# The Relationship Between Luminance Uniformity and Brightness Perception

*Peter Y. Ngai*

Current lighting design practice, especially in indirect and direct/indirect lighting, relies on luminance uniformity as an important performance measure.[1] However, the significance of luminance uniformity should be viewed in the context of brightness perception. Brightness uniformity, luminance gradient, change in overall luminance level and frequency of occurrence of maximum and minimum luminance affect brightness perception and can alter the effect of luminance uniformity.

### Background

The psychophysical relationship between a physical stimulus, luminance (L), and the psychological response of brightness (B) has been investigated by, among others, Fechner[2], Q.E. Adam and P.W. Cobb[3], R.G. Hopkins[4], S.S. Stevens[5-6] ,and A.M. Marsdan[7]. One of the more widely known models is that of S.S. Stevens, which, in its simplest form, states that

$$B = KL^n \tag{1}$$

where n is an exponent in the order of 0.33, and K is a constant.

**Equation 1** shows that the sensation of brightness increases monotonically with the cubic root of luminance.

More recently, Bodmann, Haubner and Marsden presented Haubner's Model, which unifies a lot of previous research.[8] Haubner's Model states that

$$B = C_T(\phi)L^n_T - B_o(L_B,\phi)$$

and

$$B_0 = C_T(\phi)[S_0(\phi) + S_1(\phi)L^n_B] \tag{2}$$

where B is brightness; $B_0$ is brightness induced by background luminance; $L_T$ is target or test-field luminance; $L_B$ is background luminance; n is an exponent (0.31 ± .03); $\phi$ is the angular size of the target; and $C_T$, $S_0$, and $S_1$ are model coefficients that are size ($\phi$) dependent.

**Equation 2** shows that brightness is not only affected by test-field luminance, but also by the size of the test field and its background luminance. For an extended, large luminous field where the test field is indistinguishable from its background, Bodmann and La Toison showed that

$$B(L_B) = K1 \cdot L^n_B - K2 \tag{3}$$

where K1 = 17.346 and K2 = 1.6506[9].

**Equation 3** resembles Stevens' equation (**Equation 1**) closely.

In this paper, we will use the brightness-luminance relationships stated above to derive various aspects and consequences of luminance uniformity. **Equation 3** will be used to describe situations where change of luminance is not drastic at localized areas of analysis—i.e., a relatively smooth surface in terms of luminance. To describe luminous surfaces with abrupt variations in luminance, **Equation 2** will be used.

Before we can examine the relationship between luminance and brightness, let us establish a means to describe the luminance on an extended surface.

### Luminance and brightness distribution function of an extended surface

Let L (x,y) be the luminance distribution function of an extended field such that

$$L(x) = L(x,y).$$

That is, y is constant for a given x. The purpose of making this assumption is to simplify the illustration of the concepts, especially in the graphical presentations, and by no means to change the outcome of the analysis.

In addition, let

$$L(x) = L(x+P). \tag{4}$$

**Equation 4** shows that L(x) is a periodic function with a period of P. In lighting applications, **Equation 4** can be interpreted as a repeated luminance pattern of an area such as ceiling or wall luminance.

Combining **Equations 3** and **4**, then,

$$B(x) = B(L(x)) = K(L(x))^n - K2. \tag{5}$$

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**Equation 5** is the brightness distribution function. It describes the pattern of brightness of the extended surface given the pattern of luminance. As an example, let

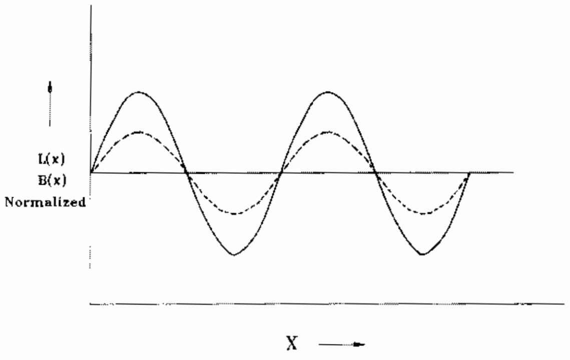
$$L(x) = A + B\sin\left(\frac{(2\pi)}{P} \bullet x\right) \qquad (6)$$

where A and B are constants and P is the period. Then,

$$B(x) = K1 \bullet \left[A + B\sin\left(\frac{(2\pi)}{P} \bullet x\right)\right]^{n} + K2. \qquad (7)$$

