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Evaluation of Subjective Response to Lighting Distributions: A Literature Review

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Abstract

The research literature on the subjective response to lighting and luminance distributions is reviewed. It includes an assessment of the lighting design parameters and system features which have been linked to occupant response, both positive and negative. Features such as uniformity, color, visual clarity, glare, gloom, daylighting, task lighting, and lighting geometry are addressed. Occupant response is discussed in terms of affect, preference, and behavior. Both laboratory and field research results are reviewed. The review of the literature suggests strongly that luminance distribution and patterns play an important role in determining positive psychological response to lighting. These findings have important implications for lighting design.

Keywords: Color, lighting design, luminance, luminance distribution, occupant, psychology, subjective response, uniformity.

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1. Introduction

The primary goal of the current review of the psychological effects of lighting is to determine areas where agreement exists on the reliability and validity of the research base on the subjective response to lighting. A secondary goal is to define promising areas where further research into subjective responses to lighting appear needed and promising. In the present review, the terms *psychological* and *subjective* are used to define the emotional or affective response to lighting as distinguished from visual or task performance.

Areas that are reviewed in the current document include visual clarity, color, design features, uniformity, task lighting, preferred lighting levels, daylighting, gloom, lighting geometry and post-occupancy evaluation. Both laboratory and field research projects are discussed in some detail - to describe the methodology used and to draw conclusions about the knowledge of psychological response to lighting. At the end of each section, conclusions are drawn from the summarized research.

The methodologies used to elicit subjective responses to different types of lighting designs and installations fall into four major classes - direct adjustment of lighting hardware, attitude scaling, behavioral observation, and questionnaires. Adjustment of lighting hardware involves the user setting illuminance levels on tasks or surfaces to achieve some desired criterion or effect. Semantic differential scales (one form of attitude scales which uses bipolar adjective scales) are often used to identify the dimensions of psychological response to lighting. Further analysis of these data using multidimensional scaling analysis is used to identify physical dimensions responsible for the response. Behavioral observations include recording behaviors such as seat selection, way finding, body position, individual modifications to lighting, or similar activities, and again relating these to physical lighting parameters. Finally, questionnaires include ascertaining people's response to lighting conditions using a variety of predetermined questions, which can include attitude scaling. Several different methodologies are often used within an experiment to maximize the amount and the type of data obtained.

Techniques for varying the lighting and room characteristics to obtain evaluative responses include small scale models, full scale models, laboratory facilities, film or graphical representations, and real spaces (usually offices). Ideally the physical characteristics of the lighting and the space itself are carefully controlled and measured during an evaluation of psychological responses to a test space. Such control and measurement becomes increasingly difficult, as the space becomes more complex and more "real". Use of new instrumentation such as video photometers and luminance scanners, as well as chromaticity meters offers promise for more accurate and comprehensive physical measurements. Nevertheless, failure to characterize the physical parameters of test spaces adequately has been a major contributor to the uncertainties surrounding the evaluation of the psychological responses to lighting systems. Yet, the review of the literature suggests strongly that specific lighting designs can elicit certain psychological responses reasonably reliably and consistently. These responses will be explored in the following pages.

2. General Design Features

The present review of the literature opens with a discussion of research which attempted to link specific lighting design features with subjective responses. Clearly, the most effective way to influence future design is to identify those lighting features which have a demonstrable, repeatable influence on human psychological or subjective response. Some of the subjective responses that have been assessed include *clarity, spaciousness, complexity, pleasantness, intimacy, evaluation, gloom,* etc. A number of studies, most notably by Flynn and his coworkers in the United States and by Hawkes and others in the United Kingdom, have been conducted to relate these responses to specific lighting designs.

2.1 Overall Psychological Response

A number of researchers evaluated the general, overall psychological response to markedly different lighting configurations in office-type laboratory spaces. In these studies, lighting systems were arranged in different designs, varying from simple overhead to distinctly peripheral. These designs resulted from different geometrical layouts of the lighting systems, ranging from an overhead system located only in the center of the room, to a system which only lit the walls and not the center of the room. Observers indicated their impressions of the spaces by completing adjective scales which produced a *psychological* description of the space. An early study of this type which sparked considerable interest in evaluating the subjective response to lighting was conducted by Flynn, Spencer, Martyniuk, and Hendrick (1973).

Using an easily modified office space, Flynn, *et al.* evaluated the effects of environmental lighting for six different lighting installations. User impressions and behavior were studied using judgements on semantic differential rating scales for 96 observers. The results indicated that the six lighting designs were consistently rated differently. Furthermore, there was agreement among the ratings when the rooms were observed initially, and when comparisons were made among the six installations. The authors then analyzed their results using factor analysis to determine the *underlying* factors responsible for the impressions. They identified five factors - *evaluative impression, perceptual clarity, spaciousness, spatial complexity, and formality.* The first three factors were significantly related to different lighting installation designs. In the next step Flynn, *et al.* compared the semantic differential data with data obtained from multidimensional scaling in which 46 subjects judged the degree of change from one lighting installation to the next, using a 10-point scale. This analysis indicated that a three-dimensional model of human response afforded the best explanation of the data, with the three polar dimensions being identified as *peripheral/overhead*, *uniform/non-uniform* and *bright/dim.*

Results from the two procedures were then analyzed to determine which common dimensions of perceptual experience were operating. Flynn *et al.* concluded that *bright/dim* and *perceptual clarity* were extremely closely correlated ($r=0.99$). Ratings of *pleasantness* were closely correlated with the *overhead/peripheral* and *uniform/non-uniform* dimensions ($r=.92$) such that pleasant lighting installations scored higher on the peripheral and non-uniform ends of the scales. *Spaciousness* appeared to be predicted best by a combination of the three dimensions ($r=.98$). In addition, the authors also used a behavioral technique in which they observed where a small number of people sat in a coffee bar with different types of lighting. They found that people tended to select seats in darker areas but face toward the light, even when the pattern of lighting in the lunchroom was markedly altered.

In a subsequent paper, Flynn (1977) discussed the impact of specific lighting design approaches on subjective effects such as visual clarity, spaciousness, relaxation, privacy (intimacy), and pleasantness based on semantic differential and multi-dimensional scaling research. He evaluated the effect of different illuminances, color temperature, and lighting distributions on the subjective response to seven lighting designs as a way of providing information for meeting lighting energy budgets while maintaining acceptable interior lighting. Flynn's analysis demonstrated that a central overhead mode at 22.6 watts/m^2 received higher ratings for visual clarity and spaciousness than a peripheral overhead mode (at 25.8 watts/m^2). Impressions of spaciousness and satisfaction were reinforced by use of peripheral lighting, particularly wall washing. Use of warm light tones with non-uniform peripheral lighting also reinforced positive evaluative impressions. In a discussion of visibility level, Flynn and Subisak (1978) applied data from the subjective impressions research, noting that impressions of clarity seem to relate to the brightness of the periphery, "whiteness" of the light source, and illuminance at the seated position. They also observed several groups of ten subjects each who entered a classroom to take a "test" and noted that they tended to sit in areas of the room with higher illuminance. Flynn and Subisak concluded that extremely nonuniform lighting design may result in areas with poor subjective clarity which in turn create negative subjective impressions. Cautioning that users seem to want both high task visibility and clarity, they noted that the visibility level approach combined with data from subjective assessments appear to offer the best means of achieving high quality design. Bernecker and Mier (1985) report that using a side lens with an indirect luminaire relative to the indirect luminaire alone significantly increased the perceived brightness of the space (although the overall illuminance was not altered) and improved the subjective assessment of the space.

Using both factor analysis and multidimensional scaling techniques, Flynn and Flynn, Hendrick, Spencer and Martyniuk (1979) ultimately identified nine psychological factors which he felt could reliably be elicited by different lighting configurations. These factors included:

Visual Clarity	Spaciousness
Pleasantness	Glare
Spatial Complexity	Color Tone
Privacy/Public	Relaxed/Tense
Preference	

Flynn's untimely death precluded him from determining whether specific lighting configurations could be identified which would reliably elicit these reactions.

The term *lighting quality* is often used synonymously with a positive evaluative response to the lighting in a space. Hawkes, Loe, and Rowlands (1979) conducted an experimental evaluation of lighting quality as a function of 18 different lighting designs. Using a windowless office, they had subjects make a series of judgements of different designs, involving recessed luminaires (with four different types of diffusers), wall washing, down lights, desk lights, and track lighting. The lighting designs were selected to be as realistic as possible and supply a constant illuminance (500 lx) on the working surface. A total of 28 observers were used - 15 males and

13 females. All observers saw designs 1 (recessed units) and 2 (downlights plus wall wash) first, and designs 3 (wall wash) and 4 (desk light plus side light tracks) last. The order of the other 14 designs was randomized to minimize order effects. Observers made two types of assessments - a numerical value indicating the degree of difference between the current lighting situation and the immediately previous one; and ratings of each lighting configuration using 15 semantic differential scales. At the same time, Hawkes, *et al.* made physical measurements of the lighting situation in terms of horizontal and vertical illuminance, spherical illuminance, illumination vector, mean cylindrical illuminance, equivalent sphere illumination (ESI), vertical illuminance, and visual comfort probability (VCP).

The assessments of the degree of difference between the lighting situations were analyzed using multidimensional scaling techniques, and revealed no conclusive results. Analysis of the semantic differential scales revealed that two factors - subjective brightness and interest - accounted for 79% of the variance. The semantic differential data also provided information on preferences, obtained from the judgements on the *pleasant-unpleasant* and *attractive-unattractive* scales. Hawkes, *et al.* commented that they believed the problems with the multidimensional scaling were due to the use of sequential, rather than simultaneous viewing conditions.

Hawkes, *et al.* also attempted to relate the semantic differential results to the physical lighting conditions of the space. They found that the bright-dim data were highly correlated with illuminance, particularly log cylindrical illuminance (0.69). The correlation improved to 0.81 if one lighting situation were excluded from the analysis. This lighting situation, although having high illuminances, was perceived as *dim*, perhaps because it was a situation in which only one side wall was illuminated. Hawkes, *et al.* then examined the data for the interest factor and found that all situations which used only diffuse sources were rated toward the uninteresting side of neutral, while those situations which used focused sources were rated as more interesting. Hawkes *et al.* suggested that there may be two reasons for the differences: first, that there are sharper boundaries between areas of light and dark in the more *interesting* situations; and second, that the extent of variation in luminance distributions in the space relate to its interestingness. Together, the data for the two factors suggest that situations that are judged as being *brighter* and more *interesting* (or complex) are also preferred. Hawkes, *et al.* (1979) commented that spaces become more attractive as they get both brighter and more complex but that it is not clear if this relationship continues to extremes or diminishes beyond certain levels. They note that "*it can be seen that situations using only one type of luminaire occur lower down on the slopes, particularly the common recessed luminaires. Also, the smaller source luminaires, with more directional quality, are concentrated towards the preference peak*" (p. 120). Finally, they stated that regular arrays of luminaires were the least preferred way of lighting an office - an effect which may have been enhanced because of the lack of windows. "*Complexity and brightness together: perhaps that is what people want in the lighting of their offices*" (Hawkes *et al*, 1979, p. 120).

Of particular interest for lighting design is the finding for one lighting system (K) which was judged to be *dim*, while measured as *bright*. This result suggests that luminance patterns in the overall space are important determinants of occupant preferences and perceptions of brightness. Hawkes *et al.* suggested in fact that analyzing the patterns and developing histograms of luminance in a space might be a valuable way of predicting interest. "*It is possible that a wide* *range in luminances as shown in such [hypothetical] graphs would be produced by 'interesting' situations, and the presence of more than one peak would be evidence of some articulation, of a distinction between focal areas and general background, which distinguishes the special and mysterious, from the commonplace and obvious.*" (Hawkes *et al.* 1979, p. 118).

Overall Psychological Response - Conclusions

- Particular lighting configurations elicit specific subjective responses:

Configuration	Response
Peripheral/Overhead	Pleasantness, Spaciousness
Uniform/Non-Uniform	Spaciousness
Bright/Dim	Clarity

- Central overhead lighting is associated with the perception of greater visual clarity and spaciousness.

- Peripheral and wall washing systems are associated with greater perceived spaciousness and satisfaction.

- Extremely non-uniform lighting designs are associated with poor visual clarity and dissatisfaction with the lighting system, particularly for office-type environments.

2.2 Perception of Spaciousness

One particular psychological response elicited by different lighting configurations is that of *spaciousness*, or the perception of openness opposed to enclosure. Consideration of the results from both Flynn and Hawkes, *et al.* discussed in 2.1 suggested that a central overhead lighting system is associated with perceptions of both greater visual clarity and spaciousness, while peripheral and wall wash systems are associated only with perceptions of greater spaciousness. Extremely non-uniform lighting systems are associated with poor visual clarity and dissatisfaction with the lighting. Other researchers have expanded on these results by examining specific perceptions of a space resulting from different lighting designs. Several researchers in Japan used attitude scaling techniques to evaluate psychological reactions such as the perception of the spaciousness created by different lighting configurations. Unlike the research by Flynn, Hawkes and their coworkers, small scale models were used. This technique allows changes to lighting systems to be made much more easily than in a full-scale facility, although some findings have been validated in real offices.

Inui and Miyata (1973, 1977) conducted two scale-model studies which evaluated the relationship between characteristics of the visual environment and the perception of spaciousness. In the first study, Inui and Miyata (1973) evaluated the role of physical variables such as window size, sky luminance, interior illuminance and room size on the perception of spaciousness. They defined spaciousness as the visual feeling of *openness* or *enclosure*, with no sense of good/bad evaluation.

Using four different scale models, Inui and Miyata (1973) simulated an office with variable depth, width, and window areas, as well as horizontal illuminance and external sky luminance. Observers used the method of magnitude estimation to assess spaciousness. In this technique, observers are given a standard condition, against which all other conditions are compared by giving them a number relative to the standard. Numbers smaller than the standard mean less of an attribute; larger numbers mean more of the attribute. In this experiment, the standard condition had a sky luminance of 500 cd/m^2, an average horizontal illuminance of 200 lx, a room volume of 192 m^3, and a window width of 4.8 m. This design was near the center of the range of each variable and was given the arbitrary value of 100. Ten observers viewed all combinations of variables. They gave each design a number relative to the standard value such that numbers above 100 meant more spacious and those below meant less spacious.

Analysis of the results indicated that *spaciousness* increased with increases in horizontal illuminance, percentage of window opening, and room volume, and that this increase was greater as sky luminance increased. Inui and Miyata found an interaction between sky luminance and average horizontal illuminance, and between sky luminance and window percentage, however. They found that *spaciousness* increased linearly as interior horizontal illumination increased from 10 to 1000 lx for five different room volumes, although larger rooms were consistently perceived as more spacious. A similar relationship was observed for increasing window size, defined as the percentage projection of the window area at the viewing location. These findings led to the development of a power function for the perception of *spaciousness* as a function of interior illuminance, room volume and percentage of the window for a given sky luminance condition. Use of this formula showed good agreement with the scale model results and suggested that *spaciousness* could be predicted from knowledge of the illuminance, room volume, window percentage, and sky luminance. The authors found no systematic differences in the perception of *spaciousness* as a function of the different scale models used or of the shape of the room in terms of ratio of width to depth.

Inui and Miyata (1973) then verified their findings for 43 actual rooms chosen to represent a wide range of volumes, window sizes, interior illuminances, and sky luminances, with eight observers. They again used the method of magnitude estimation to evaluate *spaciousness.* Physical measures were obtained for the sky luminance, horizontal illuminance, room size, window percentage, and nearby obstructions. Analysis of the data indicated good agreement, $\pm 20\%$, with the power function and scale model results.

The last step undertaken by Inui and Miyata was to relate the sensation of *spaciousness* to its acceptability, again using a scale model with eight observers. The results of several different assessments revealed that observers were not willing to set an upper bound on acceptable *spaciousness* or indicate a "just right" amount of *spaciousness.* They were able, however, to determine a lower limit of acceptable *spaciousness.* The results of two different assessments suggested that "*just acceptable spaciousness*" should be at least 100 and preferably 200 on the arbitrary scale of *spaciousness.*

In a subsequent study, Inui and Miyata (1977) evaluated the relationship between different aspects of the visual environment and the perception of *spaciousness, satisfaction,* and *friendliness* using a 1:15 scale model. In this experiment, they varied two levels of each of 5 physical parameters. Sky luminance was either 5 or 500 cd/m^2; interior illuminance was either 200 or 800 lx; window size was either 33% or the full window wall (with a fixed sill height of 1 m); the illumination method was either incandescent lamps with louvers or fluorescent lamps with translucent panels; and furnishings were either carpet, settee and easy chairs, or floor tiles with office furniture. The effect of these different variables on the type of activity performed in the space was also assessed. Twenty subjects viewed all 32 conditions. As in the previous experiment, *spaciousness* was assessed by magnitude estimation, while satisfaction and friendliness were assessed by response to each of 10 seven point adjective scales.

Inui and Miyata's results indicated that factors which influenced spaciousness were sky luminance, interior illuminance and window size. Window size had the strongest effect, suggesting that a big window provides a strong feeling of satisfaction. The type of illumination or the kind of furnishings had no effect. Factors which influenced rated satisfaction were interior illuminance, window size and furnishings, while the method of illumination and the kind of furnishings influenced friendliness. Spaciousness was closely linked to satisfaction but not at all to friendliness. Activities such as meditation and contemplation were closely related to a low level of spaciousness (but a high level of friendliness), while lecturing and meeting were linked to a high level of spaciousness. These results suggest that the amount and type of illumination, including daylight from windows, has important effects on the apparent size and friendliness of a space.

Spaciousness - Conclusions

- Perceived *spaciousness* increases with horizontal illuminance, percentage of window area, room volume, and sky luminance.

- *Spaciousness* can be predicted from knowledge of illuminance, window area, room volume and sky luminance.

- Although there is a lower bound to "just acceptable" *spaciousness*, there does not appear to be an upper bound (in which a space is too spacious to be acceptable).

2.3 Perception of Pleasantness

Another characteristic which Flynn cited as elicited by lighting is that of *pleasantness*. Sato, Inui, Nakamura, and Takeuchi (1989) evaluated the relationship between the perception of a *pleasantness* and the physical factors of the visual environment for power plant control rooms. In a two-part experiment, they assessed the visual factors which affected the perception of pleasantness using semantic different ratings. Two (1:15) scale models simulating a standard and a comparison control room were used.

Physical factors that were varied in the comparison model included: type of lighting system, color and reflectance of control panel and floor, illuminance level, ceiling height, potted plants, accessory colors, and windows. In the first part of the experiment, 15 patterns in which one to four physical factors were changed, were evaluated, while in the second part, 12 such patterns were assessed. Twenty-one observers viewed both models and completed twelve 7-point semantic differential rating scales, which described the model. Factor analysis identified the minimum number of dimensions on which observers based their choices. Two factors were extracted: *spaciousness* and *friendliness*. Analysis of the results indicated that the score for *spaciousness* was somewhat lower for the standard model than for the comparison, while the score for *friendliness* was substantially lower. Analysis of the data for part 1 indicated that *spaciousness* could be obtained by manipulating factors such as ivory color on the control panels, luminous ceilings, higher illuminances and ceilings, and medium value floor coverings. *Friendliness* was obtained by factors such as medium-valued or beige-colored floors, higher illuminances and ceilings, luminous ceilings with recesses, the presence of plants, or the use of accessory colors. Some combinations of physical factors increased both *spaciousness* and *friendliness*. Thus, one of the greatest increases relative to the standard model was for the combination of ivory colored control panels with beige-colored floors, plants and accessory colors.

