Visual Performance as a Function of Spectral Power Distribution of Light Sources at Luminances Used for General Outdoor Lighting

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The need to provide outdoor lighting for orientation, identification, and safety at a cost that is reasonable in terms of both dollars and energy has resulted in the use of light sources that differ significantly in spectral power distribution from those used in interiors and for which almost all data on visual performance have been accumulated. Furthermore, the illuminances used in most outdoor lighting applications ($0.01\ cd/m^2$–$10\ cd/m^2$) are vastly lower than those under which the greatest amount of visual data is available. Under such conditions, the visual system is, at best, in a mesopic state for which the standard definition of "light," the lumen, is almost certainly inappropriate.

The lumen is defined as visually evaluated electromagnetic radiation. Its magnitude was initially derived using viewing conditions that limited the visual response to one that was mediated exclusively by the cone receptor systems of the human eye. Most critically, a high level of retinal illuminance and a central 2 degree visual field was used, which effectively eliminated any significant contribution by the rod system which is largely absent from that area of the retina. The relative spectral sensitivity of the eye under those conditions is nominally described by the 1924 CIE Standard Observer for Photometry (V_λ).[1] For larger fields, or when retinal illuminances are insufficient to adequately stimulate the cone systems, the use of the lumen to predict the human response to light is questionable. As a result, additional spectral sensitivity functions have been described for larger fields (1964 CIE Observer for 10 degree fields—$V_{10\lambda}$)[2] and for very low retinal illuminances (1951 CIE Scotopic Observer—V'_λ).[3]

Although spectral sensitivity functions are adequate to predict the amount of energy required to stimulate vision, they are very poor at describing the perceived effect of suprathreshold lights. For example, it is well known that perceived brightness differs significantly from photometric luminance under all but very restricted viewing conditions.[4-6] The discrepancy between perceived effects and photometric quantities is especially sensitive to conditions where lights are of different color or where viewing conditions are markedly different from those under which the light units were defined.

The interest in the role of spectral power distribution on visual performance, originally of concern only to theoreticians trying to understand visual physiology, became of practical significance with the introduction of gaseous discharge sources for general illumination. Because of the obvious advantages of using such energy efficient and long-lived lamps for general illumination, studies were performed to evaluate their performance relative to the more conventional incandescent and fluorescent illuminants. Mercury, sodium (both low and high pressure), and metal halide lamps have all been studied in some detail at high illuminances with the result that suprathreshold visual performance, measured in terms of speed and accuracy on achromatic tasks, is relatively independent of light source color or type as long as contrasts are equated.[7] Although the color characteristics of HID lamps have reduced their use in interior applications, they are widely employed for outdoor lighting.

In the last few years two separate, but related, groups of investigations have raised new questions about the effects of both spectral power distribution (SPD) and light source color on performance. Berman et al., at the Lawrence Berkeley Labs, have shown that both pupil size