**Figure 1** shows in graphic form how **Equations 6** and **7** behave. Throughout the rest of this paper, we will use B(x) and L(x) to describe the brightness and luminance distribution on an extended surface.

**Figure 1—Graph of brightness and luminance distribution function.**



With the brightness and luminance distribution functions established, we can now look into various aspects of luminance uniformity on brightness perception.

### Brightness uniformity vs luminance uniformity

From **Equations 4** and **5**, it is possible to locate two points (Xmax and Xmin) within a period P such that L(Xmax) is the maximum luminance; L(Xmin) is the minimum luminance; B(Xmax) is the maximum brightness; and B(Xmin) is the minimum brightness.

Luminance uniformity (LUR) is defined as a ratio of L(Xmax) and L(Xmin), or

$$LUR = \frac{L(Xmax)}{L(Xmin)}. \qquad (8)$$

Similarly, the corresponding brightness uniformity ratio (BUR) can be defined as

$$BUR = \frac{B(Xmax)}{B(Xmin)}.$$

$$= \frac{K1(L^{n}(Xmax)) - K2}{K1(L^{n}(Xmin)) - K2}. \qquad (9)$$

LUR is the ratio of a pair of physical luminance values. By itself it does not connote any visual meaning until it is converted to BUR. The importance of BUR is that it offers us a direct interpretation that is visually significant: A 2:1 BUR tells us that one location is twice as bright as the other.

From **Equations 8** and **9**, it is clear that for a given pair of L(Xmax)and L( Xmin)

$$LUR > BUR.$$

BUR always compresses the corresponding LUR. For example, on a surface with 400 cd/m$^2$ maximum luminance and 80 cd/m$^2$ minimum luminance, the LUR is 5:1. According to **Equation 9**, maximum brightness will equal 109.5 and minimum brightness will equal 65.8, which results in a BUR equal to 1.66:1. In other words, a LUR of 5:1 does not mean that one area will be perceived as five times brighter than another; it will actually be perceived as approximately 1.6:1, the BUR.

### Estimation of brightness uniformity based on luminance uniformity

It would be convenient if we could estimate brightness uniformity from luminance uniformity. If we examine **Equation 9**, it should be clear that constant K2 is relatively insignificant. Dropping K2 from **Equation 3** at 10 cd/m$^2$ will create a difference of less than five percent. The higher the luminance, the smaller the difference. It should be noted that a five-percent difference in brightness can be significant in areas related to visibility, but in terms of uniformity ratio for the purposes of this discussion, it is not critical. Therefore, **Equation 9** can be restated as

$$BUR = \left(\frac{L(max)}{L(min)}\right)^{n} = LUR^{n}. \qquad (10)$$

This very convenient process yields a value very similar to the result of the example in the **Equation 9**. For an LUR of five, the BUR will be

$$(5)^{0.31} = 1.65.$$

One of the consequences of **Equation 10** is that BUR can be regarded as independent of actual luminous values L(Xmax) and L(Xmin). Only LUR is needed.

The above discussion assumes a relatively smooth gradient. That is, the field luminance does not change abruptly with respect to X. In these cases, it can be assumed that the brightness difference between points X, X+Δ, and X-Δ is reasonably small. This is the case if the brightness gradient $\left(\frac{d(B(X))}{dx}\right)$ is gradual and small.