In part 2, the physical factors included both interior and exterior windows (which had been excluded from part 1), lighting systems (in terms of louver reflectances), ceiling height (up to 4.2 m), floor color, illuminance level, and potted plants. In this part two to four physical features were changed for each comparison, to isolate the complex, interactive effects of multiple factors. Thirteen semantic differential scales (one was added specifically on friendliness) were used with sixteen observers and twelve comparison models. *Spaciousness* and *friendliness* were again extracted as the primary factors. Again, the set of physical factors showing the greatest increase in both *spaciousness* and *friendliness* were identified as beige-colored floors, luminous ceilings with recesses, inside windows, louver reflectance, and plants.

Sato, *et al.* cautioned that commented that both interior and exterior windows increased the perception of *spaciousness* while outside windows increased the feeling of *friendliness*. Use of louvers with 40% reflectance diminished both perceptions, while higher ceilings tended to increase them. The authors commented that using plants, accessory colors and higher ceilings was most effective in increasing both *friendliness* and *spaciousness*. Sato, *et al*, cautioned that, *"the prevention of glare, the reflections of light sources from the CRT glass surfaces, outside disturbances, etc., must be considered together in the case of a control room"* (1989, p. 105).

<u>Pleasantness - Conclusions</u>

- Lighting variables contribute importantly to feelings of both spaciousness and pleasantness.

- Increasing horizontal illuminance, providing windows, increasing room volume, and using light colors all increase the perception of spaciousness both in scale models and in actual rooms (for the first three variables).

- Spaces that appear to be more spacious are considered to be more friendly, with no apparent upper limit to spaciousness.

2.4 Perception of Gloom

The psychological responses that have been addressed so far are the positive ones, in which the lighting elicits feelings of pleasantness or satisfaction. Information on lighting situations in which the opposite response occurs is also extremely valuable in defining the boundaries of the psychological lighting experience.

One response which could be termed the opposite of *pleasant* is that of *gloom*, in which a lighted space is perceived as *dim* or *gloomy*. Shepherd, Julian, and Purcell (1989) initiated an assessment of *gloom* as a psychophysical phenomenon. They attempted to determine the characteristics of a lighted room that were consistently associated with the perception of *gloom*, to develop a predictive model of *gloom*. Shepherd *et al.* commented that many lighting installations are judged as *underlit* or *inadequately lit* even when the task illuminances are more than adequate. After reviewing the published literature on gloom, they noted that the following physical parameters have been associated with the perception of gloom:

- limited distribution of light throughout the room, not just on task;
- narrow range of reflectances of surfaces and objects;
- narrow range of contrasts;
- limited discriminability of details, particularly in dark areas of the periphery;
- lower overall light levels, with attention to mesopic luminances;
- mesopic viewing conditions which induce color and lightness shifts; and,
- rod intrusion into photopic viewing conditions.

To assess the different lighting parameters, Shepherd *et al.* evaluated occupant response to different lighting conditions in a windowless lighting laboratory. This space was equipped with three different lighting conditions. In the first condition only the center of the room was illuminated, at 5-9 cd/m^2; in the second condition both the center and the edges of the room were illuminated, at 6-11 cd/m^2; and in the third condition, again only the center of the room was illuminated, this time to much higher levels at 38-60 cd/m^2. The three conditions were designed to test hypotheses about the relationship between gloom and changes in overall light levels, distribution of light, ability to discriminate details (particularly in the periphery of the room), and mesopic luminances on room surfaces.

Shepherd *et al.* used two groups of subjects. Thirty lighting and architecture students participated in an initial pilot study, while thirty-five members of the general public participated in the main experiment. Instead of using rating or semantic differential scales, they assessed response to the room by having subjects check "yes" or "no" to each of 53 adjectives as it described the room. Selections were analyzed in terms of frequency and clustering - or the use of sets of words in conjunction with each other. Word groups were those selected by at least 70% of the subjects (for conditions 1 and 2).

Analysis of the results indicated no significant differences between the pilot study and the main experiment. Only condition 1 resulted in a common perception which could be termed gloom. "*The words gloomy, dark, inadequately lit, depressing and uninviting were consistently selected together and in association with somber and subdued to describe condition 1. This suggests that* *the subjects shared a common and negative perception of the room. That this was achieved with lighting students, architecture students, and members of the general public means that the negative perception is a robust and common perception*" (Shepherd *et al.*, 1989, p. 96). Condition 2, on the other hand, was characterized by words such as *objects clear, details, distinct, and spacious* for the pilot study, and *objects clear, shaded, subdued, and pleasant* for the main experiment. These clusters suggest that the perception of lighting condition 2 was more positive, even though the overall luminance levels (but not their distribution) were very similar to condition 1. Shepherd *et al.* suggest that this may be due to differences in the distribution of light. "*It could therefore be argued that the distribution of light or the ability to discriminate details and contrasts in the periphery is indeed and important parameter in the perception of gloom as Boyce, Julian and Jay have suggested*" (1989, p.96).

Shepherd *et al.* found a wide variation in judgements for condition 3, which had the highest luminances centered in the middle of the room. Words used to describe condition 3 included *objects clear, details, distinct, adequately lit, uninviting* for the pilot study and *clear and adequately lit* for the main experiment. Thus conditions 2 and 3 did not produce common reactions, nor did they produce a sensation similar to that produced in condition 1. The authors concluded that their results suggest "*that the perception of gloom is a complex phenomenon which cannot be limited simply to the adaptation luminance in a space. The distribution of the light and the discriminability of contrasts in the peripheral visual field are equally important parameters in determining people's impressions of a room*" (p.96).

Shepherd, Julian and Purcell (1990) continued the evaluation of gloom. They noted that others have considered that "*the adaptation level, surface reflectance, and the intensity and distribution of light in the periphery is important in the perception of gloom*" (Shepherd, *et al.*, 1990, p. 74). Some researchers have suggested that inability to discriminate details in a room's periphery with foveal vision can produce the sensation of gloom while others have suggested that high adaptation levels in the central visual field may cause objects to appear darker in the periphery and create "gloom". Lack of lighting in the edges and corners of rooms may also create the sensation of gloom. Still others have suggested that "*gloom is associated with a shift from processing of information via the cone receptors in foveal vision to the processing of information via rod receptors in peripheral vision. The cone to rod shift occurs where object luminances fall below 120 cd/m²*" (Shepherd *et al.*, 1990, p. 74). Finally one other proposal is that "*gloom is related to adaptation levels which produce unstable color perceptions. This occurs in mesopic conditions, when luminances range between 0.01 and 10 cd/m²*" (Shepherd *et al.*, 1990, p. 74).

Shepherd *et al.*, 1990 conducted two additional experiments to delineate lighting configurations which would reliably elicit the perception of gloom. In both experiments, they used the same procedures described by Shepherd *et al.* (1989), in which participants indicated the appropriateness of each of 53 adjectives as a description of the room. Again the frequency with which groups of adjectives were selected to describe a particular configuration was noted. The authors stated that results from the earlier experiment indicated "*that the experience of gloom is reliably judged by observers and is associated with low intensity light in the peripheral field of view*" (p. 75). In stage 2, the authors manipulated the amount and distribution of light in both the peripheral and task areas to determine their relative importance in the perception of gloom for twelve different lighting conditions. Their results indicated that "*the full gloom experience* *is therefore associated with conditions where task lighting is low and there is no or minimum wall lighting. When task lighting is increased, there is more spill light into the periphery which, when combined with the same wall lighting, diminishes the experience of gloom*" (p. 75). Thus, the results did not support the idea that gloom is due to the presence of dark areas but may support the idea that gloom is related to the inability to see fine details in the periphery.

In stage 2, there was also a hint that adaptation levels in the mesopic range relate to gloom. As a result, in stage 3 Shepherd *et al.* tried to separate the effects of adaptation level and brightness of surfaces. They noted that simply determining adaptation level requires some weighting of luminaires in the field of view (as well as determination of exactly what is the field of view). They stated that adaptation level determines the apparent brightness of surfaces, but lightness relates to the perceived whiteness or blackness of a surface. Lightness is thus determined by the brightest object in view (the object with the highest reflectance.) Shepherd *et al.* decided to assess the effects of range of lightness and surface illuminance. Changes in perceived lightness, apparent brightness, and adaptation level were assessed by removing all white objects from the scene. To this end, even the 53 adjective questionnaire they used was reproduced in grey, and no white or light colored objects or clothing were permitted in the field of view. In this way, the authors hoped to increase the perceived lightness of surfaces in the room. Again, conditions were chosen in which task lights were used with and without wall lighting with luminances ranging from 4.5 to 36.3 cd/m^2. Results indicated a shift in judgement for two lighting conditions from the judgements obtained when white surfaces were used. The selection of words became more positive with choices such as *comfortable, warm, and spacious* used for the condition with maximum task lights and medium wall lights. The results indicated that the use of a different (and lower) range of surface reflectances succeeded in decreasing the perception of "gloom" for two lighting conditions. It was not successful, however, for several conditions where the range of luminances was apparently too low to demonstrate the effect. The authors (1990, p. 79) cautioned, however, that "*it must be stressed that these results were obtained in a room which had low reflectance surface finishes, and that the results may not generalize to other environments...However, the implications of this study are that lower light levels can be acceptable, if the lightness of objects in the environment can be controlled.*"

A number of questions about the physical characteristics of gloom remain. They include the question of whether the impact of gloom can be reduced by lowering adaptation level and/or by lowering all surface reflectances. Furthermore, how does the perception of gloom relate to the perception of brightness, pleasantness, etc? When, and why, does a room's appearance switch from gloomy to nondescript to pleasant? Can this switch be related to specific luminance patterns and/or levels?

The Perception of Gloom - Conclusions

- Variation in the lighting distribution can result in the impression of gloom, as well as pleasantness, in a space.
- The likely physical causes of perceived gloom are the following:
  - Inadequate, uneven distribution of light in a room.
  - Details in corners and periphery not discriminable.
  - Mesopic light levels.
  - Low surface reflectances.

3. Response to Lighting Configurations

In the preceding section (2), the discussion centered on eliciting overall perceptions of a space as a function of the configuration of the lighting system and room characteristics. There was relatively little discussion of specific illuminance levels or luminance distributions. The research suggested that arrangements of the lighting - with emphasis on the center or on the periphery or a room - can elicit emotions such as pleasantness, spaciousness, friendliness, or gloom. In the studies reviewed in section 2, observers were not asked to perform visual tasks or to pay much attention to the illuminance on their work surfaces. Obviously lighting's primary role is in the provision of sufficient light to do a visual task. Yet, reaction to the lighting conditions in the room where a task is done can also be a critical factor in determining attitudes toward both the task and the work space. The studies to be reviewed in section 3 focus on the manipulation of specific lighting variables, often with the goal of determining some minimum or optimum level of task illuminance or surround luminance.

3.1 Preferred Lighting Levels and Ratios

3.1.1 Illuminance

Tregenza, Romaya, Dawe, Heap and Tuck (1974) conducted a laboratory assessment of preferred lighting levels and arrangements in a simulated office. Using 32 female secretaries, they assessed lighting levels as a function of initial illuminance settings. The experimental setup involved a laboratory configured as a single-person, windowless office in which the illuminances on six surfaces - walls, ceiling, and desk - could be controlled separately.

Six experimental sessions were conducted. In each of five sessions, participants performed a set of three office tasks (typing, reading, and sorting) under an initial illuminance level; then directed the experimenter to change the lighting (both in level and configuration) as desired; repeated the three tasks and had the lighting readjusted; and finally completed a short interview about the lighting conditions. In the final session, the participants completed a detailed questionnaire about their lighting preferences and attitudes about lighting. During the experiment, the authors visited each subject's home office and measured its lighting levels, furniture location, and room dimensions as a baseline for comparison.

In the experiment by Tregenza, *et al.*, half the participants began the experimental sessions with the desk illuminance at a low level (435 lx) and the other half began with a high level (4600 lx), with these initial conditions alternating in subsequent sessions. This design meant that subjects had the opportunity to select 5 lighting designs following each initial illuminance level. There was a statistically significant difference between the participant's selection of lighting level as a function of initial setting, with lower levels set following an initially low setting, and higher levels set for the initially higher setting. Despite the effect of the initial level, individuals were highly consistent in their choice of illuminance, with no significant difference in settings on different days for the <u>same</u> initial setting. In addition, participants who chose relatively low illuminances after a high initial setting tended to chose low illuminances after the low initial setting. Finally, 27 of the 32 subjects were able to select a preferred lighting setting, with an overall mean of 2297 lx. The data indicated that two-thirds of the participants preferred a situation in which light reflected from the walls was the dominant component of the desk illuminance, one quarter of them preferred light reflected from the ceiling, and only three subjects preferred light from the lamps directly overhead. The authors commented that "*most subjects thus preferred conditions in which the light incident on the desk was quite diffuse and not directly downwards, which supports current practice in the control of veiling reflections in office tasks*" (Tregenza *et al.*, 1974, p. 208). Participants tended to adjust illuminances on the four walls to be consistent with levels of desk illuminance, although there was a definite preference to have the wall behind the person to be twice as bright as any other wall.

Analysis of the setting choices indicated that wall:desk illuminance ratios were higher than recommended by the IES (often 0.8 to 1.0) as were wall:task and ceiling:task luminance ratios (0.51 to 0.55). There was also a positive correlation between a subject's age and illuminance setting - older people chose higher desk illuminances when the initial light setting was low. The analysis of the conditions in subjects' customary offices indicated that about two-thirds of them worked in single offices, one third in a two-person office, and one person in a three-person office. These offices tended to be small and daylit, with wide variations in desk illuminance. Of interest is that about half the subjects with windows sat with the window behind them (and tended to pick a higher illuminance in the experiment for the wall behind them). Analysis of the questionnaire results indicated that 90% would be reluctant to accept the laboratory module for an office because of its lack of windows. In addition, subjects indicated that their major concern was to light their task area, primarily by using light from the ceiling.

Tregenza *et al.* concluded that "*inexperienced subjects could make reasonable and consistent choices in lighting*" (1974, p.120). Furthermore, the subjects did not have problems in directing the experimenters to adjust the six light sources (after some initial practice), and showed consistency between their preferred setting and their responses to the questionnaire. Although there were considerable variations in selected illuminances between subjects, there was consistency in each individual's own selections, there was little variation in wall/desk and ceiling/desk illuminance settings with desk illuminance. In addition, there was some similarity between the lighting conditions in the subject's customary office and the selections in the laboratory.

"*The main conclusion that can be drawn from the preference studies is that even with a coherent group of subjects under laboratory conditions, preferences vary widely, so to design on the basis of known experimental results would be to give freedom of choice to those who work in an office*" (Tregenza *et al.*, 1974, p.120). Although the authors expressed some reservations to the idea of setting lighting recommendations based on preference (and behavioral) studies, their results demonstrated some interesting consistencies. For examples, subjects tended to pick "bright" settings, with high ratios of wall to task illuminance. They appeared to want the room as well as the task lit to similar levels. Furthermore, they tended to select relatively high illuminances (mean 2297 lx) for their offices.

The research by Tregenza *et al.* is unusual because it is a behavioral study in which subjects performed visual tasks and adjusted the light levels to those they found comfortable and desirable for their work. Although the findings were not consistent with the desire to reduce levels for energy conservation, they provide information about subjects' preferences for lighting levels.

Loe, Rowlands and Watson (1982) reported a study of preferences for illuminance levels, lamp type and lighting configuration in art galleries, using semantic differential scaling and factor analytic techniques. Concerned about light levels for conservation, they had subjects view five very different paintings under a variety of light sources, light levels, and lighting distributions in a full-scale mock-up art gallery. Lighting situations included three different fluorescent sources with different color rendering properties, in addition to natural daylight. Illuminance levels ranged from 10 to 400 lux, with little variation in light distribution for the fluorescent sources (the natural daylight had a very different distribution). Subjects viewed 24 conditions (randomized) and completed fourteen semantic differential scales assessing the paintings (including general evaluation, color quality, detail quality, and light level adequacy), and seven scales evaluating the space. In the second experiment, the distribution of luminous intensity was varied using different luminaires (ranging from the fluorescent used in the first experiment, to three different spot-lighting arrangements). Two levels of illuminance on the painting were studied - 50 and 150 lux. Analysis of the data indicated that two major factors accounted for the assessment of paintings in both experiments 1 and 2 - a discriminative factor related to the ability to discriminate detail and color; and a quality evaluation factor related to the pleasure provided by the painting. Two factors also accounted for the assessment of space in both experiments - *quality* evaluation (including pleasantness, stimulation, and attractiveness of the light distribution), and *lighting* factor (related to the brightness and starkness of the space). In a third experiment, subjects completed the Farnsworth-Munsell 100-Hue test under the light sources used in both experiments 1 and 2 (except daylight).

Analysis of the data from the three experiments indicated a steep increase in quality assessment and discrimination up to illuminance of about 200 lux with a slower rate of increase to 400 lux. The spatial assessment showed a similar pattern of sharp increase up to 200 lux with a slower rate beyond. These results occurred for all sources, including natural daylight. "*as the painting illuminance is increased, there is a progressive increase in both discrimination and quality assessment where the paintings are concerned. For the space assessment test, again the quality evaluation increases with an increase of painting illuminances, very steeply below 200 lux and less steeply above 200 lux*" (Loe *et al.*, 1982, p. 188). Results for the different distributions of light did not show a clear preference for contrast or uniform illuminance pattern. Data from the 100-hue test supported the notion of classifying lamps using a color gamut[1] approach, rather than the Color Rending Index (CRI). Loe *et al.* noted that the appearance of the paintings varied extensively as the illuminance increased from 50 to 300 lux. Loe *et al.* (1982, p. 189) stated that "*In conclusion, the experiments indicate that the preferred artificial lighting conditions for viewing works of art are a painting illuminance approaching 200 lux from lamps with good color rendering characteristics, e.g. a CIE Ra index of >85 and a large gamut area. There should be a degree of non-uniformity in the light pattern within the space, which it may be possible to quantify using the ratio of average cylindrical illuminance to painting illuminance. This experimental work indicates a value of 0.3; however, further work needs to be done to explore more precisely the validity of this concept particularly considering size of space, lighting technique and wall surface reflectance.*"

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1 Discussed in Section 4.1

Preferred Illuminance Settings - Conclusions

- Subjects were able to set consistently preferred illuminance levels for office-like situation, with mean illuminance of 2297 lx.

- In an office-type situation, subjects set lighting levels such that wall luminance provided the dominant source for task illuminance, with only one-quarter of the illuminance being provided by the ceiling luminaires.

- Preference was for the wall behind person to be the brightest wall in space, and to adjust illuminances accordingly for an office-type situation.

- In an art gallery, there was a sharp increase in the assessment of quality and detail discrimination as light levels increased up to 200 lx, with a smaller increase up to 400 lx when lamps with good color rendering characteristics were used.

3.1.2 Preferred Luminance Ratios

Other researchers concentrated on evaluating preferences for surface luminances rather than task illuminance as the key to human response to a lighted space. Collins and Plant (1971) performed an extensive evaluation of preferred luminance ratios and distributions in windowless spaces. Using a 1/12th scale model, they varied the pattern and distribution of luminances on interior surfaces in a windowless open-plan office. In their initial assessment, three different configurations of lighting installation were assessed - recessed fluorescent with louvers of three different reflectances combined with opal acrylic ceiling panels; surface mounted fluorescent luminaires, and surface mounted tungsten luminaires. Observations were made by separate teams of 18-21 observers. The experiment was intended to determine the contribution of different patterns of ceiling luminance to the subjective response of the pleasantness of the character of the interior. Collins and Plant used a three-criterion method in which observers determined when ceiling or luminaire luminance was "just too low", "just right", and "just too high". Subjects first observed the interior without any additional lighting, and then used a control to adjust the luminance of the ceiling or of the luminaires to improve the appearance of the room. At the same time, detailed photometric measures of the luminances in the overall installation were obtained.

