative illuminance increment predictive of performance, as considered by Bullough et al. (2012b).

The effective intensity formulation is based on the concept that the intensity and duration of a light source can be traded off in order to maintain detection performance. As mentioned by the IALA (2008), the original effective intensity formulation developed by Blondel and Rey (1912) is primarily applicable to threshold detection of signal lights viewed directly (on-axis) from long distances (and seen as point sources of light) under dark adaptation conditions. In comparison, the visual signals in the present study were viewed under high light levels common to office and other interior applications, and under indirect viewing, could fill a relatively large portion of the field of view and often in the visual periphery.

Under such conditions, the use of Equation 1 in its current form may not be warranted for specifying indirect detection. Two concepts were explored to develop alternative formulations for the effectiveness of flashing lights when viewed indirectly under interior light levels.

4.1. Partial Temporal Summation

Equation 1 assumes a linear, proportional tradeoff between instantaneous intensity and flash duration. Baumgardt and Hillman (1961) found, for relatively large, 7.5°-diameter luminous stimuli presented 20° off axis under dark conditions, that for short durations the intensity and duration could be traded off proportionally so that the threshold occurred when the product of the intensity and duration was a constant value. For longer flash durations, the product of the square or cube root of the intensity and duration was constant for the same level of detection.

In Equation 1, the term $I(t)\,\mathrm{d}t$ was raised to an exponent having different values lower or greater than 1 was used to estimate a possible indirect effectiveness quantity. None of the values resulted in relationships between the indirect effectiveness quantity and detection performance or rated ease/difficulty or urgency, that appeared much different from the graphs for the experimental data shown in Chapter 3 (Results) of this report. This suggests that the concept of partial temporal summation was not applicable to the data presented here.

4.2. Integration Times

Another aspect of Equation 1 that pertains to the specific experimental conditions used by Blondel and Rey (1912) in their studies underlying the effective intensity formulation is the value of the constant a in the equation. A value for a of 0.2 s was empirically determined by

Blondel and Rey (1912). The constant *a* is thought to be related to the temporal integration time of the visual system during which intensity and duration could be traded off for equivalent performance at detection threshold under dark conditions when the primary photoreceptors used for vision are rods, which have relatively long integration times of 0.1-0.2 s. For the conditions used by Blondel and Rey (1912), the conditions included point-source size signals, viewed under very dark conditions using on-axis vision, when the signals were just barely able to be detected.

Other values for *a* have been found in various studies, but there has been relatively little systematic investigation between the optimal value for *a* and specific viewing conditions differing from those used by Blondel and Rey (1912). One exemplary study was conducted by Schmidt-Clausen (1971), who investigated the role of background luminance, size of the signal light, and eccentricity in the field of view on the optimal value of *a* in Equation 1. Schmidt-Clausen (1971) found that lower values of *a* were found for higher background luminances, larger signal light sizes, and greater eccentricities. This is consistent with data from Battersby and Schuckman (1970) who reported that temporal integration times for cone photoreceptors, which are the primary receptors the visual system uses under daytime light levels, were on the order of 0.01 s.

Modification of the value of *a* in the denominator of Equation 1 found, consistent with the shorter integration times of the visual system under high light levels (Battersby and Schuckman, 1970), and with the experimental data from Schmidt-Clausen (1971). The data from Experiments 1 through 6 were compared with different values of *a* and it was found that a value for *a* of 0.01 s resulted in many of the curves for different signal durations being superimposed over each other.

Figure 16 shows the detection data for Experiments 1 through 6 (data for Experiments 1 and 2 were combined since there was no difference between the 1 Hz and 2 Hz data in these experiments), Figure 17 shows the ease/difficulty data, and Figure 18 shows the urgency data when Equation 1 is modified using a value of 0.01 s for *a* in the denominator.