There are situations, however, in which luminance does change abruptly, as in the case of a high-brightness striation resulting from the use of a highly specular reflector or a concentrated spotlight on a wall. In these instances, change in luminance $\left(\frac{d(L(X))}{dx}\right)$ and its corresponding brightness gradient $\left(\frac{d(B(X))}{dx}\right)$ can be steep.

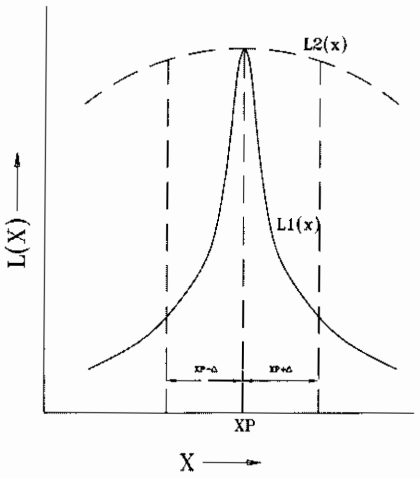


Figure 2—Graph of L1(x) and L2(x) vs X.

## Brightness and luminance gradient

Let's consider **Figure 2**:

In this example, L1(X) and L2(X) are two separate luminance distribution functions. Around X = XP, L1(X) has a very steep luminance gradient while L2(X) does not. Also assume at XP that L1(XP) = L2(XP). That is, they have the same luminance.

From **Figure 2**, we can see that for L1(X),

$$L1(XP - \Delta) << L1(XP) >> L1(XP + \Delta). \qquad (11)$$

For L2(X),

$$L2(XP - \Delta) \approx L2(XP) \approx L2(XP + \Delta). \qquad (12)$$

For brightness values associated with **Equation 11**, **Equation 3** is not applicable because it assumes a gradual change in luminance (small increments of change from point to point). In order to evaluate B1(XP), **Equation 2** should be used. For comparison purposes, we will use **Equation 2** for B2(XP) as well.

Therefore,

$$B1(XP) = C_T(\phi)L1^n(XP) - C_T(\phi)[S_0(\phi)+S_1(\phi)L1^n(XP \pm \Delta)] \qquad (13)$$

and

$$B2(XP)=C_T(\phi)L2^n(XP)-C_T(\phi)[S_0(\phi)+S_1(\phi)L2^n(XP \pm \Delta)]. \qquad (14)$$

From **Equations 11** and **12**, we can conclude that

$$L1(XP \pm \Delta) < L2(XP \pm \Delta).$$

Therefore, based on **Equations 13** and **14**,

$$B1(XP) > B2(XP). \qquad (15)$$

**Equation 15** states that two identical luminance values will have different brightness depending on the luminance gradients at that location. The steeper the gradient, the higher the brightness values. That is, brightness is not simply proportional to LUR, but is influenced by gradient. (This is why a striation on the ceiling always appears to be very bright, even though it may not have the highest luminance value on the luminous surface.) This phenomenon can be used to understand the Mach Band Effect, first reported by Ernst Mach in 1865.[10]

Conversely, in **Figure 3**

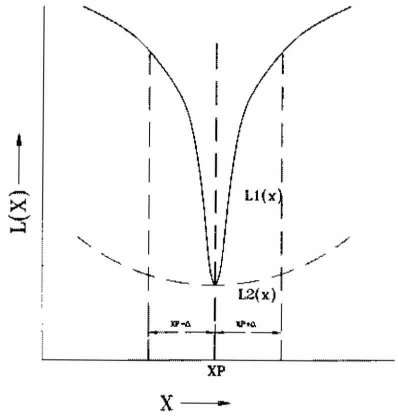


Figure 3—Graph of L1(x) and L2(x) vs X.

Due to the steep brightness gradient between L1(XP ± Δ) and L1(XP), B1(XP) will appear much darker than L2(XP). This condition describes what often happens when an indirect luminaire is located close to the ceiling. If the luminaire is constructed with a highly specular reflector underneath the lamp, it creates an area of darkness on the ceiling directly above the lamp, along its length. While the luminance of the ceiling at that area is actually close to maximum, the sharp gradient at that location makes the area look dark.