The first measure was of preferred ceiling luminance for each of three task illuminances and louver reflectances (0.8, 0.35, and 0.18). Results indicated that the distribution of preferred ceiling panel luminances were similar for the louvers with reflectances of 0.18 and 0.8 with peaks at about 125 and 175 cd/m^2 but quite different for the louver with 0.35 reflectances. The latter had a much broader distribution of luminances centered at about 150 cd/m^2 but extending well past 300 cd/m^2. A distribution of both luminance and illuminance was determined for the optimum setting of panel luminance for each value of task illuminance and louver reflectance. Examination of the data indicated that higher ceiling panel luminances were required for higher task illuminances and louver reflectances. The data suggested that preferences for ceiling brightness were determined by louver brightness. In the next portion of the experiment, Collins and Plant assessed the preferred luminance values for different lighting luminaire, both small and extended, as a function of three levels of task illuminance (500, 700 and 1000 lx). Although there was a wide spread of preferred luminance values for all task illuminances, observers indicated a preference for a lower luminance for the luminaire when there were higher illuminances on the task.

Collins and Plant concluded that when louvered or other low brightness luminaires are used, satisfaction with room appearance is greatest when the ceiling luminance is roughly equal to the fitting luminance at about 130 cd/m^2. They noted that when darker luminaires are used, ceiling luminance should be lower, but not as low as that of the luminaire; for brighter luminaires, ceiling luminance should be brighter, but not as bright as the luminaire. The range of luminances for optimum settings of illuminance for each task illuminance setting and louver reflectances were between 10:3:1 and 10:3:3, for the task luminance, immediate surround, and general environment. An important finding was an inverse relationship between preferred luminaire luminance and room luminance which suggested that "*in an environment of relatively low luminance, the occupants require brighter fittings [luminaires] to give the most pleasing effect than they do in one of higher luminances. It seems that the fitting luminance is needed to compensate for the general impression of lower brightness produced by the reduced luminances of the room surfaces*" (Collins and Plant, 1971, p. 230).

Van Ooyen, Weijgert, and Begemann (1986) conducted a study of the preferred ratios of task, working-plane, and wall luminance in a small office for several different types of task. In their experiment, three identical two-person offices were assessed by a total of 180 subjects. Lighting in each office consisted of four two-lamp luminaires. Reflectance of the working plane remained constant; wall reflectance was varied in all three rooms. The use of paint with different reflectances and luminaires with different light distributions caused wall reflectances and hence luminances to vary between 12 and 92 cd/m^2. Wall hue remained nearly constant, however. Working plane luminance was varied between 20 and 200 cd/m^2 by means of desk tops with different reflectances. Task illuminance on the working plane was maintained at about 750 lx so that a nearly constant luminance was provided for both reading and writing material.

In each office, two subjects at a time performed four office tasks - reading a magazine, writing on matte paper, using a VDT, and participating in a conference or interview. After finishing each task, they assessed the brightness of the desk top by using a 7-point semantic differential scale ranging from "too dark" to "too bright". At the end of each session, they rated each room using a 38-item semantic differential questionnaire.

Analysis of the results for preferred luminances indicated that while the preferred luminance for the walls was independent of working plane luminance; the preferred working plane luminance was related to wall luminance. Preferred wall luminance was also dependent on task type. Thus, preferred wall luminances for reading, writing, and interviewing were between 30 and 60 cd/m^2, while preferences for wall luminances for work with a VDT display (which used bright text on a dark background) were lower - between 20 and 45 cd/m^2. Preferences for desk-top luminance followed a similar pattern with preferences for reading, writing, and interviewing of 45 and 105 cd/m^2, but only 40 and 65 cd/m^2 for VDT use.

Based on the results, Van Ooyen *et al.* suggested some preferred luminance ratios. They stated that if the luminance of the visual task is fixed at 10, then the following preferred ratios of task (L_T), working plane (L_{WP}), and wall luminance (L_W) are obtained:

$$L_T:L_{WP}:L_W = 10:4:3$$

Data from the semantic scales indicated that these ratios could be modified to produce different responses. Thus, the room appeared restful when working plane luminance was increased slightly, while wall luminance was decreased for a ratio of 10:5:2. Ratios of 10:3:4, with higher wall luminance relative to the working plane luminance resulted in a perception that the room was stimulating. Van Ooyen *et al.* commented that these ratios applied to situations both with and without daylight. They concluded that "*wall luminance contributes most to the way a room is experienced. With increasing wall luminance, the room is felt to be more stimulating and it is found easier to concentrate on the task*" (Van Ooyen *et al.*, 1986, p. 104). Furthermore, using a VDT decreased the preferred wall luminance for both the wall and the working plane.

In a review of the relevant research, Hentschel (1990) discussed preferred luminance ranges for interior lighting, noting that earlier researchers had suggested that the best visual performance could be expected when the task luminance is balanced with that of the visual surroundings, typically in ratios of 1:1 to 1:3. He reviewed results from at least five earlier researchers who suggested preferences for ratios of task to immediate surround (table top) of 0.35 to 0.55; for wall to task luminance of 0.4 to 0.7 or even 1.0 (depending on the color of the wall). He suggested that a summary of the results showed that luminance relationships depended both on visual adaptation, as well as on surface reflectance and color. In analyzing the results from Tregenza's study (discussed above), he commented that the results indicated luminance ranges of about 0.85 for the ceiling to task, and about 0.53 for the wall to the task. Hentschel then discussed an earlier study of luminance ratios in a test room with 27 observers. Observers assessed the luminance of room surfaces including ceilings, walls, table surfaces and partitions, as a function of task luminance. Observers indicated when the luminances were "balanced" being neither "too dark" nor "too bright" using a five point scale. Hentschel defines the perception of "balanced" luminances as "stable". A wide range of "stable" luminances was found with a range of 0.3 to 0.7 for table to task; 0.3 to 0.6 for partition to task; and 0.1 to 0.8 for wall to task, for task illuminances of either 500 or 750 lux. Analysis of the results indicated that lower luminances were preferred in the area immediately adjacent to the visual tasks (that subjects considered this area to be part of their adaptation zone), while higher luminances were acceptable in more distance zones such as the ceiling. Hentschel noted that the results indicate considerable scope for setting luminances within a space, with the following parameters important in determining subjects' responses:

location and apparent dimension of the surface;
simultaneous contrast of surfaces;
reflectance and colors of surfaces; and
glare from windows (or other sources).

Hentschel stated (1990, p. 132) that "*These results permit luminance planning for larger surfaces according to the distribution of the task zone, immediate surroundings and middle distance within the visual field.* Furthermore, there is a "*mutual dependence within the total luminance* *configuration of the room. Thus a simultaneous contrast was found between partitions and ceiling, which exceeds significantly one grade of the bidirectional perception scale*" (p. 133). After reviewing the data collected in the various studies, Hentschel concluded (p.133) that if the mean adaptation luminance area is between about 20 and 200 cd/m^2 then the range is in the Weber-Fechner range where "*a perceived change in the brightness of one step is proportional to the same relative change ∅L of the luminance L, which is equivalent in this range to the brightness being in direct logarithmic proportion with the luminance. It can therefore be concluded that the balanced luminance range in the visual field is perceived as a defined brightness range i.e. Weber-Fechner range. A correlationship has thus been established*". Hentschel then concluded that the following recommendations could be made for practice[2] -

Immediate surroundings

Working surface to visual task	$0.7 > L_u{:}L_t > 0.2$
Partitions to visual task	$0.7 > L_{pw}{:}L_t > 0.2$
Walls to visual task	$0.7 > L_w{:}L_t > 0.2$

Middle apparent distance from the task:

Ceiling to visual task	$3.0 > L_D{:}L_t > 0.2$

The absolute upper limits should be set according to the glare limit of light reflected from ceilings and limitation of VDU reflections". Furthermore, "*Higher luminance ratios in the visual field are more disturbing in the side and lower areas than in the upper areas* (p.134)" - an experience which is contained in Hentschel's proposed recommendations. Questions that remain to be answered include whether preferences are determined primarily by lighting on the task surface, the vertical surfaces, or all room surfaces? What is the role of the ceiling, the floor, etc.

Luminance Ratios - Conclusions

- Suggested luminance ratios for desk, immediate surround, walls, and ceiling which are likely to produce positive psychological effects:

Surface	Ratio	Psychological Effect
Desk:Surround	2:1 or 3:1	Preferred
Desk:Surround:Wall	10:4:3	Effective
	10:5:2	Restful
	10:3:4	Stimulating

2 Here, L_t = task luminance; L_u = working surface luminance; L_{pw} = partition wall luminance; L_w = wall luminance; and L_D = ceiling luminance.

3.2 Lighting Distribution

An early assessment of the effects of variation in lighting distribution on the psychological response to a space was conducted by Flynn (1977). In this evaluation, Flynn evaluated two non-uniform modes, in which two zones of the room (one small and one equal to the central area) were unlighted for the central overhead configuration, with this pattern being reversed for the peripheral overhead configuration. Eight groups of 10 subjects each participated in the experiment which used semantic differential ratings. In the central condition, the lighting system was an overhead fluorescent (cool white) luminous ceiling with a luminance of 340 cd/m^2 (and 2.1 watts/ft^2) which provided an illuminance on the desk of 520 lux. For the peripheral condition only two luminous ceiling areas were lit which provided a ceiling luminance of 188 cd/m^2 (2.4 watts/ft^2) and a desk illuminance of 520 lux. Flynn found that the "central overhead" mode of lighting received higher ratings of spaciousness and clarity compared with the "peripheral overhead" design, even from people who were sitting in the darker portion of the room. Flynn noted that "*this suggests that the central overhead mode would apparently be the better non-uniform design approach when general impressions of clarity and utility are desired; while an overhead system that leaves the center of the room relatively dark will be perceived as less clear and distinct*" (1977, p.12). Flynn stated further that lighting can be used to cue different types of subjective impressions such as clarity, relaxation, or spaciousness. Overhead lighting seems to elicit the most favorable response for achieving impressions of utility and general clarity. Furthermore, non-uniform overhead systems that light the central portions of the room appeared to be more effective than overhead systems that permit noticeably lower light levels in the central area. When luminance in the central area was reduced, so was the impression of clarity. Use of wall lighting produced favorable evaluative and spaciousness impressions. Flynn commented that subjective ratings seemed to correlate more with the pattern of light than with precise physical measures of luminance.

Variation in light source position obviously affect the distribution of luminances within a room, and of course, the appearance of the room. One problem in assessing these luminance effects lies simply in the measurement of the distribution itself. In the traditional approach, numerous spot luminance measures are taken, a tedious, time-consuming, and somewhat imprecise process. To facilitate this process, Rowlands, Loe and Brickman (1984) developed a scanning photometer using a V_λ corrected silicon photodiode in a motorized cradle for measuring luminance distributions in a particular field of view. They noted that such measurement capability is essential for evaluating the relationship between the luminance and perceived brightness of a space, as well as between discomfort glare and luminaire luminance, and between perceived lighting quality and luminance patterns within an interior. Their scanning photometer, which is connected to a computer for data collection and analysis, can scan a field of view and measure the pattern of luminances during one measurement period. It can take 7200 luminance values in a field of view (about 144° azimuth, and 162° elevation, or an area in excess of normal human binocular vision). Luminance distributions and frequency histograms can be created and then compared with subjective response or other types of data. The authors commented that "*this instrumentation, therefore, can provide sufficient data for many types of analysis: it is hoped that it can provide a method for quantifying lighting quality. It is possible that the instrument could be used for other research projects requiring luminance distribution measurements, e.g. discomfort glare and visibility*" (Rowlands, *et al.*, 1984, p. 189). Rea and Jeffrey (1990) described a similar type of scanning photometer which uses a charge-coupled device (CCD) video camera as the detector. This instrument also provides the capability for measuring light distributions in real spaces.

Rowlands, *et al.* stated that their previous research suggests that users of a lit space prefer a certain degree of non-uniformity in the patterns of luminance for a space to be visually pleasing. This may be achieved with lighting, or with a combination of variation in lighting and surface reflectances. Although their work has "*indicated user dissatisfaction with a high degree of luminance uniformity, it has not been possible so far to identify the degree of non-uniformity preferred or the point where the non-uniformity becomes excessive, and therefore unacceptable. It is believed that this is because detailed information about the luminance pattern has not been available*" (Rowlands *et al.*, 1984, p. 187). In their succeeding studies, Rowlands, *et al.* used the scanner to measure luminance distributions in real spaces.

Rowlands, Loe, McIntosh, and Mansfield (1985) conducted a series of studies which attempted to relate subjective response to physical lighting conditions by using semantic differential scales. They were concerned with questions about the physical features of a lighting system that determine its acceptability: task illuminance, illuminance uniformity on a horizontal plane (particularly the task), pattern of light on surfaces (particularly vertical surfaces), brightness of the luminaire, or some combination of features. The research was aimed at increasing knowledge of the physical parameters that can predict response to a lighting installation to make it possible to design better installations. They began with a full-scale mock-up of a typical office (4.6 x 3.1 x 2.4 m) in which lighting parameters such as down lights, side panels, wall washing, surface luminaires, and task illuminances could be varied. Reflectance of the room surfaces was relatively high. The arrangement of luminaires made it possible to change the luminance of the luminaires, as well as the amount of light directly on horizontal planes and vertical surfaces. Sixteen lighting conditions were assessed by 16 observers using 19 semantic differential scales. Scales included questions related to: lighting in the room, lighting of the task, pattern of light in the room, room characteristics, and perception of other people. Physical measures included vertical and horizontal illuminance, as well as a series of luminance measures from which average luminance in different parts of the visual field could be derived.

Rowlands, *et al.*, also made similar physical measures and subjective assessments in four actual offices lit with different lighting configurations. In this assessment, ten observers assessed the lighting installation from three positions within the office. Results from this evaluation indicated a strong correlation between the adequacy of the task lighting with horizontal and vertical illuminance and the average luminance directly in front of the observers. The authors concluded that the 'brighter' the appearance of the space, the more adequate the lighting is perceived to be. Furthermore, horizontal illuminance, average vertical illuminance, and average luminance of the whole view were highly correlated with each other and with perceived lighting adequacy, as well as with the overall 'brightness' of the space. The authors commented that some of the correlation may have been due to high surface brightnesses in a relatively small space, since they did not find a strong correlation between lighting adequacy and luminaire luminance. Other results indicated that as the luminance of the area of binocular vision increased, so did the assessment of lighting quality except when the luminaire luminance exceeded 8000 cd/m^2. This latter situation was considered 'glaring'. The most preferred installation types included those using wall-lighting luminaires, while the least preferred were those rated as 'dim' which also had low values for luminance in the area of binocular vision. Rowlands *et al.* (1985, p. 35) stated that "*these results are tending to show that the fairly central areas of the visual field are more important in terms of visual preference than the whole field or the vertical illuminance at the viewing position.*"

Results from the companion study of office lighting also indicated a strong relationship between lighting adequacy and horizontal illuminance and average luminance of the field of view. Installations providing a horizontal illuminance greater than 800 lx were considered to have slightly too much light, while installations considered *bright* had at least 'adequate' lighting for the task. Pleasantness and attractiveness were correlated with luminance in the binocular and whole field of view. The most preferred installation used recessed low brightness luminaires while the least preferred had surface-mounted prismatic luminaires. Rowlands *et al.* commented that their results indicate the importance of *surface lightness* of the interior in providing adequate lighting. In addition, luminaire luminance by itself did not bear much relation to lighting adequacy - with some preference for low brightness luminaires, as long as vertical surfaces were not dark. There was an indication in the scale model study that the average luminance in the binocular field of view was strongly correlated with pleasantness and attractiveness, while the field study suggested that the luminance pattern in this area might be more important. Rowlands *et al.* (1985, p. 37) concluded that: "*For a lighting installation to be successful - considering both adequacy and quality, there is some evidence that it should be subjectively bright with particular reference to the central region of the field of view: however, the brightness should be provided by lit surfaces and not by bright luminaires. Further, there should be some variation in the brightness pattern to create interest and attractiveness: this will be dependent not only on the design of the space and considering in particular the size and position of surfaces and their reflectance, color and possibly texture.*" They noted that the luminance scanning device described above was developed in parallel to define the pattern of luminance in the field of view more precisely.

In a recent extension of this research, Loe, Mansfield and Rowlands (1991) explored the effects of variations in luminance patterns on subjective assessments made of a small conference room by 12 observers. Loe *et al* stated (1991, p. 41) that "*It has long been understood that lighting, in addition to providing the means to accomplish a task, can provide a quality to the visual environment which induces a feeling of well-being and a feeling of comfort and security...a particular aspect of the perception of the lit environment is to do with the sensation that there is sufficient light, particularly related to the activity or space type. Usually this aspect of lighting is considered with regard to the amount of light on the task, i.e., the task illuminance: however, there are many examples where apparently an appropriate amount of light is provided and yet the occupants complain of an insufficient amount of light.*"

To evaluate the effects of light patterns and relate these to physical measurements, Loe *et al* constructed a room which resembled a small conference room - 6m x 4.1m x 2.9m - which was lit in 18 different ways. Loe *et al* conducted three experiments in which the impact of very different approaches to lighting the space were evaluated. In these experiments, each of twelve observers assessed each lighting configuration using a set of semantic differential scales. Each observer viewed the lit room from a fixed opening in the center of one of the walls.

In experiment 1, the luminance was provided by banks of luminaires placed at the side walls surrounding the center opening. Because these lamps were attached to dimmers, the amount of light could be varied without dramatic changes in the relative pattern of the light. In this experiment, luminance ranged from 5 to 372 cd/m^2. In the second experiment, the lighting system was varied from completely peripheral to completely overhead, by adding wall washers, spotlights, uplighters, as well as overhead luminaires to the vertical lighting studied earlier. Illuminance on the conference table was maintained at 300 lux. In experiment 3, only the luminaires located over the center table were used and the uniformity of the lighting pattern varied, all while maintaining an illuminance of 300 lux on the center of the conference table.

In the experiments by Loe, *et al*, the luminance distribution from the position of the observer was measured using a scanner developed at the Bartlett School of Architecture in London. Individual luminance measurements were made for circular areas covering about 0.8 milli-steradians, with a total measurement area of approximately five steradians. The authors calculated luminance values from these measurements, including average luminance, luminance range, and some luminance contrast measures. In addition they obtained ratings on 10 semantic differential scales. Analysis of the semantic differential data indicated two main factors responsible for the subjective assessment. These included "interest" which appeared to be related to lighting uniformity; and "brightness" which seemed to relate to gloominess and spaciousness. Inspection of both sets of data revealed that lighting installations which were considered to be "interesting" had more non-uniform lighting which was typically provided by two lighting systems (such as spotlights and over-table lighting; spotlights and uplighting; or wall washing and over-table lighting). Those seen as less "interesting" had uniform lighting (and often a low light level as well.) Installations seen as "bright" had a uniform pattern of light at a high level or a noticeably bright surface in the field of view. Further evaluation of the data indicated that installations that were evaluated as "bright" had average luminances of 100 cd/m^2 or greater in the central 40° field of view. The "interest" factor could be related to a ratio of the maximum to minimum luminances within the central 40° band. Loe, *et al's* data suggest that this ratio must be at least 15 for the lighting to be acceptable. Loe, *et al* cautioned that their data apply only to office-type spaces with reasonably high surface reflectances (their space had wall and ceiling reflectances of 0.88-0.89). Although further work remains to be done to explore maximum levels of brightness and luminance contrasts within the field of view, the research by Loe et al represents a promising start.