Inspection of these figures shows that the curves are located closer to one another than the curves in the previous chapter of this report (Results) and in many cases yield very consistent predictions for the flashes of light with different durations. In addition, the curves seem to also be consistent with the data for the xenon source in Experiments 4 and 5 in Figures 16 through 18. This also suggests that an indirect effectiveness quantity based on Equation 1, but using a value of 0.01 s for *a*, may be a useful predictive metric for performance.

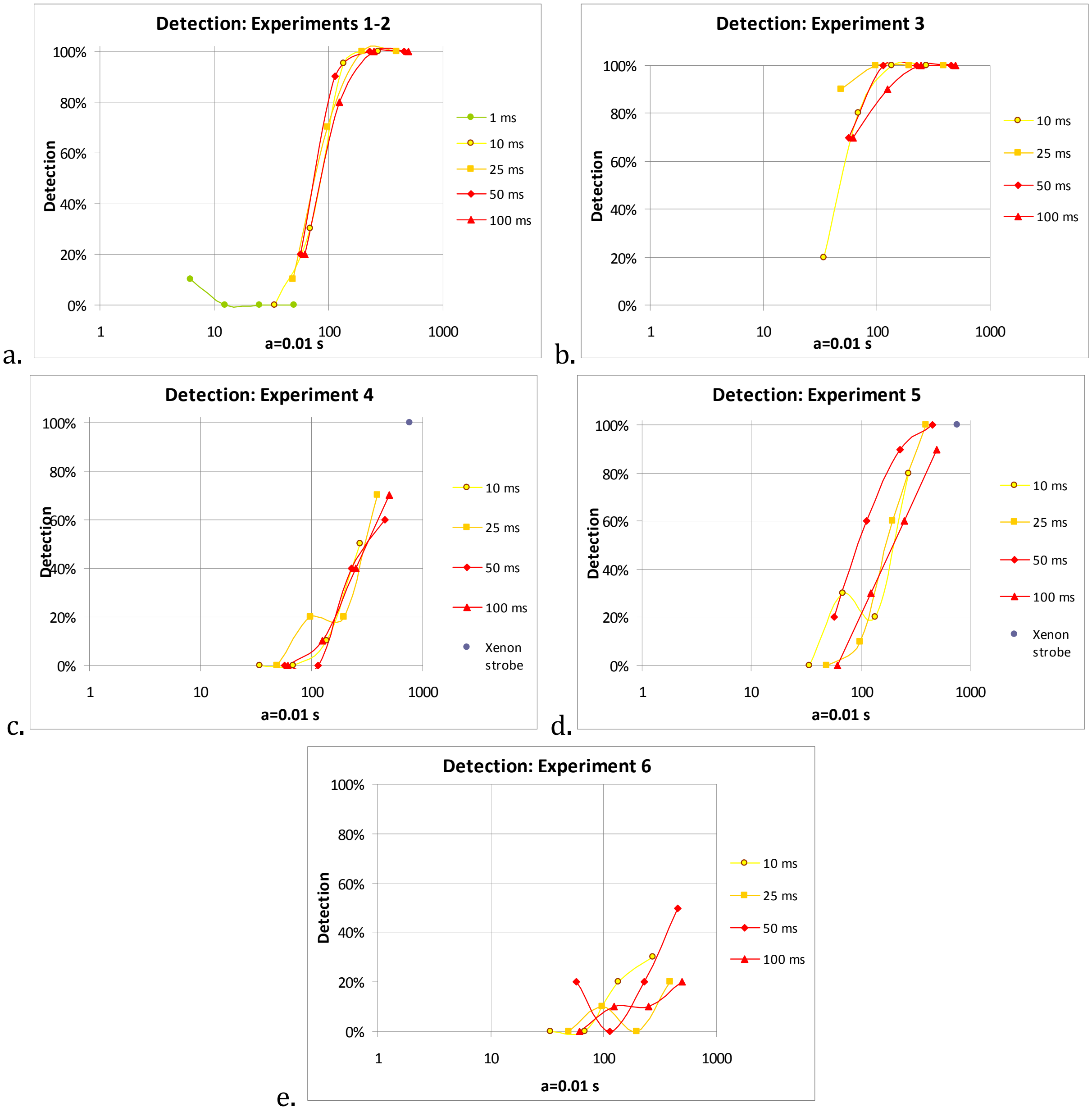
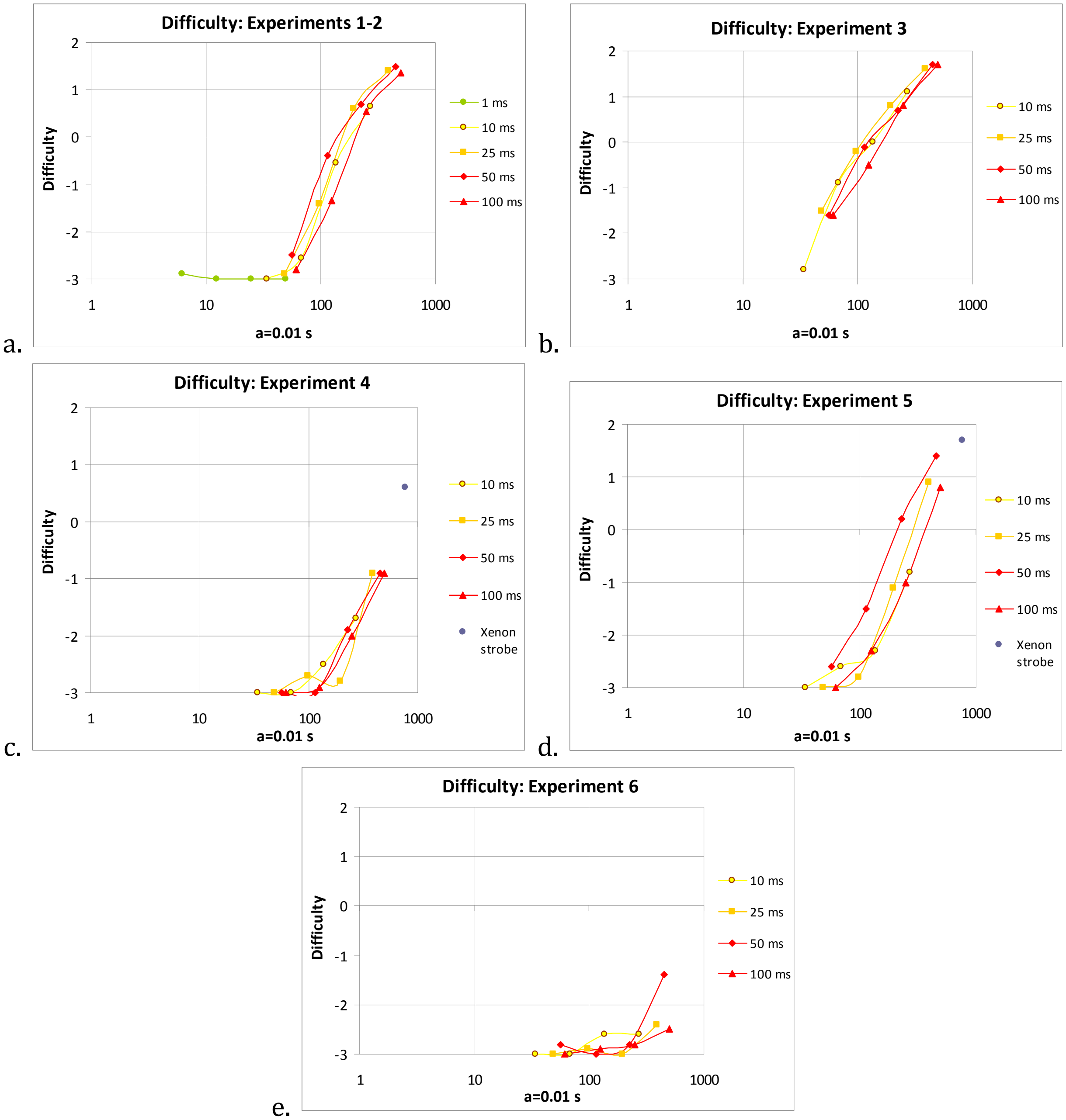