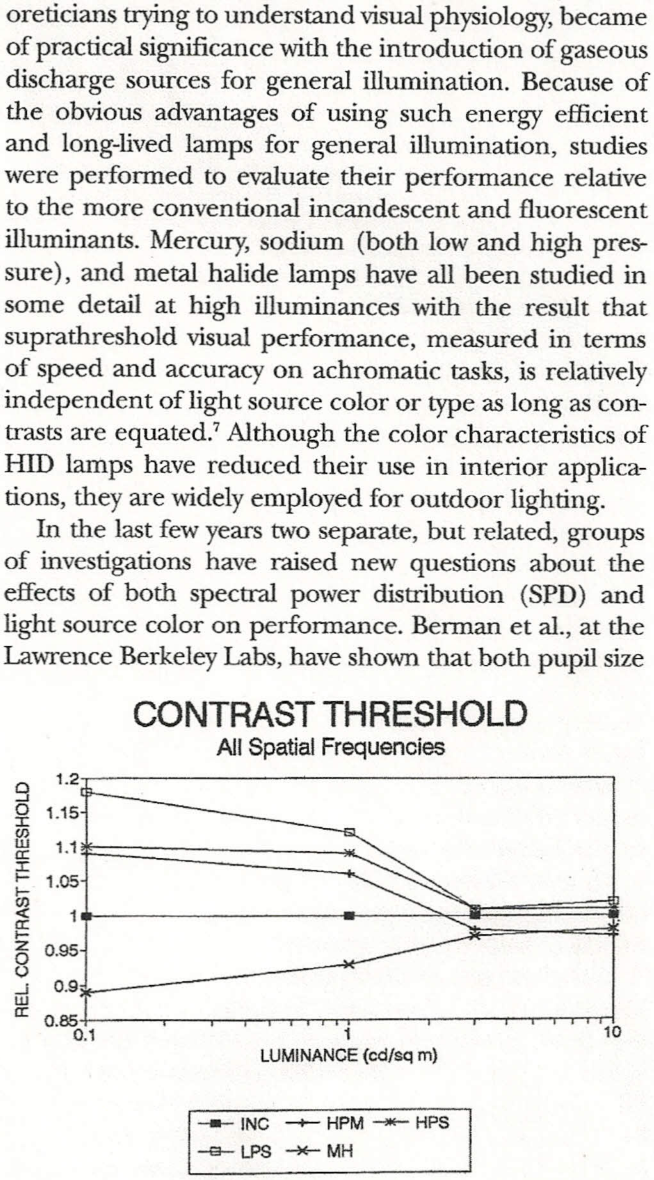

Figure 1—Relative contrast threshold as a function of adapted luminance (mean luminance of sinusoidal gratings) for five illuminants (incandescent, low pressure sodium, high pressure sodium, high pressure mercury, and metal halide). Thresholds are plotted relative to those obtained with an incandescent source. Luminances were 0.1, 1.0, 3.0, and 10.0 c/m^2.

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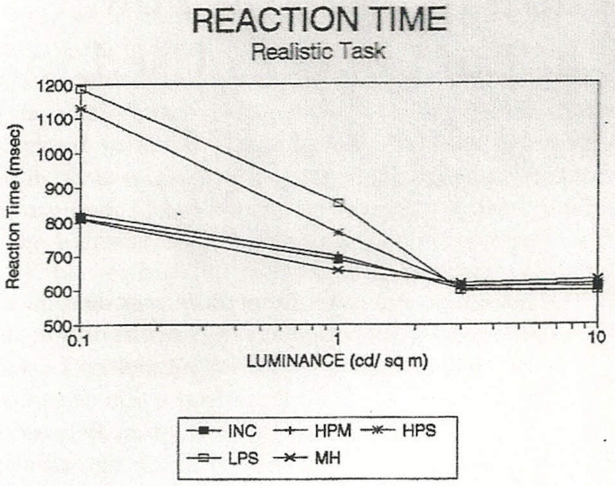

Figure 2—Mean time to correctly identify the orientation of a grating as a function of adapted luminance for five illuminants (incandescent, low pressure sodium, high pressure sodium, high pressure mercury, and metal halide). Luminances were 0.1, 1.0, 3.0, and 10.0 c/m^2.

and brightness are differentially affected by SPD;[8,9] i.e., environments that produce equal photopic luminances, but which differ in SPD, produce unequal responses—even under nominally photopic conditions. They attribute the differences to the fact that both pupil size and brightness sensation are mediated, in part, by the rod system which has a different spectral sensitivity than does the cone system. The differences exist even when the sources are metameric.

Kelly[10] found up to a 40 percent increase in brightness sensation using yellow filters as compared to an equiluminous white light at luminances between 7 and 40 cd/m^2. She also attributed the effect to rod activity because the effect was present only under conditions where rods are presumably active.

Kinney et al.[11] showed an increase in visual performance (defined as a decrease in reaction time) for some spatial frequencies when lights were viewed through yellow filters. Kinney's group did not investigate the cause, but speculated that it was due to reduced inhibition in the chromatic processing system.

While there is no doubt that SPD has important ramifications for the perception of lights, it is not so clear that these effects translate into benefits that are of engineering significance. Indeed, if the effects are as large as have been reported by Berman and Kelly, it is surprising to some that most controlled and properly analyzed studies have shown little or no effect of SPD on visual performance with achromatic tasks. However, since several investigations have suggested that the effects are rod-mediated, and since most of the performance tasks studied have been dependent primarily on the resolution of high spatial frequencies (for which the rods are not particularly sensitive), perhaps it isn't so strange after all. Indeed, Kinney showed a spatial frequency dependent effect in her study. Such results are not inconsistent with the known properties of the dual visual system (known variously as the transient/sustained, X/Y, or magnocellular/parvocellular systems) found in most vertebrate animals, including humans.

General experimental parameters

Subjects

Subjects were five paid students each of whom met the following criteria: (1) no current ocular disease or anatomical anomaly; (2) refractive error less than ± 0.50 D in any meridian without correction; (3) normal color vision (Ishihara PIP); and (4) normal visual fields (Humphrey 30–2).