Bernecker (1980) discussed the potential for improving lighting design by using luminance data and by considering the whole space, stating (p. 8) that "*The concept of a total visual environment implies design that accounts for the light distribution and intensity on all surfaces within an architectural space. The obvious quantity of light to use in this respect is luminance - obvious because it is a measure of the lighted character of a surface that accounts for the incident light and any special reflectance on transmittance properties*". In reviewing Flynn's work, Bernecker (1980) noted that Flynn had identified different subjective impressions that were fairly reliably elicited by different characteristics of lighting systems. These included four lighting modes: overhead/peripheral, uniform/non-uniform, visually warm/cool, and bright/dim. Each mode appears to elicit different responses such as visual clarity, spaciousness, relaxation, privacy/intimacy, and pleasantness/preference. Since the modes are not defined specifically, Bernecker commented that "*If somehow these modes could be more specifically defined through the use of luminance in a room, it appears that a direct quantifiable relationship between* *subjective impressions and luminances would also exist*" (p. 9). Because the eye does not see luminance but brightness, Bernecker suggested translating luminance data into brightness data. ("Brightness" is determined by physical luminance and the observer's adaptation state.) Bernecker then used a formula developed by Marsden to compare luminance to brightness. This formula relates brightness to a ratio of luminance to maximum luminance.

Bernecker then converted luminance calculated by a computer program to brightness using the Marsden formula. His next step was to generate a contour plot of each surface in the room, and correlate these with Flynn's lighting modes. Subjects then rated the three lighting systems for which contour plots were developed, using bipolar rating scales. The three lighting systems were chosen to represent the overhead/uniform, peripheral, and non-uniform/peripheral modes. Subjects, in fact, used the bipolar scales in accordance with these modes and also sketched the luminance distributions. Bernecker commented that the resulting contour plots appeared to represent what the subjects see, and offer the potential for a useful design tool. Thus, providing contour plots of luminance in a computer graphics approach would allow different lighting designs to be simulated and evaluated rapidly.

In a very different type of approach to studying the preferred distribution of lighting, Inui and Nakamura (1987) theorized that the natural environment may provide clues for optimizing lighting distributions even inside buildings. They therefore measured the range of luminances available in a variety of scenes, including both natural and artificial (with manmade elements) scenes, using a projection camera with color image processing. This procedure was used to create luminance distributions for a visual angle of about 0.65° for 22 photographs.

Luminance contours and frequency distributions were obtained for each photograph. Inui and Nakamura pointed out that the frequency distribution for a natural (mountain) scene formed two different, but well-ordered and approximately normal curves. Yet, the luminance distributions observed for three scenes with man-made (artificial) elements did not form such regular and apparently stable curves. In addition, when luminance ratios between adjacent scenes were calculated, a greater frequency of ratios in excess of 2.3 was found for an artificial scene as compared with a natural scene. Luminance ratios for artificial scenes also tended to be bimodal - either identical or very different (typically 1 or 2+). Inui and Nakamura (1987, p. 180) stated that "*the average of all the luminance ratios between the two adjacent small areas in a picture indicates the harshness (or the flatness) of the total brightness pattern. This may safely be called the contrast. The exponent of a power function, n, indicates the steepness (or the gentleness) of the slope of brightness, which is, in other words, the spatial distribution of the contrast.*" Use of this approach demonstrated that natural scenes tend to have contrasts less than 1.2 and power function exponents, n, around 3 indicating weak contrasts and gentle spatial distributions of the contrast. Artificial scenes tended to be have greater contrasts, or steeper slopes - or both. Inui and Nakamura (1987, p. 181) suggested that "*contrast and spatial distribution of contrast seem to be two key indices for assessing the feeling of the brightness pattern*". They noted that their approach might provide a fruitful method for evaluating luminance patterns in interior environments.

Luminance Distributions - Conclusions

- Variations in luminance distribution have a marked effect on the overall appearance of space both in terms of brightness and interest.

- Scenes considered *bright* have high surface luminances (above $100 cd/m^2$) in the central field of view (rather than simply having luminaires with high luminances).

- Luminances above $800\ cd/m^2$ are considered *glaring* rather than *bright.*

- Scenes considered *interesting* have variations in the brightness pattern (discussed in terms of the ratio of maximum to minimum luminances) with non-uniform lighting distributions in the central 40° field of view.

- British research at Bartlett paralleled US research at Penn State in determining that lighting moods/perceptions such as bright/dim, uniform/non-uniform, and overhead/peripheral can be reliably elicited by specific variations in the luminance distributions. Use of scanning photometer for measuring luminance distributions was initiated at Bartlett.

- Japanese research suggests that artificial luminance distributions tend to have much higher contrasts as well as a greater spatial distribution of such contrasts than natural scenes. Comparison of luminance contours and frequency distributions for natural and man-made scenes suggests a promising methodology for evaluating the response to interior illuminated environments which should be researched further.

3.3 Task Lighting

The lighting designs discussed so far in section 3 have generally been overhead systems rather than task or desk mounted lamps. Yet the use of task or task/ambient lighting is increasing partly because it allows overall illuminance levels (and lighting power density) to be reduced while allowing users some control over the level and location of the lighting system in their immediate areas.

Using a four person simulated office, McKennan and Perry (1984) evaluated the response of 30 office workers to ten different types of lighting installations. Nine of the installations involved different types of commercially available task lighting (excluding furniture mounted) systems with an indirect ambient lighting system. The tenth installation was a direct fluorescent system. Task installations included five desk standing or mounted luminaires, three ceiling mounted luminaires or downlights, and one wall mounted fitting, or as the authors classified them - six local, three localized, and one uniform lighting system. (The local systems included the desk and wall mounted systems; the localized systems included the ceiling mounted systems.) Where possible 200-250 lx was provided as background illuminance, while 500 lx was provided on the task itself. Eight draughtspeople and 22 general office workers participated in the experiment. In addition to performing routine office tasks, they completed a subjective evaluation of each lighting installation and two visual search tasks, as well as 35 semantic differential scales.

Analysis of the comments about the lighting systems indicated that comments about sufficiency, evenness and lack of shadows were made more frequently for the uniform and localized systems than for the local systems. When all subjects rank ordered the lighting systems, two localized systems were among the highest ranked while four local systems were among the lowest. These latter included three desk mounted luminaires. No significant correlation was found between test performance and illuminance on the desk although there was a negative correlation between one test performance measure for draftspeople and satisfaction with the lighting system. The final portion of the experiment involved a comparison of the most favorably rated installation (two ceiling suspended luminaire each with 1200 mm 40 W *white* fluorescent lamps as the source) versus that configuration plus 3 x 180 mm 75/85 W *white* fluorescent lamps in ceiling mounted luminaires with prismatic diffusers. Although the results were similar for both systems, subjects were consistently more satisfied with the direct system when forced to choose between the two.

Localized task lighting appeared to be a reasonable alternative to uniform lighting with people being about equally favorable to both, but reacting to local installations less favorably. McKennan and Perry (1984) remarked that the illuminance ratios for the local systems were outside the recommended practice. In addition, the local systems were located on the desks and created some clutter. When subjects were forced to choose between lighting systems, they preferred the direct uniform installation, but there was no difference in their ratings of the direct and indirect background lighting. The authors concluded that a task/background lighting scheme could be effective providing that it was carefully designed.

Using a mixture of attitudinal and behavioral methods, Boyce (1979) conducted a study of occupant attitudes toward different types of task lighting. Ten users assessed four different types of task lighting and two types of ambient lighting. This assessment revealed a clear preference for an adjustable fluorescent lamp. Subjects commented that it provided good luminance uniformity, with no glare or flicker in a very flexible arrangement. This lamp was then evaluated by 20 subjects in a variety of performance tests and subjective assessments. Subjects selected the illuminance they preferred for different tasks such as reading, collating information, referring to documents, and viewing Landolt rings. Median illuminance for the tasks ranged from 800 to 1200 lx. (The background lighting provided about 150 lx in the space.)

Boyce observed that subjects adjusted the positioning of the lamp as a function of the task, with a mean height of about 400 mm for the Landolt ring task and about 500 mm for the easier tasks. Subjects had no trouble adjusting the lamp to a comfortable position except for reading from a glossy magazine. Veiling reflections from the glossy page proved to be a problem for this task. Performance on the Landolt ring test was in the range expected from practiced subjects. Answers to questions about the task lighting revealed generally positive ratings. Subjects indicated a general willingness toward working at a desk with task lighting, finding it to be quite satisfactory. They agreed that the balance between task and background lighting was suitable, and that the uniformity of lighting on the desk was satisfactory. Glare and flicker were not considered to be problems.

Boyce (1979, p. 163) commented that these data "*provide a number of pointers to what are likely to be necessary conditions for local lighting to be acceptable*", with uniformity of the luminance distribution being one of the most important, followed by flexibility of positioning. He noted that a uniform area of about one square meter appeared to be required with lower luminances prevailing outside this area. Control over light output was another important consideration--one that appears to require individual dimming and switching control as well as positioning. Boyce noted the importance of a good balance between overhead and task lighting with background illuminance around 150 lx likely to be satisfactory. Choice of light source showed advantages and disadvantages for both incandescent and fluorescent lighting. Two problems that arose were the finding of some users to position the source to minimize glare to themselves--but possibly cause glare to others in the office, and veiling reflections. Boyce noted, however, that despite all these recommendations, a strong preference for task lighting did not emerge from his subjects.

In a more recent study, Inui, Nakamura, and Lee (1989) evaluated lighting designs, including task lighting, to provide high quality lighting for open plan offices with VDT's. Three types of lighting systems were evaluated - conventional general lighting with nearly equal illuminance in all parts of the offices; general lighting using special louvers to send light downward to limit glare on VDT screens, and a combination of task and background lighting. Inui *et al.* evaluated the psychological effects of the three systems in terms of perceptual response to 1:15 scale models and luminance distribution data in the models. Twenty-two different lighting configurations that were variations of the three major systems were assessed. Illuminance on the desk top was maintained at about 1000 lx for all lighting configurations.

Twenty-nine observers assessed each installation on 13 semantic different rating scales. About half the observers were lighting specialists. Factor analysis of the semantic differential data indicated three factors: brightness, based on *bright, cheerful, spacious*; comfort based on *comfortable to be or work in*; and variation. The authors subdivided the 22 lighting configurations into 6 subgroups including various types of task and background lighting, general lighting, and general lighting for VDT's.

Analysis of the results indicated that the situation using task lighting with or without minimal background lighting appeared dark and was rated as mediocre for comfort. Use of higher task and background lighting resulted in somewhat brighter perceptions and higher ratings of comfort. Although the four conventional lighting systems were all rated as *'bright'*, only the system with ceiling recessed lighting with mirrored louvers resulted in the perception of a *'comfortable'* environment. Each of the two task and background lighting situations was considered to have good variations, while the four general lighting systems were considered to have small or no variation. When Inui, *et al.* attempted to relate the ratings of variation in luminance distributions, they found no straightforward relation between wide variations in luminance and perceived variations. Thus the office with conventional lighting actually had the widest variation in luminance, but was considered monotonous. Inui, *et al.* theorized that this occurred because people were used to it. They noted that scores for comfort increased from general lighting to general lighting for VDT's to task/background lighting. As a result, they concluded that task/background lighting is the best lighting for today's offices followed by general lighting for VDT's. They suggested that the use of conventional general lighting should be re-thought for modern offices where VDT's are used.

Task Lighting - Conclusions

- Conflicting results have been obtained about the desirability of task and ambient lighting with both negative and positive perceptions of task lighting.

- Unbalanced luminance distributions with extreme differences between task and surround luminances cause very negative reactions.

- Perceived brightness of the work place is an important component of lighting satisfaction, and is importantly affected by the mix of task and ambient lighting. Data from field studies reinforce the notion that control over task lighting is desired.

3.4 Glare

While extensive research has been done on the performance decrements associated with glare (which are really outside the scope of the present document), relatively little research has been done on the purely psychological effects of glare. Both the Commission Internationale de l' Eclairage (CIE) and the Illuminating Engineering Society of North America (IESNA) have developed predictive glare indices, in the form of the unified glare rating (UGR) and visual comfort probability (VCP), but these are intended to rate fixtures and predict glare, rather than predict the psychological response to glare. To assess the latter effect, Kanaya, Manabe, and Narisada (1987) evaluated the effects of glare and discomfort on the psychological perception of an interior office space. For their investigation, they used a full-scale, windowless model of an office, with two different groups of luminaires. One group of luminaires generated different patterns of glare, while the other maintained illuminance on the horizontal plane at a fairly constant distribution. The groups of luminaires providing the glare produced viewing angles of 49°, 70°, 77°, 80°, and 82°. Two different types of luminaires were simulated - those with luminous sides and ones without. This allowed six of the CIE glare limitation configurations to be reproduced. The glare sensation produced by these different configurations was evaluated for two illuminance levels, 250 and 1000 lx, measured 0.8 m above the floor.

Kanaya, *et al.* had 61 observers evaluate twelve experimental conditions. Five to six observers at a time viewed the model from the front and rated their impression of the room on 13 seven-point semantic differential scales. Kanaya *et al.* concentrated on the two most extreme glare configurations for their analysis, comparing the effects of the luminaires without sides to those with sides, for the two illuminances. Analysis of the profiles of the response to the semantic differential scales revealed that different pairs of adjectives could be related to either the illuminance level or the glare condition. Observers, for example, tended to choose the words *beautiful, comfortable, and clean* when the illuminance levels rose, but as the luminaire became more glaring, they chose words such as *hard, violent, and tense*. Glare level had no effect on the words chosen to describe illuminance. A factor analysis of the data extracted two factors. The adjectives could be divided into three groups - one with high loadings for the first factor, but low for the second; one with low loadings for the first factor but high for the second; and one with moderate loadings for both factors. The first factor was characterized as *comfort*, while the second was characterized as *psychological tenseness*. Kanaya, *et al.* noted that the first factor contributed much more to the subjective assessment of the room. They concluded that illuminance had a greater effect on *comfort* than did luminaire luminance, while the latter had a greater impact on *psychological tenseness*. Of interest 1000 lx was consistently rated as *brighter* than 250 lx with some reduction in assessment for the different luminaire types.

Psychological Response to Glare - Conclusions

- Light sources considered to be *glaring* produce sensations of psychological tenseness

- Physical factors which contribute to the sensation of discomfort glare include:

    - Lack of balance between light source and surround brightness

    - Displacement of the source from viewing direction

    - Number and size of sources (including windows)

3.5 Dynamic Lighting

In the research reviewed so far, the discussion has centered on the psychological effects of changes in a lighting distribution in space. The systems evaluated have tended to be relatively static lighting systems in which there was little change in the lighting level or distribution over time. These systems also tended to be regular in spacing as well so that the resulting lighting is uniform and non-dynamic.

Nevertheless, a few researchers have examined the effects of dynamic changes over time in more conventional interior lighting. Aldworth and Bridgers (1971, p.8) challenged the idea of providing purely uniform lighting in work areas, saying that "*general lighting has always been open to criticism for the flat, uninteresting appearance it provides. Close spacing of luminaire to provide the higher illumination values being called for today only increases the uniformity and flatness of the lighting*". They suggested that the time had come to design variety into lighting to maintain alertness and reduce monotony and defined *Variety* as the "*absence of monotony and uniformity*". Aldworth and Bridgers used the concept of pervading luminance in which light flows within an interior to characterize dynamic (or varied) lighting distributions.

Aldworth and Bridgers created a lighting installation in which the effects of both static and dynamic lighting could be assessed. The static lighting (200-250 lx) was provided by recessed fluorescent luminaire with louvers, while dynamic lighting was provided by fluorescent lighting on 3 walls and a random array of tungsten lights. The dynamic lighting was controlled by a series of dimmers which randomly varied the lamps. Nine office workers participated in a series of eight tests of the lighting. The data analysis revealed no significant differences in the performance of a visual task for the two lighting systems, although both the work rate and the percentage of errors improved slightly under the varied lighting. The workers also rated the lighting system as they finished each of the eight tasks. They tended to rate the varied lighting as "good", "comfortable", "pleasant", and "cheerful". Aldworth and Bridgers (1971, p. 15) commented that "*it has been found in earlier experiments by others that the measurement of* *differences in work rate and accuracy is seldom rewarding and that subjective tests provide a more sensitive means of indicating change*".

In another assessment of the dynamic effects of lighting, Taylor, Sucov, and Shaffer (1975) had 77 subjects perform an addition task under three different types of lighting; uniform fluorescent, non-uniform incandescent, and psychedelic lighting (a combination of incandescent, flickering pendant, rotating shade, and christmas tree lighting). The results indicated no difference in addition accuracy between the lighting conditions and slight (but non-significant) trends in addition speed, with the non-uniform lighting showing slightly better results than either the uniform or the psychedelic responses. Taylor, *et al.* also had their subjects perform a secondary task in which they responded to one of two randomly lit red lamps. Thus, subjects had to look up from the addition task to see the lamps. Although not all subjects did the secondary task, the data indicated slightly better performance for those who did under the non-uniform lighting system than the other two systems. Analysis of the semantic differential rating data indicated that the nonuniform lighting condition was rated as more unsociable. Taylor, *et al.* concluded that office work performance could be increased by using a non-uniform lighting system; although the data they presented to support their contention were only trends that were not statistically significant. The only information given about lighting levels in the experiment was that 1506 lux were provided on the desk in all test conditions.

Of course, conventional office lighting systems are often supplemented by windows which do provide variation in lighting over both space and time as the sun moves and sky conditions change. Their benefits will be addressed in section 5.3.

Dynamic Lighting Conclusions

- Temporal variability and dynamic change in lighting seem to be preferred, at least up to a point.

- Questions remain about the extent and desirability of dynamic variability particularly the addition of potentially distracting light sources within the field of view.

4. Response to Light Source Characteristics

In the preceding sections, the psychological response to a lit environment has been discussed in terms of lighting levels, position, and distribution, both in space and time. Other important subjective responses to lighting include the perceptions of visual *clarity* and *colorfulness* in an interior space - both related to the spectral properties of a light source as well as to its intensity. Still another set of important perceptions are *sparkle* and *clarity* related to the position and sign of a light source. Research into these psychological responses will be discussed in section 4.

4.1 Visual Clarity

Aston and Bellchambers (1969) evaluated a concept they termed "*visual clarity*" related to the color rendering of a lamp. In their experiment, observers determined the "*visual clarity*" of two scenes placed side by side. One side was lit by a high-color rendering lamp while the other was lit by one of several commercially available fluorescent lamps with poorer color rendering. Observers adjusted the illuminance of the lamp with the poorer color rendering to provide equal *visual clarity* as the scene lit by the high-color rendering lamp. The results indicated that the latter lamp always was judged to provide better visual clarity, and was typically set at lower illuminances than the comparison lamps. Bellchambers and Godby (1972) found similar results for an experiment with a set of light sources with a wider range of color rendering. They claimed that higher efficacy sources with poorer color rendering have to be set at illuminances some 25% higher than lamps with higher color rendering to achieve similar "visual clarity" and satisfaction. They stated that "good color rendering lamps not only provide better color rendering but give a higher degree of visual clarity than do high efficacy lamps at equal values of illuminance" (Bellchambers and Godby, 1972, p.106). Aston and Bellchambers also commented that the more similar a light source is to daylight, the better visual clarity it will provide, although they conducted no experiments to test this hypothesis.

DeLaney, Hughes, McNelis, Sarver, and Soules (1978) examined visual clarity noting that the side by side viewing technique used by Aston and Bellchambers introduces the problem of chromatic adaptation in which observers are adapted to neither source. They had observers perform several different tasks, including a color discrimination task using the Farnsworth-Munsell test, a subjective appraisal test using 14 rating scales, visibility measurements using an Eastman visibility meter, and performance measures using pairs of letters for lamps of different color temperatures. Their results indicated that observers tended to prefer lamps with cool white color temperatures for assessments related to clarity and brightness, but found lamps to be equally satisfying regardless of color temperature. Although Delaney *et al.* suggested that observers rate visual clarity differently from satisfaction, they did not find any evidence of improved performance or greater preference for a prime color type of lamp. Thornton and Chen (1978), however, defined visual clarity in terms of distinctness of detail. They presented a model which explained why prime color lamps should result in greater visual clarity. Worthey (1985) evaluated the visual clarity of black and white objects under different illuminants and found a slight tendency for these objects to have greater visual clarity under higher color rendering lamps.