Figure 16. Experimental detection data for Experiments 1-6 plotted as a function of quantities using Equation 1 with a value for *a* of 0.01 s.



a. b. c. d. e.

Figure 17. Experimental ease/difficulty data for Experiments 1-6 plotted as a function of quantities using Equation 1 with a value for *a* of 0.01 s.

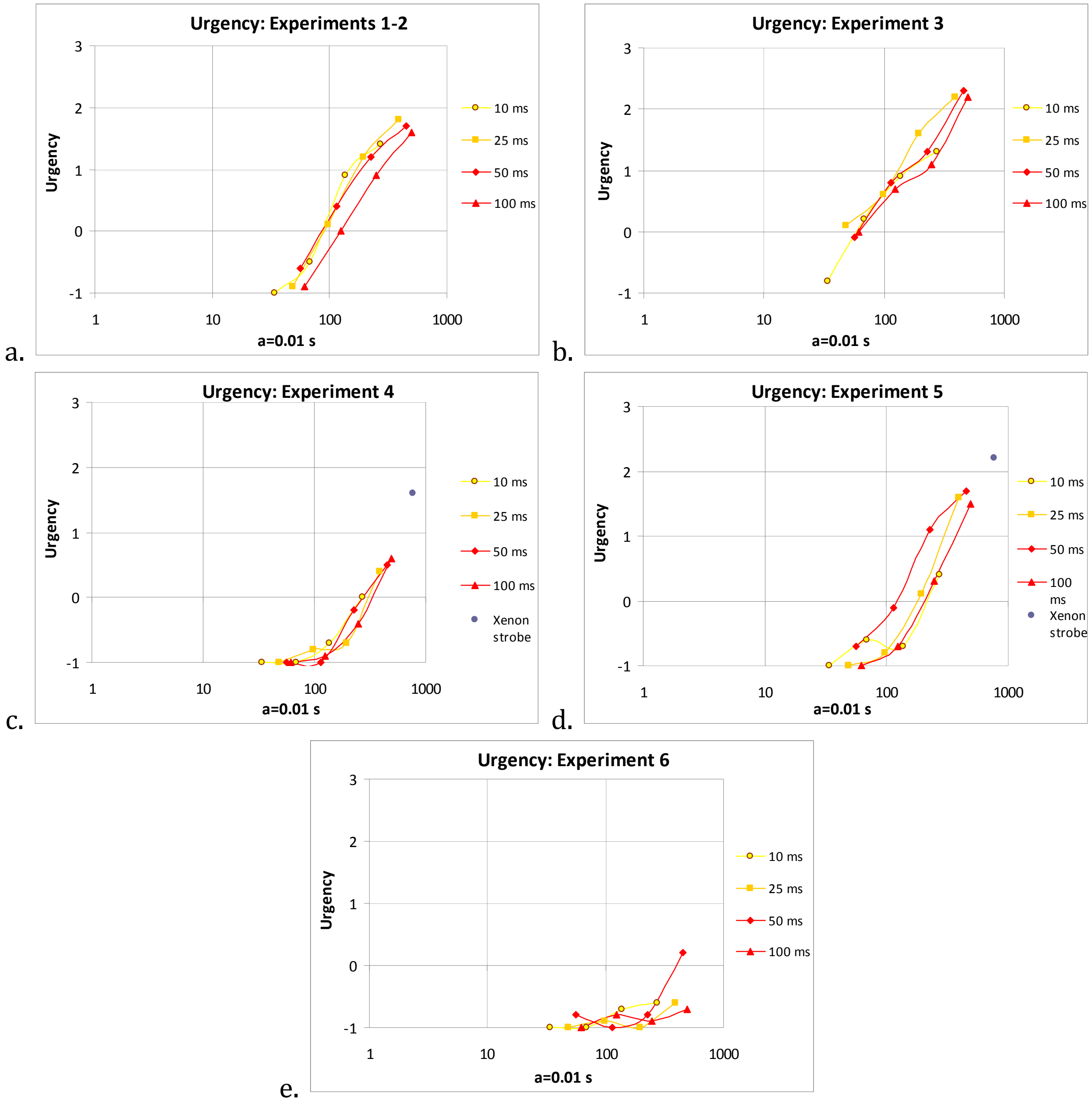


Figure 18. Experimental urgency data for Experiments 1-6 plotted as a function of quantities using Equation 1 with a value for *a* of 0.01 s.

5. Conclusions

The present experimental results and analyses conducted using variations on the formulation for effective intensity suggest that the conventional effective intensity formulation in Equation 1, using a constant value of 0.2 s in the denominator, is not a suitable metric for predicting the performance of a signal light viewed indirectly. Nor is the relative instantaneous illuminance increase a useful metric.

It appears that a useful predictive metric (here called an indirect effectiveness quantity) can be developed from Equation 1, but using a smaller value for the constant a. Setting a=0.01 s allows the data for flashes of light having different durations to be superimposed over each other. As a rough approximation, and using the performance when subjects were aware of the nature of the experiment but were performing the NVT and not looking at the facing wall, the indirect effectiveness quantity needs to be approximately 500 cd when the ambient illuminance is 500 lx, and 250 cd when the ambient illuminance is 250 lx, in order to achieve a detection percentage of 75%-80%. [In order to achieve a detection percentage of 90%, a criterion used by UL (1991), the indirect effectiveness quantity should be 750 cd for an ambient illuminance of 500 lx, and 375 cd for an ambient illuminance of 250 lx.]