There were three men and two women aged 20–23. They were informed of the nature of the experiments, but not of the ultimate experimental questions.

All testing was performed on the same five subjects who were carefully selected and highly trained in psychophysical measurements. Training on threshold and reaction time determinations was conducted for each subject for several weeks until asymptotic performance was achieved. Training was conducted in the same apparatus used in the experiment, but was accomplished using different gratings (e.g., square waves instead of sine waves) and sources (e.g., fluorescent) from those employed in the experiments. The decision to use a few highly trained subjects rather than a large number of untrained persons was made to reduce the noise in the data so that small performance differences would be more apparent. Subjects served as their own controls. All testing was done monocularly using the subject's right eye; all subjects were right eye dominant. Data-gathering sessions were of approximately 20 min duration after which a minimum of 15 min of rest was permitted.

Sources

Five sources were used for each condition of the experiments, chosen because they are commonly used in outdoor lighting installations. They were incandescent, high pressure mercury, high pressure sodium, low pressure sodium, and metal halide.

Spectral power distributions were measured using an Opticon Spectroradiometer that was calibrated with a standard traceable to NIST. Relative spectral power distributions for each source are given in the Appendix. Luminances were adjusted to account for the actual SPDs rather than relying on filtered photometers (although a photometer was used to monitor for possible changes in luminance during each experimental session). Luminances were calculated using the formula:

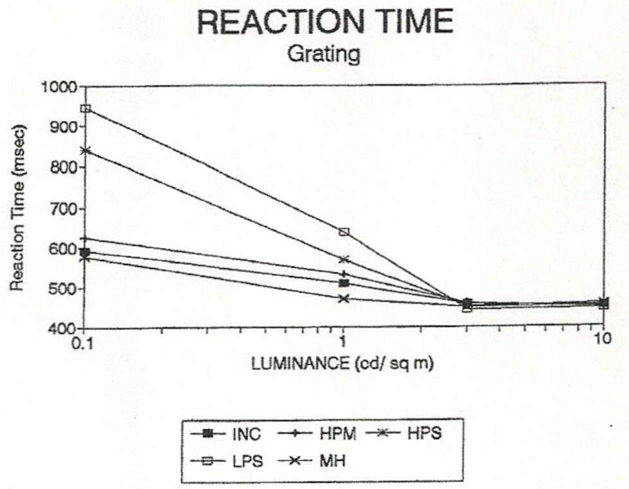

Figure 3—Mean time to correctly identify the facing direction of a pedestrian located adjacent to a roadway (the scene was photographically displayed) as a function of adapted luminance for five illuminants (incandescent, low pressure sodium, high pressure sodium, high pressure mercury and metal halide). Luminances were 0.1, 1.0, 3.0, and 10.0 c/m².

$$L = 683 \sum_{728}^{390} L_{e\lambda} V_{\lambda} \Delta_{\lambda}$$

where L_e = spectral radiance (W $ster^{-1}$ m^{-2}) and V = relative spectral efficiency of the eye (1924 CIE Standard Observer).

Experiment I: Visual performance as a function of spatial frequency

Contrast thresholds to sinusoidal contrast gratings were measured using a series of back-illuminated, photographically produced transparencies which varied in contrast in steps of approximately 0.1 percent. A two-alternative forced choice (2AFC) procedure using the method of constant stimuli was employed. A 75 percent probability of seeing was chosen to represent threshold. Thresholds were determined by varying the contrast in small steps around a value determined for each subject in preliminary testing.

Stimuli were presented in Maxwellian view so that retinal irradiance would not be affected by fluctuations in pupil size. Four spatial frequencies (0.5, 1.0, 3.0, ans 10.0 cpd) were tested at four levels of luminance (0.1, 1.0, 3.0, and 10.0 cd/m²). The visual field size of the gratings subtended approximately 13 degrees wide x 10 degrees high. Stimuli were controlled by an electronic shutter and were presented in a pre-determined random order for a 750 msec duration every 3 sec. To maintain adaptation, a uniform field of the same space-averaged luminance replaced the gratings between presentations.

Table 1—Relative contrast threshold.

Luminance	INC	HPM	HPS	LPS	MH
-0.01	1	**1.09**	**1.10**	**1.18**	**0.89**
1.0	1	**1.06**	**1.09**	**1.12**	**0.93**
3.0	1	0.98	1.01	1.01	0.97
10.0	1	0.97	1.01	1.02	0.98

Cells in bold are significantly different from incandescent at that luminance ($p < 0.05$).