Let's look at another aspect of the relationship between brightness and luminance: how the overall luminance level affects perception of brightness.

### Perception of brightness difference at different luminance levels

For the purposes of this paper, luminance level means the overall luminance level of the extended surface and can be considered the average luminance. For example, a low luminance level might be a reduction in luminance from a high luminance level by means of a dimmer. All the photometric properties of the low level are the same as the high level, except they are lower in value.

The reason for specifying maximum and minimum values of luminance of a surface (a ceiling, for example) is to make sure that the variation in brightness on the surface does not go beyond a certain point. When a surface's luminance changes from one level to another, neither the LUR nor the BUR changes, but the absolute values of maximum luminance and minimum luminance will change. Therefore, brightness differences will change.

Bodmann and La Toison established that the requirement to maintain brightness difference between two pairs of luminance values (L1, L2 and L'1, L'2) at two different luminance levels is

$$\Delta B = \Delta B' \qquad (16)$$

where $\Delta B = B(L1) - B(L2)$ and $\Delta B' = B(L'1) - B(L'2)$.[9]

Again, let us assume two points on an extended surface, Xmax and Xmin, and the associated brightness difference between these two points will be

$$\Delta B = K1\,(L^n(Xmax) - L^n\,(Xmin)).$$

Substitute $LUR = \dfrac{L(Xmax)}{L(Xmin)}$

then

$$LUR = \left( \frac{K1L^n\,(Xmax)}{K1L^n\,(Xmax) - \Delta B} \right)^{\frac{1}{n}} \qquad (17)$$

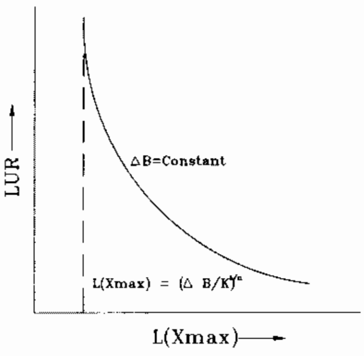


**Figure 4—Relationship between LUR and L(Xmax) with constant ΔB.**

**Equation 17** establishes the relationship between LUR and brightness difference. For a given ΔB, LUR varies with Xmax.

Both **Equation 17** and **Figure 4** show that for a given brightness difference, LUR at higher luminance levels will need to be less than that at low luminance levels.

Such is the case in VDT lighting. The difference between maximum and minimum ceiling luminance will create brightness patches on the VDT screen. As we increase the overall luminance level of the space, the patch luminance will increase accordingly. This will create a higher sensation of brightness. In order to restore the screen to the previous brightness difference at this higher overall luminance level, we have to decrease the maximum luminance or increase the minimum ceiling luminance. Therefore, the ceiling uniformity ratio will decrease. In other words, if at 25 fc 8:1 luminance uniformity provides good screen perception, then when the overall luminance level is raised to 50 fc, we will have to use a lower luminance uniformity to see the screen as well as we saw it before. (It is important to note that we are concerning ourselves with brightness sensation and not visibility of the VDT screen.)

Another example is in highlighting or spotlighting—for instance, lighting a framed picture. If the desired brightness difference between the highlight and its surround is to be maintained, then the luminance ratio between the highlighting and its surround will be different, depending on the overall luminance level. If one decreases the overall luminance level (including the spotlight) by half, then the brightness difference between the picture and its surround will decrease, therefore the picture will not stand out as much. In order to make the picture stand out, the luminance of the spotlighting must be increased (i.e., the LUR must be raised).

### Change of contrast on VDT tasks at different luminous levels

There is yet another phenomenon related to LUR that occurs in changing luminance level, and that is the effect on visibility.