In an experiment which extended some of the visual clarity results, Boyce (1977) assessed the balance between illuminance and lamp color properties on satisfaction with the visual appearance of an office interior. Using a 1/12th scale model, he examined the effects of illuminance, source type (lamp color) and interior colorfulness on the appearance and illuminance of an open plan office. Three lamps (common to the UK at the time of the experiment) were used, "White", "Natural", and "Kolor-rite", with Color Rendering Indices (CRI) of 56, 85, and 95, respectively and correlated color temperatures (CCT) from 3500 to 4000K. Three levels of interior colorfulness were used - high, medium and low (with correlates in Munsell space given for each color) while two levels of illuminance were used - 350 and 600 lx.

The scale model was divided into two offices by a vertical wall, each with the same arrangement of furniture and amount of interior colorfulness, but different lamp types. In the experiment, individual subjects sat with their head in the model itself and viewed one office at a time. Subjects first rated the appearance of the first office on a set of 34 seven-point semantic differential scales. Second, they rated the pleasantness and colorfulness of the interior as well as their satisfaction with illuminance level and clarity of detail for both offices. Third, subjects adjusted illuminance in the second office until it matched the first office in visual appearance. The first office was set to one of the two standard illuminances. Subjects followed these procedures for both standard illuminances with one level of interior colorfulness and one type of lamp. A total of 144 subjects were used in 12 conditions.

Boyce reported the illuminances obtained when the two offices were set to be equally satisfactory in visual appearance in terms of a ratio between the lamp illuminances in each office, rather than absolute illuminances. Analysis of these data indicated no significant differences due to office location (left or right with the same lamp type). Significant differences, however, were obtained for all other lamp type combinations. There was a significant difference in illuminance settings at the high colorfulness conditions but not the medium or low conditions. The major factor, however was lamp type. The office interior lit by either the *Natural* or *Kolor-rite* lamps was matched as having an equally satisfactory appearance as the same interior lit by a *White* lamp, but at an illuminance level about 25% lower. Analysis of the data also indicated that illuminance produced a significant effect on rated pleasantness, with higher illuminances producing a more pleasant interior. Similarly, rated colorfulness was greater for higher illuminance. The highest degree of internal colorfulness was also rated as most colorful for all lamps as well. In addition, the *Kolor-rite* lamp gave significantly higher ratings of colorfulness than the *white* lamp. Boyce (1977, p.15) summarized these effects as follows: "*illuminance, interior colorfulness and lamp type all affect ratings of colorfulness; the higher the illuminance, the greater the interior cheerfulness and the better the color properties of the lamp, the higher will be the ratings of colorfulness*". Boyce also found that while higher illuminance was more satisfactory, the two lamps with the higher CRI were rated as more *satisfactory*, as well as having greater visual clarity at the standard illuminances. The rating scale data further confirmed that illuminance plays an important role in determining satisfaction with an interior's visual appearance. Thus, use of a 600 lx illuminance produced ratings which indicated that the offices were more pleasant and colorful, that satisfaction with illuminance was greater, and that details were more visually distinct.

Boyce questioned why CRI should be strongly correlated with the results. He suggested instead that the Color Discrimination Index (CDI), which is a measure of color differences in a set of colors, might be a better predictor. The CDI provides an estimate of *gamut area* or a measure of the color differences among a set of colors lit by a specific light source. With bigger gamut areas, color differences are greater, and so are the saturations of individual colors. Boyce commented that the saturation of colors and hence the gamut of colors lit by the *white* lamp with both a lower CRI and CDI is less than that for the *Natural* lamp. As a result, it is reasonable for the *white* lamp to match the *Natural* lamp at a higher illuminance since this increases the saturation of the colors and thus should provide both interiors with about the same range of color differences. To test this hypothesis, Boyce conducted a short study using a *Grolux* lamp which has a very low CRI (9) but very large Gamut Area. Results for twelve subjects for this lamp indicated that the office interior was in fact rated as more colorful with greater clarity of detail than the interior with a *Natural* lamp. These results support the contention that CDI rather than CRI was the relevant variable, since the *Grolux* lamp produces large color differences but has a low CRI.

Next Boyce assessed the effects of lamp type on the perception of achromatic interiors. In this experiment, lamps varied in CRI, CDI, and correlated color temperature (CCT). Along with the *Kolor-rite* (CRI = 92, CCT = 400, large Gamut Area) and *White* (CRI = 56, CCT = 3500, small Gamut Area) lamps, two other lamps were added. These were a *Northlight* (CRI = 95, CCT = 6500, large Gamut Area) and *Daylight* (CRI = 65, CCT = 4300, small Gamut Area). Two illuminances were again used as the standard, 300 and 600 lx, along with achromatic and chromatic color schemes. Sixty subjects participated in five groups, seeing both colorfulness and illuminance conditions but only one pair of lamp combinations. Subjects completed the rating scales and illuminances adjustments as before, but answered a short questionnaire describing the appearance of the offices instead of using semantic differential scales.

Boyce evaluated the illuminance settings in terms of the ratios obtained when the two offices were matched for equal satisfaction with visual appearance. Analysis of the results for the chromatic interiors indicated that as before the 600 lx condition was rated as more pleasant for all lamps. There was an interaction with illuminance level with the two lamps with larger Gamut Areas and higher CRI (*Kolor-rite* and *Northlight*) being rated as more pleasant than the other two lamps at the 300 lx condition. Interiors lit by the Northlight and Kolor-rite lamps were also viewed as more colorful and as having greater visual clarity. Satisfaction with illuminance increased for all lamp types, except *Kolor-rite* as the interior illuminance increased raised from 300 to 600 lx.

Analysis of the results for the achromatic interiors were less straight-forward and more difficult to analyze. Significant results were obtained for the illuminance ratios, particularly for the *Kolor-rite/white* and *Kolor-rite/daylight* combinations. Interiors were rated as significantly more pleasant for the *Kolor-rite* and *White* interiors at 600 lx than 300, with a general tendency for the higher illuminance to be rated as more pleasant. While there was little effect of lamp type on the rated colorfulness of the interior, there was a tendency for increased illuminance to produce ratings of greater colorfulness as well as greater satisfaction with the lighting. Clarity was also rated as greater with increased illuminance.

Boyce commented that because only the *Northlight/Daylight* and *Kolor-rite/white* combinations showed an effect for the colored interiors, this appears to rule out correlated color temperature as responsible for the effect, since no effect occurred for a *Northlight/Kolorite* combination with

CCTs of 6500 vs 4000 K. Similarly, the color rendering index explanation did not agree with the lack of effect for the *Kolor-rite/Daylight* combination (CRI 92 vs 65). As in the previous experiment, the results fit the color discrimination index (CDI) best, suggesting that lamps with high CDI make colors appear more saturated and contrast more with other colors. Thus the two lamps with a high CDI, *Northlight*, and *Kolor-rite* produced interiors that were rated as more colorful than the poor CDI lamps. Similarly, ratings of clarity of detail were higher for the *Northlight* lamp than for the *Daylight* or *White* lamps. Results for the achromatic condition did not seem to follow the same pattern as those for the colored interior. Boyce (1977, p. 22) concluded that his results suggest that "*Lamps with a high CDI can be installed at a lower illuminance than those with a low CDI and still produce equal satisfaction with visual appearance, at least for offices and domestic interiors.*" He cautioned, however, that these results are limited to a consideration of satisfaction with visual appearance, and that visual performance was not assessed - noting that "*It would be a mistake if, in the search for energy economics, the illuminance of an interior were reduced to a level where performance is likely to be worsened*" (p. 24).

Wake, Kikuchi, Takeichi, Kasama, and Kamisasa (1977) evaluated the effects of illuminance, color temperature, and color rendering index on the perception of the visual environment. They used a 1/5 scale model simulation of an office for their assessment. Six lamp types were used - HPS, mercury, mercury fluorescent, incandescent, daylight fluorescent and white fluorescent with color temperatures ranging from 2100 K to 6500 K, and CRI's ranging from 29 to 100. An acrylic panel, simulating a luminous ceiling, was used with all lamps. Illuminance on the floor was varied mechanically from about 41 to 8800 lx depending on the source. Subjects observed the room, which contained furnishings typical of an open-plan office as well as a doll simulating an office worker, through a small viewing window. They rated the office on 40 adjective scales to provide information on its *image* and completed 25 evaluative items. For the image assessment subjects indicated how well each adjective described the room on a scale of 1 to 7. For the evaluative test, subjects judged different aspects of the room on a seven-point scale of "very good" to "very bad". A total of 48 subjects viewed all combinations of lamps and illuminances in a total of 42 randomly presented conditions.

A factor analytic evaluation of the results from the image test indicated that four components accounted for 95.2% of the variance. The first component represented an evaluative dimension, characterized by the following adjectives: *vivid, open, free, young, fresh, bright, positive, gay, new, modern, beautiful, rich, healthy, broad, heavy, and novel* (in Japanese). The score for this component increased as illuminance increased for all light sources, although the scores for HPS and mercury were always lower. Wake *et al.* suggested that both illuminance and color rendering determine the responses to this first factor. The second factor was termed *mental composure* and described as *calm, restful, in keeping, and quiet.* The authors commented that this dimension also appeared to be related to *activity* as discussed in studies of the affective response to color. Of interest, when the scores on this factor were plotted against illuminance, they remained nearly flat up to 2000 lx where they began to drop. In fact, scores for HPS consistently fell from as the illuminance increased from 99 to 8800 lx. The authors claimed that this factor represents the effects of glare. The third factor was described as representing *warm feeling* or *potency*, and characterized by adjectives such as *soft* or *warm.* This factor did not relate straight-forwardly to illuminance, although the scores for incandescent lamps were always positive, while those for mercury were always negative and declined with increasing illuminance. Wake, *et al.* commented that this factor appears to represent the differences in color temperature and color rendering of the lamps. Scores were higher for lamps with higher color rendering indices and lower color temperature, such as incandescent. The final factor, which accounted for only 1.7% of the total variance, was related only to *overcrowding* and appeared to be determined by interior furnishings, rather than to illuminance or other lamp characteristics.

When Wake, *et al.* evaluated the results for the subjects' "evaluative" responses, they also extracted four factors. The first component, accounting for 72.5% of the variance, was termed *general evaluation* and represented response to the *total impression, light source color, ceiling color, color harmony, type of illumination, room color appearance, total appearance, etc.* Responses to this factor increased with illuminance for all light sources except HPS. Differences among response to this factor by the different lamps appeared to be a response to their CRI, such that incandescent lamps received the most favorable evaluation and HPS the least favorable. The second factor, accounting for 9.8% of the variance, had substantial loadings for adjectives related to *glare*. Scores on this factor increased with illuminance, with no large differences observed among lamps. The third factor related to room characteristics such as interior finishes and dimensions, while the fourth factor related to the arrangement of the office. These latter factors did not relate to lighting variables in any meaningful way. A canonical correlation showed high correlation between the "image" assessment and the "evaluative" assessment.

Wake *et al.* found that brightness judgements increased as illuminance increased from 40 to 8800 lx. They noted, however, that scores for the brightness assessment of low color rendering lamps were always lower than those for high color rendering lamps. Evaluations of *pleasantness* as a function of illuminance increased up to about 2000 lx but decreased above that. Although the ratings of pleasantness for HPS did not increase with illuminance, they did decrease markedly as illuminance increased beyond 2000 lx up to 8800 lx. The incandescent and "white" fluorescent lamps received higher scores for both *brightness* and *pleasantness* than the HPS and mercury lamps, with a very marked difference among these lamp types for *pleasantness*. Wake *et al.* noted that these results are not exactly those predicted by the Kruithof effect in that HPS at any illuminance was never rated as *pleasant* nor was there an upper limit to *pleasantness* for the incandescent lamp. The authors suggested that some of the discrepancies are due to the very low color rendering indices for HPS and mercury, even though these varied dramatically in color temperature. These two sources were never rated as producing a *natural appearance of color* under any illuminance. Wake, *et al.* did find that ratings of *warm* increased with illuminance for lamps of lower color temperature (HPS and incandescent). These were consistently rated as *warmer* than lamps with higher color temperature such as mercury and daylight fluorescent. Ratings of *soft* appeared to be related more to CRI than to Color temperature. Ratings for the evaluative scale *the brightness of the office* tended to increase up to about 2000 lx, where they began to decrease, although this decrease was most marked for HPS. These results were attributed to discomfort glare, with a recommendation that 2000 lx is comfortable only if glare is avoided. Both HPS and mercury received very low ratings for the *appearance of the room* suggesting that subjects did not desire lamps with low CRI. Direct ratings of discomfort glare showed a decrease in acceptability for illuminances above 1000 lx. Wake, *et al.* (1977, p. 39) concluded that "*these evaluations made it clear that illuminance, color temperature and color rendering index were important factors for comfortable visual environments. In particular, it* *was found that the most desirable illuminance for comfortable visual environments was about 2000 lx, though it might be needed to exclude discomfort glare*".

In a somewhat different approach, Judd (1967) developed a *flattery* index for light sources which was a measure of the extent to which a lighting installation supplies the preferred colors of objects. It was an attempt to provide a supplement to the color rendering index to deal with the idea that people may prefer colors which differ from the actual color. He noted that this finding is particularly true for the human complexion which is remembered as being redder and more saturated. Judd's index was based on experimental work by Saunders on preferred colors for foods, complexions, and other test samples. Birren (1969) commented on the ability of color to produce arousal and specific moods in people (i.e. warm colors increase alertness and activity, while cool colors are less distracting allowing more concentration). He presented no experimental evidence for his conclusions, however.

The research on visual clarity reviewed in the previous pages is tantalizing, suggesting that using lamps with better color rendering improves not only the ability to make color discriminations but also improves the appearance of a lit interior. Evidence from several studies suggests that objects appear clearer, with less haze, for lamps with higher color rendering but that variations in color temperature do not seem to have a systematic effect if CRI is relatively constant. Unfortunately, each study used different procedures with different specifications for lamp "color", and often introduced complications related to chromatic adaptation, so that the evidence for visual clarity remains inconclusive.

Visual Clarity - Conclusions

- Lamps with higher color rendering indices produce greater "visual clarity".
- Color rendering appears to be a better predictor of preferred lighting than color temperature but both must be specified.
- Color gamut area is also a good predictor of preferred lighting.
- There may be a tradeoff between illuminance and CRI in which illuminance can be lower if CRI is high, for equal satisfaction with the lit interior.
- HPS lighting is often perceived as hazy and vague perhaps because its lower CRI reduces visual clarity or because its SPD differs markedly from more conventional sources such as incandescent, fluorescent or daylight.

4.2 Colorfulness

Davis and Ginthner (1990) evaluated the '*Kruithof*' effect which suggests that the use of lamps of high color temperature at low illuminances causes rooms to appear dim and cold, while use of low color temperature at high illuminances causes rooms to appear unnaturally colorful. Using 40 subjects, Davis and Ginthner evaluated the appearance of a conference room at three illuminance levels (269, 592, or 1345 lux) with lamps of two different color temperatures - 2750 K and 5000 K. The lamps had similar CRI - 89 and 90, as well as somewhat similar spectral power distributions (both single-coat halophosphor lamps). Subjects completed 8 semantic differential scales intended to elicit information about brightness, pleasantness, and colorfulness of the environment, as well as one question about the color appearance of the room. Subjects completed the nine questions twelve times per session. A total of 10 experimental sessions were conducted to minimize novelty and familiarity effects.

Analysis of Davis and Ginthner's results indicated that subjects were able to discern different lighting levels and in fact rated higher levels as 'brighter'. They also indicated a significant preference for higher light levels. Finally, they rated the higher color temperature lamps as cooler, and the lower color temperature lamps as warmer. Subjects did not display any evidence for the "Kruithof" effect; there was no interaction between illuminance level and color temperature. Rather, subjects preferred higher light levels, regardless of the color temperature of the lamp. Davis and Ginthner (1990, p. 33) concluded that "*The primary conclusions from this experiment is that in a color-balanced environment, with high color rendering light sources, subjective ratings of preference were influenced only by light level and not by color temperature...Thus the results of this experiment, combined with the lack of consistent support found in the literature reported earlier, indicate that there is little basis for the Kruithof curve suggestions regarding the influence of light source color temperature on subjective preference judgements*". The data clearly indicate that subjects responded to both light level and to color tone, but that there was no interaction between the two variables. The authors suggest further that the absence of a preferential response to color temperature was likely due to the use of high color rendering sources and a relatively color neutral experimental setting.

In another evaluation of the Kruithof effect, Boyce and Cuttle (1990) evaluated the effect of correlated color temperature (CCT) on the overall perception of a lit interior, and on the performance on a color discrimination task. Typically studies of the Kruithof effect have varied both lamp color temperature and color rendering in a non-systematic fashion, so that the results could be attributed to either attribute. As a result, Boyce and Cuttle evaluated the effect of four different fluorescent lamps with a relatively constant CRI (82-85) with correlated color temperatures ranging from 2700 to 6300 K. They performed two experiments - the first in a room with two chambers with matte grey walls; and the second in a room with one chamber with blue walls and the other with pink walls. (Reflectances were very similar for all wall colors.) The furnishings themselves were achromatic in all conditions. Color was added for some conditions in the form of flowers and fruit.

In the first experiment, 15 subjects completed both the Farnsworth-Munsell 100-Hue test and the Davidson-Hemmendinger color ruler. Then they described the lighting in their own words, responded to a rating scale on the difficulty of doing the two color tasks, and completed a set of 19 unidirectional five-point rating scales. This procedure was repeated for 22 conditions in which illuminance (30, 90, 225, 600 lx), the four lamp types discussed above, and the use of flowers and fruit were varied. Ten subjects participated in the second experiment in which illuminance was fixed at 225 lx, but wall color and presence/absence of "flora" was varied along with lamp type.

When Boyce and Cuttle analyzed the data from the 19 subjective rating scales for the achromatic room, they found a significant effect of illuminance on 16 of the 19 rating scales. "*Increasing the illuminance in the room made the lighting of the room appear more pleasant, more* *comfortable, more warm, more uniform, more colorful, more formal, more friendly, more natural, less haze, less oppressive, less dim and less hostile*" (Boyce and Cuttle, 1990, p. 24). There was a slight increase in the perception of glare as illuminance increased but this was far outweighed by the increase in the favorable response to the lighting. Only one significant correlation was found with CCT - rooms were rated as "dimmer" for the 2700 than for the 6300 K lights. When subjects described the room, in their own words, they did so in terms of brightness and clarity - all of which increased with luminance, but were unaffected by the different CCTs. The authors concluded that illuminance was the major factor that affected the subjective impression of the room, not correlated color temperature.

The presence or absence of fruit and flowers produced only one significant effect of CCT, in which the room was rated as more "stimulating" at 6300 K with flora. Again, increasing illuminance resulted in significantly more favorable assessments of the room on 14 of the 19 scales when flora were present. The results "*show that introducing natural color into an interior, in the form of flowers and fruit, enhance the positive perception of the lighting of the room, particularly at the higher illuminances. This action leaves the apparent insignificance of the correlated color temperature of the lamps unchanged*" (p.27). When the effect of wall color was examined, the room with the pink walls was seen as more friendly, more colorful, less glaring and less harsh regardless of CCT. The pink room was seen as less bright and friendly for the 6300 K lamp, however. The positive effects of adding flowers and fruit occurred for both wall colors and were very similar to the results for the grey room.