Because there were no systematic source-dependent effects due to spatial frequency—i.e., threshold differences were similar across sources for all spatial frequencies except that the 10.0 cpd grating could not be resolved at the lowest (0.1 cd/m²) luminance—the data from all resolved frequencies were grouped. The results are presented in **Table** 1 and **Figure** 1. All thresholds were normalized to incandescent so that differences among sources would be more apparent. Data were analyzed by a single factor analysis of variance combined with a Scheffe post hoc comparison to identify means that are statistically significantly different ($p < 0.05$).

Results indicate that, for luminances at or near normal photopic levels, there are no significant differences in threshold among the five sources tested. However, at the lower two luminances, sources which have more of their spectral power in the short wavelengths (e.g., high pressure mercury and metal halide) produce lower thresholds than do those which are richer in longer wavelengths (e.g., sodium lamps).

Experiment II: Reaction time as a measure of performance

Reactions times (the interval between onset of the stimulus and the correct identification of the stimulus) were measured for the 1.0 and 3.0 cpd gratings presented at high contrast (five times above each subject's own threshold contrast). Each subject was trained to asymptotic performance in the reaction time task using a high contrast 5 cpd grating prior to the experiment. The subjects' task was to correctly identify the orientation (horizontal or vertical) of a grating as soon as possible after its onset. Stimuli were self-presented by pushing a button (the space bar of a computer) which triggered an electronic shutter which activated the replacement of a uniform field with a grating. When the grating was recognized, a second button was pushed which stopped the timer and indicated the subject's determination of grating orientation. Only correct responses were utilized in the data presented here. There was no statistically significant difference in reaction time between the two grating frequencies so the data were combined and are presented in **Table 2** and **Figure 2**.

These results are consistent with the notion that reaction times decrease as adaptation levels increase (i.e., the shortest reaction times are at the higher luminances), at

Table 2—Reaction Time (msec) to Gratings.

Luminance	INC	HPM	HPS	LPS	MH
0.1	**593**	**625**	**840**	**944**	**577**
1.0	**510**	**531**	**568**	**638**	**470**
3.0	457	459	452	444	449
10.0	452	449	457	446	454

Cells in bold indicate significant differences from other sources at that luminance ($p < 0.05$).

least for the lower luminances. At the two photopic levels (3.0 and 10 cd/m^2), differences in reaction times are not significant. Furthermore, at the two lower luminances, there are significant differences among the sources, with those that have more power at short wavelengths producing shorter reaction times than do the sources that are richer in long wavelengths.

Experiment III: Reaction time to a "realistic" task

Differences that may be significant in highly visual tasks may be less so when the task includes a larger percentage of non-visual processing for completion. For example, the detection of a spot of light on a uniform background requires almost no non-visual processing—it is either seen or not seen—and the amount of time to perform the task is limited primarily by the amount of the time necessary to process the visual information, usually well under 1 sec. On the other hand, the task of tying a shoelace includes only a small amount of time for locating the lace; most of the time is spent manipulating the lace. Only 1 percent of the time may be used to locate the lace while 99 percent would be spend in the act of tying. Consequently, a 10 msec difference in visual processing would probably be lost in the large differences in time it takes people to tie laces.

Experiment III was designed to test whether the differences found in experiment II, which was almost entirely a visual detection task, would also exist when the task included more non-visual cognitive processing. Furthermore, a task was chosen which more closely resembled the type of problem that might confront a driver who was operating a vehicle under conditions of outdoor lighting than does the grating task. The task stimuli were transparencies which depicted a woman standing at the right side of a roadway in the presence of trees and a wooden fence (these stimuli have previously shown to be effective as a discrimination task). In one transparency, the woman was facing the roadway as if to walk onto the road; in the other transparency, the woman was in the same place in the scene but was facing away from the road. The subject's task was to correctly identify which way the woman was facing.

The experimental conditions were identical to those in experiment II except for the substitution of the "real life" stimuli for the gratings. The contrast of the complex scene is not simply characterized, but was well above threshold under steady-state viewing conditions at all luminances. Because no spatial frequency-dependent effects were found in the other experiments, no attempt to characterize the task according to spatial frequency was made. Results are presented in **Table 3** and **Figure 3**.

Pupil size

Pupil size was monitored during testing at each luminance level using a modified telepupillometer (Polymetric). The pupillometer remotely measured pupil size (diameter) by using a CCD camera that imaged the pupil by means of a beamsplitter between the Maxwellian lens and the eye. The pupillometer was calibrated with a template placed in the same location as the eye. Average pupil sizes are presented in **Table 4**.