Luminance contrast (C) of a task is defined as

$$C = \frac{|L_B - L_T|}{L_B}$$

where C is the contrast; $L_B$ is the background luminance; and $L_T$ is the task luminance.[11]

When veiling luminance $L_V$ is present, then luminance contrast is reduced.[12]

$$C = \frac{|L_B - L_T|}{L_B + L_V} \quad . \qquad (18)$$

Consider a VDT task lit by an extended field of luminance. Since the VDT task is self-luminous, contrast of the task is pre-set. Veiling luminance $L_V$ of **Equation 18** can be determined by

$$L_V = \sum_{i=1}^{n} E_i \beta_{Bi}$$

where $E_i$ is the i$^{th}$ illumination piece from L(x), and $\beta_{Bi}$ is the bi-directional reflective distribution function (BRDF) of the VDT.[13]

Therefore, VDT task contrast is

$$C = \frac{|L_B - L_T|}{L_B + \sum_{i=1}^{n} E_i \beta_{Bi}} \quad . \qquad (19)$$

If the screen is perfectly diffused with reflectance (ρ), then

$$L_V = \rho \sum_{i=1}^{n} E_i \quad .$$

In this case, the screen will be blanketed by a veil of even, diffused luminance, regardless of the LUR of the luminance surface.

Let's look at the case in which the VDT contrast exhibits a certain degree of specularity. If we assume the nature of specularity to be

$$L_V = E_S \beta_S + \sum_{i=1}^{n-1} E_i \beta_{Bi} \qquad (20)$$

where $E_S \beta_S$ is luminance on the VDT produced by the specular reflectance ($\beta_S$) component of the VDT, then maximum luminance (max L)can be regarded as the main source of veiling luminance.

Substituting max L for $E_S \beta_S$ in **Equation 15** yields

$$L_V = Q \cdot max\, L + \sum_{i=1}^{n-1} E_i \beta_{Bi}$$

where Q is a quantity that converts Lmax to screen luminance.

If the overall luminance level is changed from L(X) to M • L(X) (for instance, by a dimmer) then, in order to maintain the same contrast on the VDT screen,

$$Q \cdot max\, L + \sum_{i=1}^{n-1} E_i \beta_{Bi} = N \cdot Q \cdot max\, L + M \sum_{i=1}^{n-1} E_i \beta_{Bi}$$

where N is a multiple.

This is the value of the multiple to which Lmax has to adjust in order to maintain the same veiling luminance on the VDT. It therefore follows that

$$N = 1 + \frac{\sum_{i=1}^{n-1} E_i \beta_{Bi} \, (1\text{-M})}{Q \bullet \max L} \quad . \qquad (21)$$

It should be clear from **Equation 21** that N is inversely proportional to M. The higher M is, the smaller N is. That is, if one increases the overall luminance level of the extended surface, in order to maintain the same veiling luminance—and, therefore, the same contrast of the VDT—one has to decrease the maximum luminance (in other words, decrease the uniformity ratio). It should be noted that this is only applicable to VDT tasks, not to printed tasks where the contrast is unaffected by different luminance levels.

### Frequency of the luminous periodic function

There is another aspect of LUR that needs to be addressed. Consider two surfaces described by the following functions:

L1(X) = L1(X + P)
L2(X) = L2(X+2P)

and assume that L1max = L2max and L1min = L2min where Lmax and Lmin are the maximum and minimum luminous values for the corresponding functions. **Figure 5** shows the above two equations.

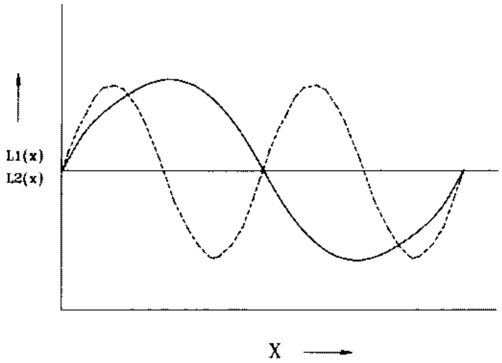


**Figure 5—Graph of two luminance distribution functions L1(x) and L2(x) vs X.**

It is evident that L1 has twice the frequency of L2. Assume that one can locate maximum luminance and minimum luminance in each period for each function. Therefore, there are twice as many Lmaxs and Lmins for L1 than L2 for a given multiple period of 2P. But for each period P for L1, one can locate L1max and L1min. This is not the case for L2 because, for the same distance P, it is only half the period for L2. One may or may not be able to locate L2max and L2min. So, for any period P for L1,