Analysis of the data for the Farnsworth Munsell (FM) 100 hue test indicated decreasing errors as illuminance increased and as CCT increased. Thus more errors were made for the 2700 K source at 30 lx, and fewer for the 6300 K source at 600 lx. The task was also rated as more difficult at the lowest illuminances. These data are not surprising in view of previous findings that performance on this test increases with illuminance, and the 30 lx condition may have actually been under mesopic, rather than photopic conditions. Furthermore, because the Farnsworth-Munsell test was designed to be performed under CIE source C with a CCT of 6740 K, performance should have been best for the 6300 K source. The presence of fruit and flowers had no impact on the error rate or the rated difficulty of doing the color matches. Surprisingly, many fewer errors were made for the two rooms with colored walls, although the task was rated as more difficult. Boyce and Cuttle attribute this finding to a practice and motivation effect since these data were obtained several days later.

The authors concluded that there is little effect on people's impressions of lighting due to the color temperature of good color rendering lamps, at least for CCTs in the range 2700 K to 6300 K. In fact, subjects did not use the terms "warm" and "cool" to describe the room when they were given the opportunity. The main effect is that of illuminance, with increasing illuminance increasing the favorable impressions of the room (at least up to the 600 lx studied). Similarly introducing flowers and fruit enhanced the positive effect created by the room (except at very low illuminances). Yet, this did not enhance performance, leading the authors to comment that "*the effect of introducing natural color is an interesting example of the weak linkage between opinions about lighting and the ability to perform tasks under the lighting*" (Boyce and Cuttle, 1990, p. 36). The authors reiterated that the lack of a CCT effect occurs for observers who are fully adapted to the lighting, and that first impressions of the rooms lit by the various lamps can be quite different. Furthermore, the response to the colored walls might have been quite different had the luminance pattern also varied.

The data from recent studies of the Kruithof effect, which are perhaps more conclusive than the studies of visual clarity, suggest that the original effect was due to failure to control color rendering when color temperature was varied. If color rendering is controlled, there appears to be no evidence of a color effect as illuminance level changes.

The studies reviewed above suggest that the *color* of the light source plays an important role in the perception of a space, the overall illuminance, and the colors within it. The next series of studies assess the effects of variation in spectral power distribution (SPD) of light sources on both subjective response and ability to identify colors. Rowlands, Loe, Waters, and Hopkinson (1971) evaluated the influence of the SPD of light sources on visual performance. In a pilot study they found an indication that the ability to locate numbers in a random display was equally good with a lower illuminance of a good color rendering lamp as with a higher illuminance of a poorer color rendering lamp. Unfortunately results from a main experiment in which subjects identified randomly oriented Landolt rings under a range of illuminances and fluorescent sources in an achromatic environment were inconclusive. There was an upward trend with illuminance (which leveled off above 300 lx) for both the simple and complex tasks, but no effect for lamp color. It would be interesting to extend this type of approach to HID sources where variations in SPD are much greater. Mi'lova' (1971) evaluated performance with Landolt rings under two fluorescent sources, one at 2700K and the other at 5700K at 500 lx. Although an earlier experiment had shown some performance decrements attributable to source color, these were not borne out for the experiment with the two lamps. About 60% of the observers preferred the white lamp color; 23% of the observers complained of visual fatigue under the lower color temperature lamp.

Using semantic differential and multi-dimensional scaling techniques, Flynn and Spencer (1977) evaluated the subjective impressions related to visual warmth and overhead/peripheral lighting produced by lamps with different SPD's. In the experiment they maintained horizontal illuminance reasonably constant across light sources, while varying light source color. Lighting was from a diffuse overhead source in a room that was neutral in color (light beige and natural woods with few strongly chromatic objects). They found clear differences in observers' evaluations of the visual clarity, visual warmth, preference, and pleasantness of the space as a function of the different lamps (warm white, cool white, HPS, and deluxe mercury) but no effect of lamp color on spaciousness. The extremes in clarity were between the cool white and HPS lamps. HPS in particular was seen as *hazy* and *vague* but not *dim* or *subduing*.

Light source spectral power distribution also determines the appearance of colored objects within a space. The effects range from the subjective response to color to the ability to match or discriminate colors. Color is used, for example, to code safety information, organize complex displays, or create moods (Cole and Vingrys, 1985). Accurate color judgements are required in a wide range of industries, including textile, automotive, paint, meat processing, etc, and require both discrimination and recognition decisions. While the ability to detect and recognize colors is influenced by the size of the colored patch, overall illuminance, luminance, and background characteristics, the largest impact is that of the illuminant. The use to HID (High Intensity Discharge) sources with higher energy efficiencies but poorer color rendering capabilities has created major difficulties in the accurate recognition of highway and other types of safety signs. In this situation changes in the illuminant can erase the ability to perform the task (namely recognize a color accurately). Jerome (1977), Thornton (1977), Glass, Howett, Lister, and Collins, (1983) and Collins, Kuo, Mayerson, Worthey, and Howett (1986) reported studies on the identifiability of safety colors that demonstrated serious confusions for illuminants such as clear mercury, high pressure sodium, and low pressure sodium. These studies indicated that the spectral composition and illuminance provided by the illuminant seriously altered the appearance of colored objects, sometime beyond hope of accurate recognition. The effect was strongest for the HID sources, although accurate color discrimination and recognition were also affected by fluorescent sources of poor color rendering. Such distortions are likely to alter the psychological perception of a space as well.

Colorfulness - Conclusions

- Recent research has failed to replicate Kruithof effect - i.e. lamps with high color temperatures at low illuminances did not appear cold and dim, while lamps with low color temperatures at high illuminances did not appear artificial - when color rendering of the light source was controlled.

- Generally increasing the illuminance makes a room appear more pleasant regardless of color temperature, unless the spectral distribution of the source is markedly unusual.

- Drastic alterations in spectral power distribution from normal can alter or destroy the ability to match, identify or discriminate colors, as well as alter the appearance of environments lighted with such illuminants.

- There may be a tradeoff between illuminance and CRI in which illuminance can be lower if CRI is high, for equal satisfaction with the lit interior. Conversely, lower levels of illuminance with poorer sources may lead to complaints of fatigue or poorer performance.

4.3 Lighting Geometry

In addition to variations in light source spectra, the position of light sources within a room can also vary markedly. While variation is used for good effect in theater, museum and display lighting, it is rarely discussed for office environments. Cuttle (1971, 1973), however, discussed the effect of the directional nature of lighting on the perception of objects and their surroundings in more conventional environments. He advanced the concept of the sharpness and flow of light as critical parameters in determining the perception of objects, commenting that their effects go far beyond classical concepts of modelling. Cuttle suggested that "preferred" lighting is that which produces a variety of object appearances - opaque solid objects have unique patterns, while glossy objects also have highlight patterns, and objects with surface concavities have shadow patterns. Cuttle defined the "flow of light" as describing the impressions of both the direction and strength of the lighting. The strength of the lighting can be quantified by the vector scalar ratio, while the direction can be quantified by Lyne's β/ρ ratio. Sharpness of the light is due to small light sources which create sharply defined shadow patterns with clean edges and highlight patterns. If the vector/scalar ratio in a room is generally high, a strong flow of light will be perceived. Daylit rooms typically have strong flows of light from the sidewall, unlike artificially lit rooms where the flow of light is from the ceiling downwards.

Bean (1978) evaluated the usefulness of the concepts of vector/scalar ratio and cylindrical illuminances (mean vertical illuminances) in describing the lighting of objects and people. Defining scalar illuminance as mean spherical illuminance, he noted that numerous researchers had used such concepts to specify illuminance more completely than simply illuminance on a horizontal working plan. Scalar illuminance, however, does not distinguish between horizontal and vertical illuminance. Excluding side lighting, which produces a horizontal flow of light, he evaluated an interior lighting installation with regular layouts of luminaires. He compared the measured vector/cylindrical illuminance ratio with the vector/scalar ratio in a model room, and noted that these indicated that vector/cylindrical ratio was marginally superior. Bean concluded (1978, p. 149) that "*It would seem reasonable to use the vector/cylindrical illuminance ratio to determine the degree of modelling while its uniformity could be used to determine whether dramatic changes in appearance would occur as the person observed moves through the installation*".

Jay (1971) stated that lighting design is intended to facilitate perception of the environment. Objects seen in a lit environment all possess size, color, texture, and shape in definite locations. Jay presents data drawn from a number of sources which led him to conclude (p. 155) that "*perceived brightness is not simply a function of luminance and adaptation level, but is also affected by the luminance of adjacent elements in the field of view*". Contour is also an essential element of the perception of brightness with variation of brightness along a contour being enhanced. Jay noted that adaptation within the eye ensures that variations in apparent brightness are less than variations in actual luminance as the illumination changes. Furthermore, ordinary scenes are made up of sharp gradients in luminance associated with object boundaries. Within the object, changes in luminance tend to be more gradual. Contour, brightness and color of objects are the fundamental bits of information extracted by the visual system for a scene. Jay noted that the significance of perceptual theory for lighting is that vision includes information about relationships in the visual field and is not limited to physical measures such as chromaticity or luminance. Thus, the organization of the retina maximizes the effect of contrast so that perception relates to surface reflectances and not just luminance. There is also an emphasis on sharp gradients in luminance which are perceived as contours.

If accurate perception is desired, the illumination level should be high enough to allow the speedy perception of contours and details. Conditions which promote accurate perception of surface properties such as lightness, color and texture are desired. Jay noted that where variations in subjective lightness are small so also are variations in color appearance. He suggested that variation in illuminance for accurate perception should be no more than 10:1 with less being preferred. Yet, for display lighting, significant objects should have high Munsell value and be brightly lit. Maximum contrast will occur when the object of interest is brightly lit with low background luminance. Jay (1971, p. 141) commented that "*The effect of extremes in contrast in the field of view is to modify the mental concepts which visual signs normally evoke. Qualities of bright objects can be heightened to the point where they no longer seem ordinary and take on an unusual quality; dimly lit objects become ill-defined in shape, size, distance and color, so that perception becomes more amenable to suggestion and imagination*". Thus, use of lighting for effect depends on large contrasts in the field of view and requires sharp gradients of luminance. Jay theorized that gloom occurs when the gradients are low. The same lighting pattern with a few added high contrasts can lead to completely different emotional response. "*Generally speaking, brightness is perceived as the result of the lighting, while lightness is perceived as an innate property of the surface*"(Jay, 1971, p. 142). Yet, the distinction between the two is not always clear.

Lynes (1971) discussed the role of lightness, color, and constancy as tools in lighting design. He claimed that "*this tendency of lighted objects to keep many of their perceived characteristics relatively unchanged through quite large changes in the color and quantity of incident illumination is known as 'constancy'*" (Lynes, 1971, p. 24). Thus, brightness constancy refers to the tendency of a white piece of paper to appear white in both sunlight and shadow, while color constancy refers to the tendency of a green leaf to appear green in both daylight and incandescent light.

Lynes noted that constancy is a property of illuminated objects - seen in the company of other objects. It breaks down when an object is viewed through a reduction tube, for example. Color constancy can be understood in terms of the Munsell system, in which colors are presented numerically in terms of hue, chroma, and value. Lynes suggested using the Munsell system to describe changes in apparent (subjective) brightness (value), subjective hue, and subjective chroma, as the illumination changes.

Yet, while constancy tends to occur, Lynes pointed out that it is never total and the "appearance of a surface is never quite independent of the incident illumination (p. 26). He suggested the following steps for lighting to maximize constancy:

a) Avoid sharp shadows and highlights;
b) Provide adequate illuminance;
c) Use light with good color rendering;
d) Minimize disability glare;
e) Where surfaces must be poorly lit, use colors with high chroma or value;
f) Provide obvious sources of illumination;
g) Keep glossy areas small;
h) Scatter small white areas in the field of vision; and,
i) Make surface texture visible.

Lynes (1971, p. 26) stated that the maintenance of constancy may be an important purpose of good lighting. Thus, sharp shadows tend to impair constancy because the sharpness looks like a change in reflectance, while very low lighting levels can reduce visual acuity (if low enough), reduce subjective chroma, and alter subjective hue. (Using surfaces with high value and chroma can offset some of the reduction, however.) Sources with poor color rendering also alter subjective hue, value and chroma to a greater or lesser extent. Disability glare will cause problems with brightness discrimination, but also a loss of subjective chroma. Because constancy compensates for changes in the amount or color of the illumination, such compensation should be easier if the source is visible. Although matte surfaces tend to retain constancy more than glossy surfaces, small glossy or white areas paradoxically tend to improve constancy. Similarly, providing obvious texture also aids constancy. Yet, "*It would be wrong to regard constancy as an indispensable condition for good lighting. Where dramatic lighting* *is needed, constancy is undesirable. Flood lighting and display lighting, for example, are most effective when constancy breaks down, when the lighted objects lose their surface quality and even appear self-luminous*" (Lynes, 1971, p. 27).

Lynes (1971, p. 28) claimed that "*hitherto, luminance design has ignored both color and constancy. Why struggle to design in terms of luminance, which makes no difference between a rise in illumination and a rise in reflectance, when we know that whenever we recognize a lighted surface, we perceive illumination and reflectance independently*". He then pointed out that examination of brightness contours shows that surface reflectance is lower at high illuminances for equal luminance than at low illuminance. Halving the reflectance changes apparent brightness more than halving the illuminance. Furthermore, an experiment by Hopkinson shows that surfaces with the same luminance do not necessarily have the same apparent brightness. Lynes (1971, p. 33) commented that "*Indirect lighting or luminous ceilings which approach the geometry of the overcast sky inevitably reduce the vividness of surface colors, thus impairing color constancy. Conversely a flow of light enhances constancy; it reveals texture, and it provides the low* β/ρ *which are essential for maximum subjective chroma*". Diffuse lighting reduces subjective chroma in much the same way as a reduction in luminance. Lowering illumination levels results in decreases in subjective lightness decreases and causes colors to appear colder. "*White objects will stand out, and although modelling contrasts seem harsher, objects look less solid. The word gloom can be used to embrace all these effects of low illumination and diffuse lighting; although an emotive term, it is commonly used in this sense*" (Lynes, 1971, p. 33)

Lighting Geometry - Conclusions

- "Flow of light" which is related to the vector/scaler illuminance ratio, is used to describe both the direction and strength of lighting within a room.

- Vector/cylindrical illuminance ratio can be used to predict the amount of modelling produced by a light source on an object.

- "Good" lighting acts to maintain both lightness and color constancy, although departures from constancy are often deliberately used to create particular atmospheres and emotional responses.

5. Response to Field Lighting Installations

Up to this point, the effects of lighting on the psychological response to the environment has been largely in laboratory or theoretical research in which more stringent control can be exercised over lighting variables. While such studies often offer great flexibility in altering lighting environments, they cannot assess the long-term effects of working under a particular lighting configuration. On the other hand, numerous field studies, often involving post-occupancy evaluations, have been conducted to evaluate the impact of lighting and other environmental factors on occupant satisfaction and only indirectly on performance. These studies have demonstrated clear effects on satisfaction; they have not successfully demonstrated any effects on productivity. Because they are field studies, rather than laboratory experiments, they do not allow much variation in lighting parameters during an experiment. Nonetheless, they do provide insights into what people like and dislike about specific lighting configurations and provide hypotheses that could be evaluated in subsequent laboratory experiments.

5.1 Post-Occupancy Evaluations

A post occupancy evaluation (POE) is typically conducted after a building has been built (or renovated). It is designed to determine occupant attitudes toward different environmental features such as lighting, temperature, space, noise, ventilation, etc. When linked with physical measurements of these features, it can provide valuable clues to occupant response to the environment as well as suggestions for altering these features.

Ne'eman, Sweitzer and Vine (1984) conducted a post-occupancy evaluation of occupants in a nine-story office building in St. Louis, MO. A major concern in the study was occupant attitudes toward lighting, windows and controls. After administering a questionnaire survey to 162 people, Ne'eman *et al.* took a variety of physical measurements in the offices. These included work surface illuminance, source luminance, temperature, background sound levels, and physical dimensions of representative furniture. Analysis of these data indicated a range of task illuminances from 320 to 650 lx, with a mean of 550 lx. Illuminance was provided largely by ceiling mounted fluorescent fixtures with a mean luminance of 3000 cd/m^2. Daylight from both windows and a central atrium was available in many work stations, although its specific contribution to overall illuminance was not measured. About 51 % of the sample was located along the periphery of the building.

The questionnaire asked people to rate the importance of, and their satisfaction with, 24 features of their offices on separate four-point rating scales. They also rank ordered the three most and three least important features of their offices. Analysis of these data indicated that more than 90% of the occupants considered the quality and amount of light for reading and writing to be very important. This was the highest percentage for any environmental feature. Similarly, the amount and quality of light for specific tasks such as computing, filing, and other tasks were considered to be very important, as were means to control glare. Amount of space and chair comfort were considered to be very important by 75% of the occupants, while temperature and ventilation control were considered very important by 60% of the occupants. Only 20% felt that the kind of view or the control available for lighting and window shading was very important. (Ne'eman *et al* commented that this response may have arisen because the view out was not particularly good, however, and consisted of high rise buildings to two sides, parking garages to another, and older low rise structures to the fourth side.)

The ranking of environmental features revealed that occupants considered the amount of space, summer temperature control, privacy for phone and office conversations, amount of light for reading, and control over ventilation to be among the most important features. View out, privacy of the work area, and availability of controls were among the least important features. The occupants were the most satisfied with the size of their work space, light for reading, and chair comfort, and the least satisfied with the interior temperatures and conversational privacy. Of interest, "*the results indicate a negative relationship (statistically significant) between how an individual evaluated the importance of a particular features of his/her working environment and his/her satisfaction with it*" (p. 166). Thus workers who were not at all satisfied with temperature and ventilation control considered them to be very important. They did, however, consider lighting for reading and writing to be among the most important factors, and expressed moderate satisfaction with them.

Ne'eman *et al.* subjected their data to a principal factor analysis which revealed that eight factors accounted for the bulk of the variance. The factor analysis was an attempt to isolate attitudinal dimensions which reflected occupants' basic conceptions of their office spaces. While it isolated dimensions that appear reasonable, it was of course constrained by the questions asked in the survey. While the first factor was related to thermal controls, the second, third, and sixth factors related to lighting - in terms of controls, specialized tasks, and general tasks. This is further evidence of the importance of lighting to office workers.

The authors also related other environmental features to the occupants' responses. These included variables such as floor level, work station location, type of office, orientation, time in space, age and gender. This analysis revealed that "*there was a strong relationship between people's physical location in the building and their perceived importance of and satisfaction with certain lighting controls and other work space conditions*" (Ne'eman *et al.*, 1984, p. 169). In addition, many women and younger workers were less satisfied with features of their environment. This finding suggests that position within the organizational hierarchy can result in less satisfactory environmental settings - or in the perception of inadequate working conditions. Ne'eman *et al.* commented that the dissatisfaction expressed with interior temperatures appeared reasonable since many areas were overheated in the winter. Similarly, the lack of importance of window control devices and view out to the occupants may have been related to rather limited existing devices (i.e. venetian blinds only) and restrictions on the view out.

Louis Harris and Associates surveyed attitudes toward the office environment for Steelcase (1987). Using a telephone survey, they questioned 1000 U.S. workers, 250 Canadian workers, 150 CEO's, 150 designers, and 150 facility managers to determine the importance of various features of the office environment. While many questions were directed toward issues such as productivity and job satisfaction, a number of questions dealt with design features. Of interest is the importance that CEO's, designers, and facility managers placed on comfort as the key to increasing productivity. Toward this end, each group placed a great deal of emphasis on office layout, furniture, and chairs. Workers placed considerable importance on privacy, improved temperatures, and reduced distractions or noise.