These values for the indirect effectiveness quantities (for a detection level of ~75%-80%) also result in a mean ease/difficulty rating near zero (the borderline between easy and difficult to detect) and a mean urgency rating of about one (slightly urgent). Thus it seems that achieving these values or higher with a signal light that is viewed indirectly would begin to ensure that the signals were easy to detect and interpreted as urgent. Of course, responses for the unalerted, naïve subjects in the final experiment were lower than for the previous six experiments and this may be a consideration for setting performance specifications.

In addition, the response data for the narrow beam conditions were quite poor in terms of detection percentages and rated difficulty and urgency. Based on the present data an emergency notification signal intended to be viewed indirectly should illuminate a relatively larger area of the room surfaces (e.g., producing a beam angle of at least 40^o) in order to be reliably detected.

The present study used an LED light source with a CCT of 3200 K, matching the ambient illumination in the test laboratory. The xenon source tested has a CCT closer to 5000 K. Although the results from the present study do not suggest the difference in CCT between these sources made a large difference in detection, much larger chromaticity differences such as the use of colored illumination, might be easier to detect than the nominally "white" light sources employed in the present experiments.

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Appendix: Experimental Data

Data from all seven sets of experiments are summarized in this sppendix. For each experiment, the mean detection percentages and the means and standard errors of the mean (S.E.M.) for the subjective ratings (ease and urgency) are listed.