$$\text{Luminance uniformity for L1} = \frac{\text{L1max}}{\text{L1min}} \quad .$$

Within the same interval P, which is one-half the period for L2, one can also locate L′2max and L′2min, where L′2max and L′2min ≤ L2min.

Hence the luminance uniformity for L2 with the interval P equals

$$\frac{L'2\ \max}{L'2\min} \le \frac{L1\ \max}{L1\ \min} \quad . \qquad (22)$$

**Equation 22** states that if two systems have the same LUR, then for a given interval the one with a lower frequency has a better maximum/minimum ratio within that interval. Another way to look at it is for the same LUR, higher frequency means more Xmax's and Xmin's than one with a lower frequency. We usually consider lower frequency as being more desirable. Therefore, in our practice of indirect or direct/indirect lighting, we cannot compare ceiling uniformity in the absence of luminaire spacing. For example, if we have two installations with the same maximum and minimum luminance, but in one the spacing is 10 ft on center and in the other the spacing is 5 ft on center, the brightness perception on the two ceilings will appear very different. The frequency of Xmax and Xmin of a luminous surface (such as a ceiling) is also affected by the angle of view of the observer.

**Figure 6** shows that for the same angle of view (θ), the farther the distance from the observer, the higher the number of Xmax's and Xmin's. That is, in practice, for luminaires with the same suspension distance and spacing, brightness perception of the lower ceiling will appear to be better.

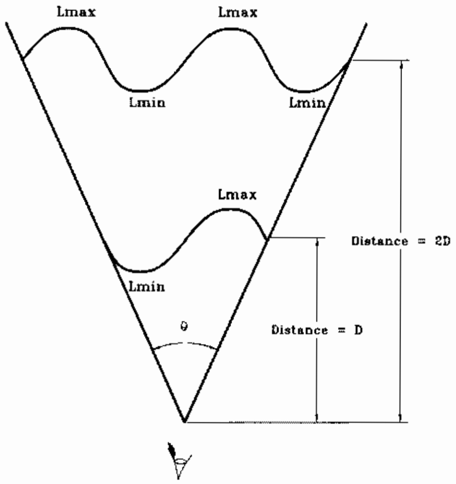


**Figure 6—Frequency vs distance for a given angle of view.**

A related phenomenon describes what occurs in observing the brightness on a large luminance surface from the observer's point of view. Assuming a luminous surface with a luminance distribution function L(X), **Figure 7** shows the geometric relationship between angle of view (θ) and distance X, where

$$X = M \tan \theta$$

*M* is the perpendicular distance from the surface to the observer.

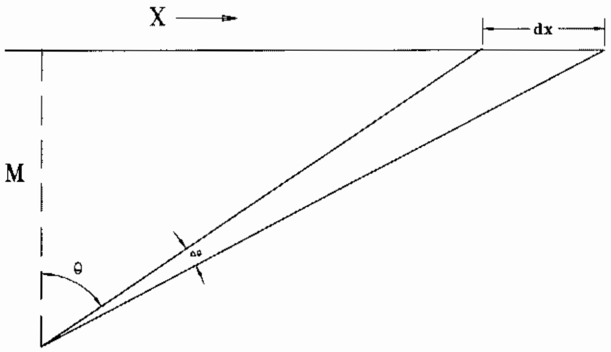


**Figure 7—Geometric relationships between distance X and viewing angle θ.**

Defining angular frequency f(θ),

$$f(\theta) = \frac{dx}{P} \text{ where P is the period}$$
$$= \frac{M}{P} \sec^2 \theta d\theta.$$

One can see that as θ increases, angular frequency increases drastically. That is, the frequency of maximum and minimum brightness will be high as one looks farther away.