Pupil diameters were difficult to measure precisely because of the iris fluctuations that continuously occur, especially during cognitive tasks. The data above represent the average horizontal diameters taken during blank field presentations. They are rounded to the nearest 0.1 mm.

Earlier mention was made of Berman et al.'s work on differences in pupil size that were found for equiluminous metameric sources.[8] It should be noted that pupil size was not a factor in the experiments reported here because the Maxwellian view apparatus concentrates the light entering the eye at the center of the entrance pupil; retinal illuminance is therefore not affected by changes in pupillary area. Nonetheless, we did find pupillary area changes of the type reported by Berman, although of lesser magnitude. This reduced effect may be due to the smaller visual field used here (~13 degrees in this study vs. Berman's full field) which probably stimulated a smaller rod population or to differences in the spectra of our sources.

Discussion

The results of this study strongly suggest that there are real and significant differences in performance under sources with different spectral power distributions, but that those differences occur primarily at levels of adaptation where the spectral sensitivity of the visual system is well known to vary from that under which "light" is commonly defined. The luminances used in this work were defined according to the photopic sensitivity function —a definition that is suitable only for moderate to high levels of adaptation. As the adaptation level decreases, the sensitivity of the eye becomes progressively greater at shorter wavelengths until, at very low luminances (< 0.2 cd/m^{-2}), the peak sensitivity has shifted downward about 45 nm.

It is, therefore, not unexpected that, at low lumi-

Table 3—Reaction time - realistic task (msec).

Luminance	INC	HPM	HPS	LPS	MH
0.1	**812**	**827**	**1129**	**1186**	**810**
1.0	**688**	**701**	**767**	**852**	**658**
3.0	614	604	609	597	622
10.0	610	595	617	596	630

Cells in bold indicate significant differences ($p < 0.05$)

nances such as those encountered in outdoor lighting environments, sources which have relatively more of their spectral power at short wavelengths will be more effective at stimulating vision and, consequently, enhancing visual performance. It remains to be seen whether the shift in sensitivity alone will account for the differences found here or whether more complex explanations will be required to account for the data. It is also important to assess whether or not the relative increase in performance found for the short wavelength-rich sources is sufficient to offset the energy efficiency advantage that is currently enjoyed by sodium sources because of the (incorrect) photopic assumption.

The only statistically significant effects of light sources occur at the lower two of the four adaptation levels used in these experiments. This suggests that the choice of source for outdoor lighting is dependent on the luminance provided by the lighting installation. For relatively high luminances, the choice of source is less important, at least from the standpoint of visual performance. However, for luminances at or below 1.0 cd/m^{-2}, there appears to be an advantage to using sources that are relatively richer in power at short wavelengths.

A great deal of additional work under actual conditions is necessary to further quantify the benefit of such a choice and the benefit may vary with the particular visual task. The magnitude of the effect will also depend on the particular spectral power distribution of the source. Given the large effect, we would expect similar results within classes of sources (e.g., comparing metal halide to high pressure sodium lamps). The degree of advantage of one source over another will greatly depend on the particular SPD of the selected lamps.

The degree of difference between lamp types will likely also depend on the choice of visual task. A task that requires a high resolution ability and consequently relatively more foveal processing than did our task will probably show fewer differences across sources; higher resolution tasks can only be performed at higher levels of luminance where the V_λ sensitivity function is more suitable and where, consequently, the lumen is an appropriate unit of light.

Table 4—Pupil Diameter (mm) Average of five subjects.

Luminance	INC	HPM	HPS	LPS	MH
0.1	5.1	5.0	5.2	5.2	4.9
1.0	4.5	4.5	4.6	4.6	4.4
3.0	3.8	3.8	3.9	3.9	3.7
10.0	3.5	3.5	3.5	3.6	3.5

These data strongly suggest that the lumen is not an appropriate metric to characterize the visual effects of lights for tasks which are performed at low luminances and which commonly occur in many lighted environments such as roadways, parking lots, and pedestrian walkways.