Although lighting was not a major focus of the study, 91% of the designers surveyed considered lighting for tasks to be a very important characteristic of an office for helping an employee to get a job done well. In fact, this was the most frequently selected characteristic, ahead of chair comfort and proper HVAC functioning. Providing good ambient lighting was important to 81% of the designers, as well. Facility managers reported that 19% of the complaints they received dealt with glare on VDT screens, while 13% indicated that room lighting was too bright for good VDT use. Among office workers, 33% considered that inadequate or improper lighting was a *very* or *somewhat serious* office comfort problem. The CEO's were not questioned about lighting. Unfortunately, no information was obtained about the actual physical conditions in the offices, so that there is no way to determine what type of lighting systems were causing problems.

Another POE survey of attitudes toward environmental conditions was conducted by Rubin and Collins (1988) and Collins and Rubin (1988). They administered questionnaires to 621 occupants in three U.S. Army field stations, and took physical measures of lighting, temperature, noise, and other environmental conditions at the three sites. Analysis of their data indicated that concerns about temperatures, privacy, noise, lack of windows, and lighting were paramount to many of those who participated in the study, perhaps because many of the facilities were crowded and cramped for space.

Unlike the Steelcase study, a number of questions were asked specifically about lighting both in terms of overall quantity and general quality. The results indicated that lighting quality in general was considered to be *fair* to *poor* by about 20% of the respondents. About 30-40% felt that the overall amount of light was fair to poor, although this depended on the nature of the task, with those doing extensive VDT work being less negative about the amount of light. Location of the ceiling lights, and glare from these lights, however, was a problem to about 40% of those who used VDT's extensively, while some 60-80% of all respondents considered their ability to adjust light for their tasks to be fair to poor. In fact the ability to adjust task lighting (or lack thereof) emerged as one of the most salient concerns for all sites. Thus, when people were asked to select desired changes to their environments, improvements to overall lighting and the addition of task lighting emerged as frequent choices.

Inspection of the physical measurement data for the three field stations revealed that overall light levels were typically low with mean illuminances of 220-280 lx for all areas; 310 to 570 lx for purely administrative areas; and 120-200 lx for areas where primarily VDT-type tasks were performed. Illuminances were typically very low in these areas because of problems with reduced screen contrast and visible screen reflections from overhead ceiling lights. In fact, in many of these areas the occupants had deliberately reduced the overall light levels by removing fluorescent tubes or by adding paper diffusers to the fixtures.

In an extensive POE data collection, Collins, Gillette, Fisher, Marans (1989 a,b), and Collins (1990) provided insights about task lighting and other environmental issues. These authors reported POE data involving measurements of lighting power densities, photometric levels, and user attitudes for 912 work stations in thirteen office building.

In the analysis, Collins *et al.* identified seven different ambient lighting systems - three direct, three indirect, and one direct/indirect. Each system was also defined in terms of task lighting and daylight. A total of 355 work stations had no task lighting; 376 had furniture mounted task lighting; 121 had desk movable lighting; and 22 had some other type of task lighting, such as floor mounted units. Finally, 334 work stations had some daylight while 518 had very little daylight.

Collins *et al.* found that lighting satisfaction was consistently lower for work stations with furniture integrated task lighting than for work stations with other types of lighting. Furthermore, satisfaction tended to decrease with illuminance for these work stations. Dissatisfaction with lighting was greatest for these work stations without any daylight. Lighting satisfaction was not directly related to amount of illuminance on the task, but tended to be affected by the presence of daylight and fixed task lighting. (Task illuminances were generally within the range (200-1000 lux) recommended by the IESNA (1987) for performance of visual tasks of medium to high contrast or small to medium size.)

Collins *et al.* explored the responses to two different *ambient* lighting systems - direct and indirect - which were used at a substantial number of work stations with identical systems furniture and furniture integrated lighting. Comparison of the responses to the two sets of work stations revealed that 68% of those with the *direct* ambient system were satisfied with their lighting, while 46% of those with the *indirect* ambient system were dissatisfied. For these respondents, the combination of indirect ambient lighting with integrated task lighting was particularly unsuccessful. Responses to a question about the occupants' perception of the brightness of their spaces revealed that the lighting configuration which combined fixed task with indirect ambient lighting was particularly unsatisfactory. Although the mean task illuminance was higher for this configuration, nearly half (43%) of those with the indirect configuration rated it as being dim as compared to 21% of those with the direct configuration. In addition, over two-thirds (68%) of these occupants rated the amount of light available for work as low, even though the illuminances directly at the primary work station were actually the highest of the seven systems identified. One third (34%) of those with this system also felt that the lighting for reading and writing was either *poor* or not very *good*. The presence of daylight (adjacency to a window) in the work station increased the overall satisfaction with this lighting system, however. As might be expected, the two systems with task lighting had higher ratings for the *bothersomeness of glare from* the work surface and task light than the direct-only system, but lower ratings for glare from the ceiling lights.

Collins *et al.* actually obtained two subjective measures of brightness, one covering the perception of brightness at the work station, on a "bright-dim" scale and the second one dealing with the assessment of brightness, using a rating scale of the amount of light available. In addition, a composite measure of subjective lighting quality was developed by summing the scores for questions about lighting satisfaction, amount of light for work, amount of light for reading, and light hindering job performance. Analysis of the data revealed that those spaces that were judged to be too dim for working and which had *average* or *low* brightness had the lowest lighting quality assessment, while spaces viewed as *too bright* received higher assessments of lighting quality. The assessments of lighting quality were highest for those spaces which were judged to be about right in brightness availability and perceived as *bright* or *average*. About half (49%) of those responding to these questions felt that their space was *bright* with only a few (11%) of these feeling that it was too *bright* (and giving it a lower lighting quality score).

Subjective brightness was clearly an important contributor to perceived lighting quality: no space that was perceived as dim was considered to have the right amount of light for work.

Occupants at work stations with a combination of task and indirect ambient lighting frequently rated their lighting as being neither satisfactory nor bright. Furthermore, they rated this configuration as having the lowest amount of lighting quality. Yet, as noted earlier, work stations with this configuration had higher illuminance at the task than most other work stations. Consequently, a summary measure of luminance in the room (termed "average luminance") was created to explore the relation between lighting satisfaction and luminance patterns in the space. Collins *et al* stated that average luminance appeared to be a reasonable way of summarizing the ten luminance values obtained for each space, and providing a better estimate of the occupants' perceptions than one luminance measure alone. Inspection of the data revealed that the combined indirect ambient-integrated task configuration had an overall average luminance that was less than half of that for each of the other systems. The majority of work stations (68%) with the indirect system and task lighting had a very low average luminance - between 0-168 cd/m^2 - as compared with 14% and 2% of the those with the direct system with and without task lighting, respectively. In fact, 80% of the work stations with the indirect configuration had an average luminance between 0-340 cd/m^2. The mean luminance of the ceiling and brightest area in the field of view were also substantially below those for the two direct systems. Yet, task illuminance (and luminance) was consistently higher. Overall lighting satisfaction and brightness ratings were consistently lower for the indirect/task system than for the other two systems. While rated glare from the work surface tended to be higher for this system, rated glare from the ceiling lighting was lower for each average luminance category.

Collins *et al.* concluded that the perception of brightness in the work stations studied was related more to average luminance than to task illuminance. Occupants perceived spaces with lower average luminances as dim, while those with higher average luminances were perceived as bright. The relationship between subjective brightness and task illuminance was not as strong as that between subjective brightness and average room luminance. It appears that occupants may have based their judgements of brightness on overall room luminance rather than task illuminance, with the combination of a bright task surface with dim surroundings producing an unappealing lighting situation. This analysis suggests that the amount and distribution of luminance in a space was an important factor in influencing occupant satisfaction and brightness perceptions. These considerations appeared to be even more important than the amount of light on the task in determining satisfaction with lighting.

Hedge (1991) evaluated the effects of two different office lighting systems on workers in a largely windowless facility in which the primary task required using computers and VDT screens. Workers were located in small offices or cubicles (typically 3x3m or 3x4.5m). Only 18 of the 153 offices had windows. Hedge conducted three surveys - one before lighting changes were introduced, one 3 months after, and the final 15 months after the changes. The initial lighting system was a direct recessed acrylic lens fluorescent system installed in all offices in the facility. Two different lighting systems, each designed to reduce glare and improve lighting at computer work stations, were installed during the retrofit. One system was a direct system with parabolic louvers (PBL), while the other was an indirect lensed system (LIL) with T-8 fluorescent lamps (3500 K) in both luminaires. The parabolic system was designed to provide 750 lux on the working plane; the indirect system, 500 lux.

Hedge administered a questionnaire which collected data on complaints about health and environmental conditions, lighting preferences, job satisfaction and stress, and disruptions to and amount of productive work lost because of environmental and health problems (due to the work place). The questionnaire was completed by 147 workers before the retrofit; 90 workers after 3 months; and 121 workers after 15 months. Hedge also measured illumination levels at the center of each primary work surface and assessed any modifications to the lighting (such as lamps being removed or switched off). Temperature and humidity were measured in the two post renovation surveys. No measurements were made of luminances anywhere in the work space or of illuminances that were not on the working plane.

Analysis of the results indicated a generally more favorable response to the indirect fixture than to the parabolic fixture. While Hedge found no differences in job stress or satisfaction between workers with the different luminaires, he did find significantly more complaints about tired strained eyes and focusing difficulties for those with the parabolic fixtures. He also found that more workers had modified their lighting with the parabolic fixture by removing lamps or repositioning their computers, with the greatest percentage of modifications in the 3x3 and 3x4.5 windowless offices. The percentage of modifications to the windowed offices and the cubicles was much lower (20% vs 76-77%). Measurements of the lighting levels revealed illuminances for the indirect fixture of about 525 lux after 3 months and 475 lux after 15 months; and for the parabolic fixture of about 675 and 603 lux for the same times but there was no correlation between illuminance level and satisfaction with the lighting or visual health. Yet, workers with the indirect system reported fewer problems with screen glare and general office illuminance. Hedge states that "*Workers with the PBL system consistently reported more complaints of unsatisfactory lighting, uncomfortable lighting, unpleasant lighting, lighting being too bright, direct glare from lighting, glare on paper documents, and harsh shadows from the lighting ... In addition, significantly more PBL workers reported losing productive work time because of unsatisfactory lighting, uncomfortable lighting, unpleasant lighting, lighting being too bright, direct glare from lighting, and glare from paper documents*"(p.65). Of interest 80% of those with the indirect system expressed a preference for it, while 50% of those with the parabolic system also preferred the indirect system. There was a general preference for both systems over the original prismatic lensed system with a decline in the number of complaints about tired, strained eyes, however. It is unfortunate that no data on luminances on vertical and horizontal surfaces were taken and no information obtained on the number of hours per day that computer terminals were used. Inspection of the photographs accompanying the report suggest that the parabolic fixtures may have provided a relatively dark ceiling as compared with the indirect fixtures but without any luminance data it is difficult to determine luminance ratios produced by the different luminaires. The lower task illuminance produced by the indirect system would appear to be advantageous to those doing computer tasks.

Post Occupancy Evaluation - Conclusions

- Post Occupancy Evaluations offer a valuable tool for exploring response to installed lighting systems in a work space.

- Luminance patterns can be more important than task illuminance in determining perceived brightness in a space. For example, unsatisfactory luminance patterns can be created in a space by mixing very dark vertical surrounds with overly bright task areas - leading to the perception that the space is dark.

- Perceived brightness appears to be a major determinant of satisfaction with lighting in a space (assuming that task illuminance requirements are met).

- Glare and reflections from overhead lighting can cause major problem for VDT users.

5.2 Response to Flicker

Wilkins, Nimmo-Smith, Slater, and Bedocs (1989) evaluated the incidence of headaches among office workers as a function of the frequency characteristics of the lighting. They compared the response to three types of lighting: a) conventional ballast with a switch start; b) choke ballast with electronic start; and c) high frequency (32 KHz) solid state ballast. This latter type of ballast results in substantially less (only 7%) 100 Hz fluctuation in light output than a conventional ballast.

Wilkins *et al.*. had approximately 150 volunteers from a government office in the U.K. fill out a questionnaire indicating the number and severity of headaches and eyestrain during each week for a full year. A double-blind cross-over design was used in which conventional and high-frequency ballasts were randomly interchanged halfway through the experiment. Participants were not told of the change which resulted in no visible alteration to the fixture. Work surface illumination from the luminaires ranged from 400 to 900 lux but was typically supplemented by daylight in the seven-story office building.

Analysis of the data indicated no effect of baseline conditions, speed of lamp ignition, or lamp phosphor. Pulsation due to ballast type, however, had a significant effect with twice as many headaches reported for conventional lighting. In addition, there was a tendency for participants to report eyestrain somewhat more frequently with the conventional lighting. Of interest is that the frequency of headaches also decreased with the height of the office above the ground - in other words, for those offices with more daylight availability. Lamps with the conventional ballasts were also switched on significantly less frequently than the high frequency ballasts. Wilkins, *et al.* commented that their data indicate that the frequency of headaches and eyestrain was reduced by a factor of two when the high frequency ballast was used and the intensity fluctuation of the light was eliminated. These data are intriguing because they link a measurable physiological response to a specific lighting variable.

Flicker - Conclusions

- Use of high frequency ballasts can reduce incidence of headaches and eyestrain by minimizing subtle fluctuations in the light source.

- More research data are needed on the psychological response to flicker.

5.3 Daylighting

The preceding sections have concentrated on electric lighting as the primary light source. Where the effects of daylight have been addressed, it has been as a supplemental, rather than as the primary illuminant, and the effects of view out have not generally been separated from illumination. Yet, it is reasonable to expect the use of daylight might produce different psychological responses than electric light because of physical differences in the characteristics of the two types of illuminant. First, daylight is typically a side wall illuminant with a markedly different geometry than an overhead source. Second, it is a broad band illuminant with a different spectral power distribution. Third, it is a much more variable source which changes in overall illuminance and spectral power distribution over the course of a day. Fourth, the presence of a window affords not only light but view out and thus provides an additional psychological benefit (Collins, 1974). Several researchers have attempted to isolate the psychological response to daylight as an illuminant, although most research has focused on the benefits of the view out the window.

Griffith (1964) reported data from a scale model installation lit by several different lighting designs including a luminous ceiling, recessed eggcrate troffers, and sidewall daylighting. He measured the luminance of different tasks including pen, pencil, and ballpoint ink with lined paper and calculated the contrast as a function of the different lighting installations. Because his calculations indicated a considerable loss in contrast for the overhead lighting designs relative to the sidewall systems, he noted that recommended levels of illumination might eventually need to specify the location of the major illumination source. A review by Collins (1974) indicated the importance of windows to people in built environments. She suggested that the impact varies from negative in buildings such as theaters where windows are a distraction, to moderately important in offices, to essential in hospitals, where the absence of windows has been correlated with an increase in transient psychoses (Wilson, 1972; Ulrich, 1984). Unfortunately, the research into the psychological impact of windows does not define whether the effects are due to daylight, view out, contact with the outside, warmth, spectral power distribution of the daylight, or something else, but it does indicate that windows perform a desirable function for people in buildings. Further research is needed to determine whether daylight per se has any impact on task performance or psychological response.

One developing area is that of research into "seasonal affective disorder" (SAD) in which a transient depression has been linked to low light levels during the winter months. SAD patients tend to recover when exposed to high levels of light (whether natural or electric). While not a direct evaluation of windows, nonetheless one can hypothesize that exposure to daylight could mitigate the effects of SAD. Furthermore, one could theorize that people require a certain level of light for "psychological" balance.

Heerwagen (1990, p.611) evaluated the relationship between seasonal affective change and lighting preferences, noting that "*although there are many unresolved issues surrounding SAD, it is apparent that exposure to bright light during the winter months has powerful antidepressant effects that occur within 3 to 5 days of the onset of light therapy, and that the depressive symptoms return when light therapy is discontinued.*" Similar responses to light are found in people with only moderate levels of seasonal change in mood.

As a result, Heerwagen evaluated the hypothesis that people with SAD-like symptoms were "light hungry" with preferences for higher room brightnesses than people without these symptoms. Heerwagen began by recruiting people who reported themselves as having seasonal changes in mood and behavior as well as a group who did not experience such changes. All volunteers completed the Seasonal Pattern Assessment Questionnaire (SPAQ) which assesses changes in mood, weight, sleep, social activity and energy during the year. Based on the responses to this questionnaire, a total of 10 SAD subjects were chosen, along with a group of non-SAD subjects.

A windowless lighting laboratory at the University of Washington was used for the experiment. It contained dimmable overhead and wall wash fluorescent lighting as well as a simulated dimmable window. The room was 5.4m x 5.4m and painted in flat white paint. At the beginning of the experiment, the task luminance was set at 125 cd/m^2 while the wall wash was set at 50 cd/m^2. The window was set at off. (These conditions had been chosen as *just acceptable* lighting in a previous experiment.) Starting from this baseline condition, subjects performed three tasks - 1) arrange the task, wall, and window brightness to the level preferred for a working situation judging the room as a whole; 2) adjust the window lighting to be *comfortable* and *pleasant* when the task and wall wash lighting were held at the baseline conditions; 3) adjust the window brightness to be *just uncomfortable* for the baseline lighting conditions. This latter condition was intended to provide an estimate of discomfort glare. Subjects then completed several tests of mood and affective states. The procedure was repeated seven times from November to June. (No information was given on amount of exposure to outdoor light, unfortunately)

Analysis of the data indicated that the 10 SAD subjects preferred significantly higher wall and task luminance in the free choice situation. This preference was observed at all testing situations with little difference between sessions. The SAD group also had significantly higher preferences for window brightness when task and ambient light levels were held constant. There were no differences between the two groups for discomfort glare, although both groups showed changes across season with more tolerance for glare (in the form of higher window luminances) in the summer. Results from the affective measures analysis indicated no change in depression across seasons, although the SAD group scored higher. The data indicated no seasonal differences in mood across seasons (although summer effects were not studied). SAD subjects, however, demonstrated a significantly higher preference for "well-lit" rooms than the control group.

Inspection of the graphs for preferred light settings reveals that the control group tended to set the wall brightness at about 80-199 cd/m^2, while the SAD group tended to set it at 120-140 cd/m^2 - a significant increase of the 50 cd/m^2 baseline. For task brightness, the control group selected levels between 120 and 160 cd/m^2, while the SAD subjects selected levels around 200 cd/m^2. Control subjects set preferred window brightness between 600 and 900 cd/m^2, while the SAD subjects preferred luminances between 1200 and 1800 cd/m^2 - with the higher luminances being set in the late spring. These data indicate that the SAD subjects set higher luminances for all three types of lighting conditions - a difference which was consistent across all testing sessions. Of interest "*The preference for higher room brightness in the SAD group is not associated with a general tolerance for bright light, as shown by similarity between the two groups in discomfort glare judgments. Thus the SAD group appeared to prefer brightness levels that are very close to tolerance levels*" (Heerwagen, 1990, p. 626). Commenting on the fact that very few subjects demonstrated seasonal improvement in mood, Heerwagen hypothesized that this may have been because the experiment terminated in early June and the Pacific Northwest tends to have overcast winter and spring conditions. *"Despite that lack of seasonal changes in mood or other symptoms, the SAD group showed significant and consistent preferences for a more brightly lighted room as well as consistently higher levels of anxiety, tension, depression, confusion, irritability, and fatigue than did the control group"* (Heerwagen, 1990, p. 629). In addition, other researchers have suggested that SAD symptoms may tend to occur regardless of season in office workers (particularly those in windowless offices) who rarely experience light levels exceeding the 2000 lux suggested for reducing SAD symptoms. Heerwagen (1990, p. 630) commented that *"Thus for vulnerable people, the lack of light in their everyday environments may be a serious concern and may lead to the appearance of SAD symptoms regardless of the time of year."* She noted that windows, of course, can provide light levels as high as 1500 to 2600 lux which could reduce SAD symptoms, and which may explain some of the "desirability" of windows. Heerwagen concluded that much more study is needed to define the light levels that are needed for beneficial affective functioning as well as to determine the lighting design implications. Other researchers have explored the use of light therapy in shift work (Brainerd, 1990) to reduce incidence sleepiness and accidents on the night shift, while others have used light to minimize symptoms of jet lag (Czeisler, *et al,* 1989). These studies reinforce the importance of light in ensuring psychological well being and even in maintaining sound physical health.