Defining angular luminance gradient as $\frac{dL}{d\theta}$, then

$$\frac{dL}{d\theta} = \frac{dL}{dx} \cdot \frac{dx}{d\theta} \tag{23}$$

$$= \mathrm{M} \sec^2 \theta \frac{dL}{dx}$$

**Equation 23** shows that as angle of view increases, the angular luminance gradient also increases drastically. As we showed earlier, this will result in increased brightness.

As an example, using the same L(X) as in **Equation 6**,

$$L(\theta) = \left[A + \sin\left(\frac{2\pi}{\mathrm{P}} \cdot M \tan \theta\right)\right]. \tag{24}$$

**Figure 8** is a graphical relationship between $\mathrm{B}(\theta)$ and $\theta$ $(0 < \theta < 90)$. According to **Figure 8**, in a large space lit with indirect or direct/indirect luminaires, as one looks down toward the far end of the ceiling one will see the frequency of maximum and minimum luminance increase. The ceiling will appear to be less uniform as compared to the area of the ceiling directly overhead. Furthermore, because the angular luminance gradient increases as the angle of view increases, the brightness of maximum luminance will also increase. Therefore, the maximum ceiling luminance at the far end will actually appear to be brighter than the maximum luminance close to the observer.

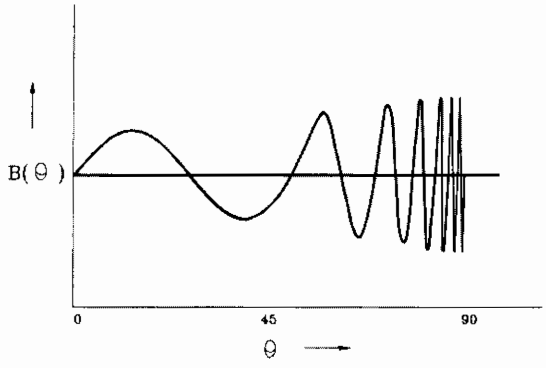


**Figure 8—Graph of brightness as a function of angle of view θ.**

## Conclusion

Luminance uniformity as a performance measure does not tell the whole story. Other considerations, such as brightness uniformity, luminance gradient, overall luminance level, and frequency should be considered as well. Perhaps this paper can serve as a first step toward refinement of our current recommendations. Looking further ahead, we need to understand more about the acceptability of luminance distribution. LURs and BURs, by themselves, help us to anchor two very important points on the luminous surface. The question still remains: What are the factors that affect the visual pleasantness of a luminous distribution on a surface? Some work has been reported in this area and the author hopes that more effort be directed toward addressing that question.[14]

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### Discussion

This paper is based upon psychophysical models that purport to represent the relationship between brightness and luminance. I have serious reservations about the underlying models, leading to skepticism of the present work. The models of Fechner, Adam and Cobb, Hopkinson, Stevens and Marsden, on which this paper is based, omit a critical factor in brightness perception—the spectral composition of the light entering the visual system. The current physiological theory of photopic visiona asserts that sight is a function of three inputs, commonly thought to replicate the sensitivities of three types of cone photoreceptors at the retina.[1–3] The inputs are often labeled red, green, and blue—referring to the parts of the spectrum where their sensitivities peak. The output from these receptors is fed into a neural system, which has an achromatic channel and two chromatic channels. The achromatic channel is thought to conform to additivity. The two chromatic channels, red-green and blue-yellow, are thought to be antagonistic or subtractive. In keeping with these theories, it has been suggested that perceived brightness may be expressed as a sum of an achromatic part and two chromatic parts.[2–9] Thorton reports the generally unknown fact that, "Perceived brightness per lumen is not constant for lights of the same perceived color, but depends importantly on their spectral content."[8] It is significant to note that this is a fundamental characteristic of vision, it is not just a fringe phenomenon associated with highly colored lights.