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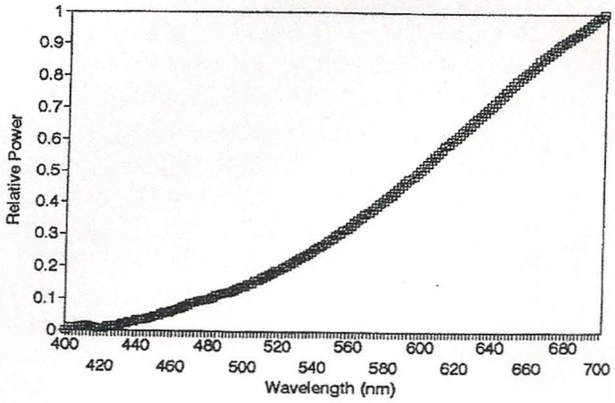
Appendix

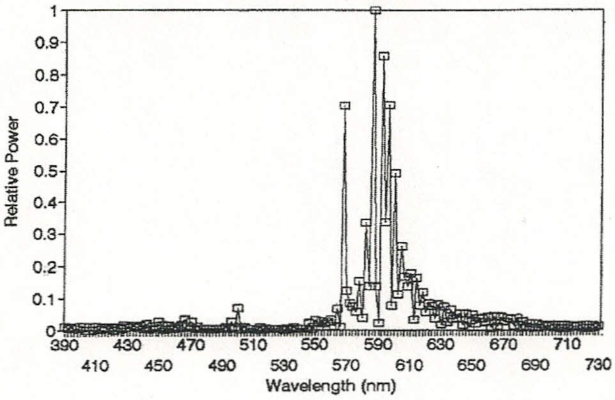
Relative Spectral Power Distributions of Illuminants

1. Incandescent
2. Low pressure sodium
3. High Pressure Sodium
4. High Pressure Mercury
5. Metal Halide

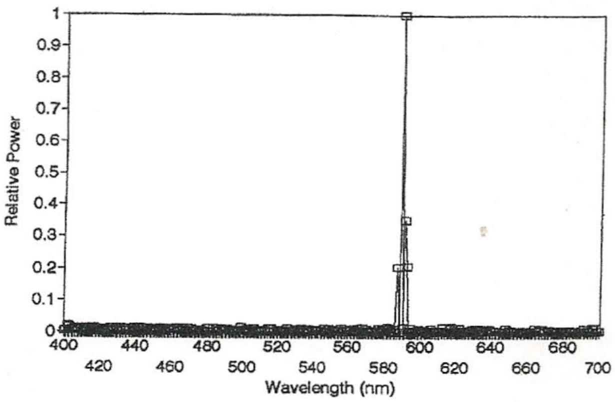
Relative Spectral Power Distribution
Incandescent



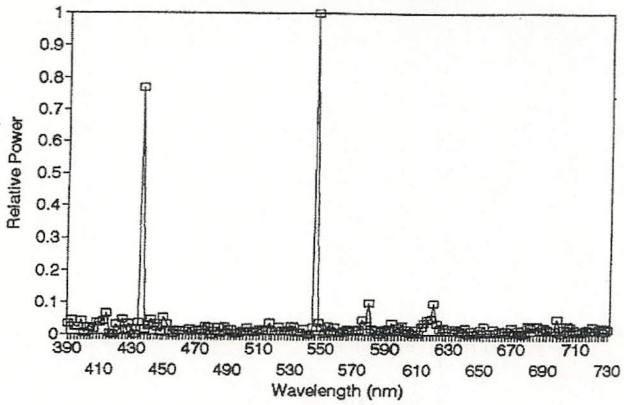
Relative Spectral Power Distribution
High Pressure Sodium



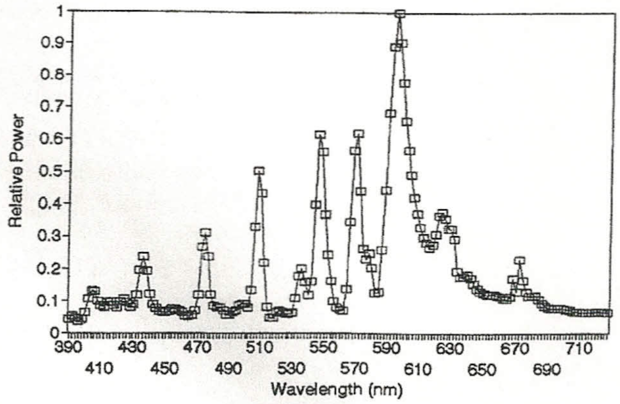
Relative Spectral Power Distribution
Low Pressure Sodium



Relative Spectral Power Distribution
High Pressure Mercury (DX)



Relative Spectral Power Distribution
Metal Halide



Relative Spectral Power Distribution
Metal Halide