<u>Psychological Response to Windows - Conclusions</u>

- Dynamic effects and view out are among the beneficial contribution of windows and daylight.

- Presence of windows and daylight contributes to psychological well-being, and may reduce incidence of transient psychoses in very restricted environments such as hospital rooms.

- Natural light is a critical regulator of circadian rhythm and can be used to increase arousal and activity.

- Light is used to reduce/remove symptoms of Seasonal Affective Disorder (SAD), jet lag, and ease shift work disturbances.

6. General Conclusions

6.1 Summary of Existing Research

In the preceding sections, research on the psychological response to different lighting configurations has been reviewed and discussed. Psychological response was defined as affective, behavioral, or subjective response (both positive and negative) to light. The review began with a discussion of the overall psychological response to lighting and whether specific responses could be elicited by particular lighting design features. This review suggested that in fact particular lighting configurations will reliably elicit the following specific subjective responses:

configuration	response
peripheral/overhead	pleasantness
uniform/non-uniform	spaciousness
bright/dim	clarity

Perceptions of clarity are associated with central overhead lighting, while the perception of spaciousness is related to the use of peripheral and wall washing systems. Finally, poor visual clarity and dissatisfaction with the lighting system are observed with extremely non-uniform lighting designs. While the underlying dimensions of psychological response were identified and associated with particular lighting designs, no indication was given as to the magnitude of the effects or the limits at which a configuration switched from peripheral to overhead or from bright to dim.

Other researchers found that the perception of spaciousness increases as the horizontal illuminance increases, as well as percentages of window area, room volume, and sky luminance. These researchers suggested that spaciousness can be determined from knowledge of illuminance, window area, room volume and sky luminance and developed a predictive formula. Furthermore, they suggested that although there maybe a lower bound to *just acceptable* spaciousness, there does not appear to be an upper bound (in which a space is too spacious to be acceptable). Specific lighting variables which contribute importantly to feelings of both spaciousness and pleasantness were identified. Specifically, increasing horizontal illuminance, providing windows, increasing room volume, and using light colors all increase the perception of spaciousness both in scale models and in actual rooms (for the first three variables). Furthermore, spaces that appear to be more *spacious* are considered to be more friendly, with no apparent upper limit.

Although different lighting designs elicit positive subjective reactions variations in lighting configurations can result in impressions of gloom, as well as pleasantness, in a space. The research suggests that impressions of gloom arise from inadequate or uneven distribution of light in a room such that the details in the corners and periphery are not discriminable. Overall light levels which are in the mesopic range as well as low surface reflectances also contribute to the impression of gloom.

Next, the research on the response to preferred lighting levels and ratios was reviewed. In an office type situation in which lighting levels could be adjusted as desired, subjects were consistently able to set preferred illuminance levels for office-like situation, with mean illuminances around 2300 lx. Furthermore, they set lighting levels such that wall luminance provided the dominant source for task illuminance, with only one-quarter of the illuminance being provided by the ceiling luminaires. They also demonstrated a preference for the wall behind them to be the brightest wall in the space, and to adjust illuminances accordingly. In a different experiment using an art gallery, while overall illuminance preferences were dramatically lower, nonetheless, there was a link between the assessment of the overall lighting quality and ability to discriminate detail as light levels increased.

The preceding discussion focused on setting desired task illuminance levels. Other researchers have examined the response to different luminance patterns and distributions in simulated offices in an attempt to set desired ratios between task and immediate surround and/or vertical and horizontal surfaces. To this end, researchers defined suggested luminance ratios for desk, immediate surround, walls, and ceiling which are likely to produce positive psychological effects. These include the following:

desk:surround	2:1 or 3:1	preferred
desk:surround:wall	10:4:3	effective
	10:5:2	restful
	10:3:4	stimulating

In addition, the review of the research demonstrates that variations in luminance distribution have a marked effect on the overall appearance of space both in terms of brightness and interest. Thus, scenes that are considered *bright* tend to have high surface luminances (above 100 cd/m^2) in the central field of view (rather than simply having luminaires with high luminances). There is a point beyond which brightness becomes excessive, however, such that luminances above 800 cd/m^2 begin to be considered *glaring* rather than *bright*. Scenes that are considered *interesting* have variations in the brightness pattern (discussed in terms of the ratio of maximum to minimum luminances) with non-uniform lighting distributions in the central 40° field of view. Many of these results were duplicated in two separate laboratories on two continents. Thus, the British research at the Bartlett School of Architecture paralleled Flynn's research at Penn State in determining that lighting moods and perceptions such as *bright/dim, uniform/non-uniform,* and *overhead/peripheral* can be reliably elicited by specific variations in the luminance distributions. The use of a scanning photometer for actually measuring the luminance distributions associated with these perceptions was initiated at the Bartlett. Recent research in Japan has suggested that artificial luminance distributions tend to have much higher contrasts as well as greater spatial distribution of high contrasts than natural scenes. Measurement of luminance contours and frequency distributions for natural and man-made scenes suggests a methodology for assessing interior illuminated environments. On the other hand, research into task lighting has yielded conflicting results about the desirability of task and ambient lighting with both negative and positive perceptions of task lighting. The data suggest, however, that unbalanced luminance distributions with extreme differences between task and surround luminances cause very negative reactions. The perceived brightness of a work place is an important component of lighting satisfaction, however, and is importantly affected by the mix of task and ambient lighting.

The research into the psychological response to variations in luminance distributions strongly suggests that *brighter* environments are perceived as more satisfying, while *dimmer*, unbalanced environment are perceived as *gloomy* and less satisfactory. Furthermore, the research has begun to suggest some reasonable luminance levels and ratios which can elicit reactions of pleasure, satisfaction, spaciousness and gloom somewhat reliably.

Nonetheless, extremes of high luminance can result in the perception of glare which can be both disabling (such that tasks cannot be seen) or uncomfortable (such that the occupant feels discomfort associated with a light source). In addition, light sources that are considered to be "glaring" can produce sensations of psychological tenseness. Physical factors which contribute to the sensation of discomfort glare include a loss of balance between light source and the surrounding brightness, the displacement of the source from viewing direction, as well as the number, size and type of light sources (including windows).

Because lighting can vary over time as well as space, several researchers addressed the response to dynamic lighting, finding that temporal variability and dynamic change in lighting seem to be preferred, at least up to a point. Beyond that point, the light sources may be distracting or appear to flicker inappropriately. Questions remain about the extent and desirability of different variations, particularly the addition of potentially distracting light sources within the field of view, as well as the effects of long exposure to such sources.

To this point, the characteristics of the light source which have been addressed have related mainly to illuminance and luminance. Yet, light sources also vary greatly in characteristics such as color and geometry. The response to color (or spectral power distribution) has been studied rather extensively, with a number of researchers assessing the factors responsible for the perception of visual clarity. They found generally that lamps with higher color rendering indices produce greater "visual clarity". Furthermore, color rendering appears to be a better predictor of preferred lighting than color temperature but both characteristics should be specified. Color gamut area is also a good predictor of preferred lighting. Several researchers have suggested the existence of a tradeoff between illuminance and CRI in which illuminance could be lowered if the CRI is high, for equal satisfaction with the lit interior. As a negative example of this hypothesis, high pressure sodium lighting has been found to be perceived as hazy and vague perhaps because its lower CRI reduces visual clarity or because its SPD differs markedly from more conventional sources such as incandescent, fluorescent or daylight. In addition, lower levels of illuminance with poorer sources may lead to complaints of fatigue or poorer performance.

In addition, the color of a lamp may affect the apparent warmth of an environment. To this end, researchers have studied the Kruithof effect which posits that lamps with high color temperatures at low illuminances will appear cold and dim, while lamps with low color temperatures at high illuminances will appear artificial. When the color rendering properties of the light source were controlled, several recent researchers failed to replicate this effect. These researchers found that generally increasing lamp illuminance makes a room appear more pleasant regardless of lamp color temperature, unless the spectral distribution of the source was markedly unusual. However, drastic alterations in spectral power distribution from normal can alter or destroy the ability to match, identify or discriminate colors, as well as the appearance of environments lighted with such illuminants.

The geometry of the lighting situation or the placement of fixtures within the room also can have a critical appearance on the appearance of objects within it, and hence the "psychological" response to the space. The concept of the "flow of light" which is related to the vector/scaler illuminance ratio, is used to describe both the direction and strength of lighting within a room. The vector/cylindrical illuminance ratio can be used to predict the amount of modelling produced by a light source on an object. In general, "good" lighting acts to maintain both lightness and color constancy, although departures from constancy are often deliberately used to create particular atmospheres and emotional responses.

Much of the research on psychological response to light has involved laboratory studies in which greater control over lighting variables is possible. Yet, information on the response to field lighting installations is also extremely valuable because it provides information on the response to "real" lighting situations to which people are exposed on a long-term basis. One of the tools which has been extensively used to evaluate office lighting is that of post-occupancy evaluation in which people's reaction to their spaces is evaluated after initial occupancy or retrofit. Such evaluations offer a valuable tool for exploring the response to installed lighting systems in a work space. Such surveys have indicated the importance of *good* lighting in achieving satisfaction with a work environment. Ability to control lighting, particularly task lighting, has emerged as desirable in several POE studies. These studies have also indicated that glare and reflections from overhead lighting can be major problem for VDT users. In addition, several studies have suggested that luminance patterns can be more important than task illuminance in determining perceived brightness in a space, thus reinforcing the conclusions cited in the earlier discussion of the laboratory research. Furthermore, perceived brightness appears to be a major determinant of satisfaction with lighting in an office space (assuming that task illuminance requirements are met). The field data also indicate that lighting situations in which dark vertical surrounds are mixed with overly bright task areas often lead to the perception that the space is dark and that the lighting is unsatisfactory.

Finally, some research into physiological responses which may underlie some of the psychological responses to lighting is discussed briefly. The two responses that were reviewed were flicker and seasonal affective depression. One study found that visible flicker from lights is perceived to be annoying and reinforced this conclusion with an assessment of complaints about headache and eye strain. This study found that the use of high frequency ballasts (rather than conventional ones) can reduce the incidence of headaches and eyestrain by minimizing flicker and subtle fluctuations in the light source. Other studies evaluated the response to windows and daylight, noting that dynamic effects and view out are among the beneficial contribution of windows and daylight. Furthermore, they determined that natural light is a critical regulator of circadian rhythm and can be used to increase arousal and activity. Finally high levels of light are used to reduce/remove symptoms of Seasonal Affective Disorder.

The review of the literature reinforces the importance of luminance distributions in determining psychological response to lighting. The distribution of light plays a critical role in determining whether a space appears pleasant or gloomy, satisfying or unsatisfying, spacious or cramped. Use of high color rendering lamps can reinforces the positive emotional response created by a luminance distribution. Moderate variation in lighting over space and time is also associated with a positive response. Thus, lighting can be used to elicit positive or negative response to an environment.

6.2 Further Research

The review of the literature presented in the preceding pages has presented considerable evidence that people find certain lighting designs to be both pleasant and satisfying. There is ample indication that the pattern of luminance in a space has a powerful impact on the *pleasantness* or *gloominess* of the space. Most of the research data tends to be general rather than specific in providing directions for achieving a desired effect, however.

Nonetheless, the overall research supports the existence of general, albeit imprecise, models which link psychological response to different physical dimensions of lighting. Thus, Flynn and his coworkers in the United States identified important dimensions of lighting which could be reliably related to physical parameters such as luminance patterns and distributions within the environment. Loe and his colleagues at the Bartlett School of Architecture validated Flynn's results while extending the measurement of luminance distributions. Julian and his colleagues at the University of Sydney identified important physical parameters related to the perception of gloom, thus indicating that lighting patterns can have a negative as well as a positive effect. Boyce and others found that the spectral power distribution of a light source plays a critical role in determining the clarity of a visual scene as well as the accuracy of the perception of color appearance. Inui and his colleagues identified lighting variables which are responsible for the perception of spaciousness within a room. Finally, Collins and others reinforced the importance of luminance patterns in determining satisfaction with actual office environments. Thus, the analysis of research into the subjective response to lighting systems reveals that psychological response is linked to the amount and placement of light within a space, as well as to its spectral characteristics.

Yet, despite the trends observed among the many studies of psychological reaction to lighting, many questions remain about predicting the effects of a particular design or type of lighting system. It is very difficult to be certain that a given light level or type of lamp or luminaire will produce the desired effect. Some of the important issues that remain unresolved involve the need to determine the parameters of the physical dimensions responsible for different psychological responses. Thus, there are few guidelines to indicate when a lighting system will be perceived as overhead or peripheral, as uniform or non-uniform, as clear or hazy, as pleasant or gloomy, or as bright or dim.

Questions remain about the role of both task illuminance and room luminance patterns as well as of the levels and distributions of light that are required to achieve specific psychological responses. For example, when does pleasantly bright become glaring, distracting, or just too bright? The findings that gloom results at levels below 10 cd/m^2, particularly with uneven distributions of light, should be replicated by other researchers in other institutions. At the same time, much more research is needed on preferred lighting levels, including documentation of the illuminances that people choose when they are free to choose. What is the contribution of different types of light sources, including daylight, to preferred illuminance levels and luminance distributions? What is the role of luminance patterns as compared with task illuminance in determining perceived brightness? There is also a need to replicate and expand the Japanese research on spaciousness and on the role of luminance contours, contrasts, and spatial frequency distributions in determining the response to interior environments.

Other questions remain about the existence of, as well as the physical metrics for, a tradeoff between task illuminance and CRI in which illuminance could be lower if CRI were high for equal satisfaction with the lighting. What is the relation between visual clarity and CRI, color gamut area, and spectral power distribution? Much greater exploration is needed of the psychological response to lighting which is dynamic in time as well as space. Many of the questions about the psychological response to lighting include the need to define the limits based on what kind of task is being performed in what type of space. For example, discos are typically lit with very dynamic, changing lighting which would drive one nuts in an office or hospital, yet which is exciting in a disco or dance hall. The research reviewed in the preceding sections also raises many questions about the effects of particularly potentially distracting light sources within the field of view as well as on the subjective response to flicker. What are the psychological effects of glare apart from discomfort? What are the effects of number of sources, the spatial separation of sources, and the size of the sources on the perception of discomfort glare?

Although the review touched on the role of view out and perceived spaciousness associated with windows, it did not really identify a response to daylighting specifically as the sole illuminant in a space. Yet, understanding of this response appears critical as investigations of SAD and other bio-psychological effects related to light levels, type of light (daylight vs HPS), duration, or timing are conducted. Finally, the review of the literature reinforces the need for much greater use of appropriate instrumentation and procedures for determining the physical conditions in a space so that the psychological response can be linked in a meaningful way. Thus in the future, we are likely to see a much greater use of luminance scanners, spectral measurements, and determination of wall/surface reflectances and colors. Despite improved instrumentation, the need for better control and measurement of both physical and psychological variables remains.

Many of the problems in determining specific, predictable linkages between lighting designs and psychological responses involve the difficulty of doing research on thinking, feeling subjects where the fact that research is being conducted may influence or determine their response. Unfortunately, sloppy research has been too frequent in the study of the psychological response to lighting. Numerous variables have often been uncontrolled and/or not measured; the stimulus and response variables have not been adequately defined; and research methods have been used which may have been inappropriate for the attribute being studied. Consequently, in many studies, the basic lighting variables such as task illuminance, surface luminance, luminaire type and distribution, or spectral characteristics have not been measured or reported. Lengthy studies are rare - subjects are typically confronted with a task that may last only 15-60 minutes and yet which is supposed to duplicate experience in a real office. Additionally, as Tiller and Rea (1992) point out, there has been an over-reliance on the semantic differential response combined with a lack of attention to other psychophysical and behavioral research techniques. Finally, the research on psychological response has been largely piecemeal and fragmented, and done sporadically at many different institutions without any commitment to a long-term series of studies.

In the vast majority of the studies reviewed in the present paper, there was a tremendous reliance on the use of both questionnaires - to determine people's reaction to specified characteristics of their environment (assumes that people report what they see and feel about an environment accurately), as well as on semantic differential research - including factor analysis and multi-dimensional scaling to relate perceptions to physical variables more directly and to elicit underlying dimensions of psychological response. Poulton (1979) has provided a critique of some of the problems inherent in using these types of approaches and indicated some important biases. Yet, other research techniques are certainly feasible and potentially quite valuable. These might include behavioral and observational research which attempts to identify how people modify their environments (by adding lamps, adding paper diffusers, moving furniture, adjusting position, etc) and determine how and where they move in space (by using light as the cue for direction, seating, or speed of movement). Manifestations of mood and attitude, including complaints or praise about the environment, as well as complaints of physical symptoms, excesses in leave (sick and annual) or conversely, extra time spent at a job or less use of sick leave, could be analyzed. Physiological measures such as arousal (such as galvanic skin response), hormonal secretions, and similar biological indicators should be explored. Pathological psychological responses to light (or the lack of light) such as depression or changes in mood (such as Seasonal Affective Disorder) should be determined.

Additionally, a very valuable area that has not been explored in detail is that of determining the response of lighting designers - or those who actually apply particular physical designs to obtain specific psychological responses. An evaluation of their designs, with careful physical measures of the lighting characteristics would allow one to obtain insight into successful and unsuccessful designs. It would also allow one to determine if the end users perceived these designs in the same manner. There is also the need to test the hypothesis that because people find a lighting installation to be pleasing they will work harder and more productively by some definable and measurable criterion, as well as determine if people who are NOT satisfied work less productively over the long term. To explore this, the physical parameters which determine pleasantness and satisfaction with a lighting environment must be identified and quantified. In addition, the working hypothesis that satisfaction with lighting is critically related to luminance patterns on the vertical surfaces must be explored for a variety of spaces and task types. At the same time, color rendering qualities of the light source should be explored, as should the role of variety in the lit environment.

Finally, the following research ideas are suggested for determining the psychological response to lighting systems. These include a thorough review of other research literatures including psychological, motivational, ergonomic, and statistics as well as the use of improved analytical and measurement techniques using up-to-date statistics, accurate computer programs, and calibrated photometric equipment. Use of other "psychological" metrics beyond questionnaires and scaling, including behavioral, observational, physiological should be considered. Of course, better definition and measurement of the physical stimuli with attention to luminance as well as task illuminance, SPD as well as color temperature is essential. The last issue involves a substantial financial and time commitment to fund multi-disciplinary effort involving psychologists, lighting designers, photometric experts, physiologists etc, from several institutions in a series of studies beginning with laboratory research under very controlled conditions and concluding with field research using carefully constructed protocols.

Despite the needs for further, more precise research, the preceding review of the literature has indicated very strongly that there are certain lighting configurations which will reliably elicit certain responses. Thus, increasing lighting levels, either for task illuminance or surround luminance, is generally associated with increased perceived brightness and satisfaction (up to some unspecified upper limit). In contrast, decreasing light level is not associated with increasing brightness and satisfaction. Similarly, increasing variety and interest are associated with positive psychological response, as is increased spaciousness. Finally, higher CRIs and color gamut areas are always preferred and viewed as more positive than lower indices of these variables. An overview of the trends in these relationships suggests that while there may be optimum levels of the physical variables, there is never a negative relationship in which lower brightness, less variety, less spaciousness, or lower CRI results in a more positive psychological response. Thus, despite the need for further research to define the limits for these physical stimuli, a great deal is known about the design of lighting systems to give pleasure to those who use them.

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