Experiment 1: Ambient illuminance 500 lx; Beam angle 40^o*; Duration 1, 10, 100 ms; Illuminance increment 1%, 2%, 4%, 8%; Frequency 1 Hz; Subjects looking at wall*

Mean detection		Duration (ms)		
		1	10	100
Illuminance increment	1%	10%	0%	30%
	2%	0%	20%	90%
	4%	0%	90%	100%
	8%	0%	100%	100%

Mean Ease Rating		Duration (ms)		
		1	10	100
Illuminance increment	1%	-2.9	-3.0	-2.7
	2%	-3.0	-2.7	-1.0
	4%	-3.0	-0.7	0.4
	8%	-3.0	0.5	1.2

S.E.M. of Ease Rating		Duration (ms)		
		1	10	100
Illuminance increment	1%	0.10	0.00	0.15
	2%	0.00	0.21	0.39
	4%	0.00	0.54	0.45
	8%	0.00	0.34	0.39

Experiment 2: Ambient illuminance 500 lx; Beam angle 40^o*; Duration 10, 25, 50, 100 ms; Illuminance increment 1%, 2%, 4%, 8%; Frequency 2 Hz; Subjects looking at wall*

Mean detection		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	0%	10%	20%	10%
	2%	40%	70%	90%	70%
	4%	100%	100%	100%	100%
	8%	100%	100%	100%	100%

Mean Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	-3.0	-2.9	-2.5	-2.9
	2%	-2.4	-1.4	-0.4	-1.7
	4%	-0.4	0.6	0.7	0.7
	8%	0.8	1.4	1.5	1.5

S.E.M. of Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	0.00	0.10	0.40	0.10
	2%	0.27	0.45	0.52	0.33
	4%	0.48	0.31	0.42	0.37
	8%	0.47	0.31	0.31	0.31

Mean Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	-1.0	-0.9	-0.6	-0.9
	2%	-0.5	0.1	0.4	0.0
	4%	0.9	1.2	1.2	0.9
	8%	1.4	1.8	1.7	1.6

S.E.M. of Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	0.00	0.10	0.31	0.10
	2%	0.22	0.28	0.27	0.26
	4%	0.28	0.29	0.25	0.23
	8%	0.37	0.33	0.33	0.27

Experiment 3: Ambient illuminance 250 lx; Beam angle 40°; Duration 10, 25, 50, 100 ms; Illuminance increment 2%, 4%, 8%, 16%; Frequency 1 Hz; Subjects looking at wall

Mean detection		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	20%	90%	70%	70%
	4%	80%	100%	100%	90%
	8%	100%	100%	100%	100%
	16%	100%	100%	100%	100%

Mean Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	-2.8	-1.5	-1.6	-1.6
	4%	-0.9	-0.2	-0.1	-0.5
	8%	0.0	0.8	0.7	0.8
	16%	1.1	1.6	1.7	1.7

S.E.M. of Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0.13	0.37	0.48	0.48
	4%	0.48	0.36	0.38	0.50
	8%	0.45	0.42	0.33	0.36
	16%	0.38	0.31	0.21	0.21

Mean Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	-0.8	0.1	-0.1	0.0
	4%	0.2	0.6	0.8	0.7
	8%	0.9	1.6	1.3	1.1
	16%	1.3	2.2	2.3	2.2

S.E.M. of Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0.13	0.18	0.23	0.30
	4%	0.29	0.22	0.25	0.30
	8%	0.31	0.31	0.26	0.28
	16%	0.26	0.36	0.33	0.25

Experiment 4: Ambient illuminance 500 lx; Beam angle 40^{o}; Duration 10, 25, 50, 100 ms; Illuminance increment 1%, 2%, 4%, 8%; Frequency 1 Hz; Subjects performing NVT

Mean detection		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	0%	0%	0%	0%
	2%	0%	20%	0%	10%
	4%	10%	20%	40%	40%
	8%	50%	70%	60%	70%

Mean Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	-3.0	-3.0	-3.0	-3.0
	2%	-3.0	-2.7	-3.0	-2.9
	4%	-2.5	-2.8	-1.9	-2.0
	8%	-1.7	-0.9	-0.9	-0.9

S.E.M. of Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	0.00	0.00	0.00	0.00
	2%	0.00	0.21	0.00	0.10
	4%	0.40	0.13	0.53	0.47
	8%	0.47	0.60	0.64	0.55

Mean Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	-1.0	-1.0	-1.0	-1.0
	2%	-1.0	-0.8	-1.0	-0.9
	4%	-0.7	-0.7	-0.2	-0.4
	8%	0.0	0.4	0.5	0.6

S.E.M. of Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	1%	0.00	0.00	0.00	0.00
	2%	0.00	0.13	0.00	0.10
	4%	0.21	0.21	0.33	0.27
	8%	0.37	0.37	0.45	0.43

Experiment 5: Ambient illuminance 250 lx; Beam angle 40°; Duration 10, 25, 50, 100 ms; Illuminance increment 2%, 4%, 8%; 16%; Frequency 1 Hz; Subjects performing NVT

Mean detection		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0%	0%	20%	0%
	4%	30%	10%	60%	30%
	8%	20%	60%	90%	60%
	16%	80%	100%	100%	90%

Mean Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	-3.0	-3.0	-2.6	-3.0
	4%	-2.6	-2.8	-1.5	-2.3
	8%	-2.3	-1.1	0.2	-1.0
	16%	-0.8	0.9	1.4	0.8

S.E.M. of Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0.00	0.00	0.27	0.00
	4%	0.22	0.20	0.45	0.37
	8%	0.47	0.62	0.47	0.60
	16%	0.47	0.35	0.16	0.51

Mean Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	-1.0	-1.0	-0.7	-1.0
	4%	-0.6	-0.8	-0.1	-0.7
	8%	-0.7	0.1	1.1	0.3
	16%	0.4	1.6	1.7	1.5

S.E.M. of Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0.00	0.00	0.21	0.00
	4%	0.22	0.20	0.28	0.15
	8%	0.21	0.35	0.31	0.45
	16%	0.27	0.22	0.15	0.37

Experiment 6: Ambient illuminance 250 lx; Beam angle 6^o; Duration 10, 25, 50, 100 ms; Illuminance increment 2%, 4%, 8%, 16%; Frequency 1 Hz; Subjects performing NVT

Mean detection		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0%	0%	20%	0%
	4%	0%	10%	0%	10%
	8%	20%	0%	20%	10%
	16%	30%	20%	50%	20%

Mean Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	-3.0	-3.0	-2.8	-3.0
	4%	-3.0	-2.9	-3.0	-2.9
	8%	-2.6	-3.0	-2.8	-2.8
	16%	-2.6	-2.4	-1.4	-2.5

S.E.M. of Ease Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0.00	0.00	0.13	0.00
	4%	0.00	0.10	0.00	0.10
	8%	0.27	0.00	0.13	0.20
	16%	0.22	0.43	0.58	0.40

Mean Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	-1.0	-1.0	-0.8	-1.0
	4%	-1.0	-0.9	-1.0	-0.8
	8%	-0.7	-1.0	-0.8	-0.9
	16%	-0.6	-0.6	0.2	-0.7

S.E.M. of Urgency Rating		Duration (ms)			
		10	25	50	100
Illuminance increment	2%	0.00	0.00	0.13	0.00
	4%	0.00	0.10	0.00	0.20
	8%	0.21	0.00	0.13	0.10
	16%	0.22	0.31	0.42	0.21

Experiment 7: Ambient illuminance 250 lx; Beam angle 40°; Duration 50 ms; Illuminance increment 4%, 16%; Frequency 1 Hz; Subjects performing NVT

Duration=50ms		Mean detection
Illuminance increment	4%	0%
	16%	100%

Duration=50 ms		Mean Ease Rating	S.E.M. of Ease Rating
Illuminance increment	4%	-3.0	0.0
	16%	1.0	0.5

Duration=50 ms		Mean Urgency Rating	S.E.M. of Urgency Rating
Illuminance increment	4%	-1.0	0.0
	16%	1.0	0.4