An enormous amount of effort has been spent over the past 75 years in an attempt to mathematically relate luminance and brightness. Indeed, a visually meaningful brightness function is greatly needed. The limited success of the proposed brightness/luminance relationships is perhaps a suggestion of an underlying problem. My own expectation is that a truly visually meaningful brightness function will be entirely independent of luminance, and will instead be derived directly from the spectrum of radiant energy. I welcome the author's comment.

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The authors have interpreted common phenomena in lighting applications using established psychophysical models. BUR on smooth-gradient extended surfaces, the effect of modulation transfer function on brightness perception on steep luminance gradient surfaces, and the influence of the reflection of the ceiling luminance distribution on the contrast of VDT tasks have been explained. This paper is very useful for helping lighting engineers and designers to recognize and understand common but sometimes overlooked phenomena in lighting applications. I hope that the author's future study will improve lighting recommendations and lighting/luminaire design.

I have a few questions, which I would like the author to address. First, I would like to ask the author how the modulation transfer function of vision could contribute to increasing brightness perception in practical visual fields. The author mentions, with regard to relatively steep luminance gradients, that the steeper the gradient, the higher the brightness values. In the case of indirect luminaires illuminating the ceiling or downlights aimed at the wall, do you think that the luminance gradient of the beam edge on the ceiling or the wall could enhance the brightness? If so, what type of luminance gradient of the beam edge could enhance the brightness perception most effectively?

Conversely, if smoothing the luminance gradients of edges of beams/luminous elements decreases brightness, easing the luminance gradients of the edges might reduce discomfort glare.

Finally, the author mentions that the maximum ceiling luminance at the far end would actually appear brighter than the same maximum luminance close to the observer. Will the author please comment on how this phenomenon would influence pleasantness and brightness impression in actual visual fields? Or does the author have any ideas for creating luminous intensity distribution for indirect/direct luminaires to increase brightness impression and to provide pleasant visual environment?

*Yukio Akashi, Doctor of Engineering*
*Rensselaer Polytechnic Institute*

The compressive nature of the function that maps luminance into brightness is well known and the models used by the author are among the most elaborate. As with other phenomenolocially based models, they have limits of application based on the range of independent variables used in the experiments from which they are formed. The author needs to address whether his proposed applications have input values that exceed these limits.

Additionally, most of Marsden's work is accompanied by tolerances that can be assigned to the predictive output of the model. That is, limits to the fineness of detail (and subsequent inferences) spring from the basic experiments. The author needs to address whether the phenomena he predicts are above these limits.

Apparently, the answers to the questions "How bright is too bright?" and "Is this a pleasing brightness ratio?" remain elusive. Anchoring the predictions made by the author will require extensive psychophysical experimentation. Perhaps some vanishing, small fraction of the vast financial resources that are now behind the author can be applied to the performance of such experiments.

*David L. DiLaura*
*University of Colorado*

This paper brings forward several useful comparisons and relationships between luminance and brightness in real-world settings. We knew that luminance and brightness are not the same. We now know that they do not change in the same ways, either. Some of these relationships are readily observable; others are more subtle or less intuitive.

The exciting thing here is the ability to quantify the luminance/brightness relationships. Is this something that could be added as a feature in lighting calculation and analysis software, such as *Lumen-Micro* or *AGI*, for the purpose of comparing differenct systems with different Lmaxs and Lmins and row spacings?

*Dawn De Grazio, LC*
*Dunham Associates*

## Author's Response

### *To Kevin W. Houser*

It is important that continual efforts are put into brightness research. Determining brightness from a spectrum of radiant energy is definitely promising. It is not appropriate here for the author to discuss the discussor's research. Suffice to say, for the past many decades, psychophysical brightness has been described reasonably well with physical luminance. Furthermore, in the context of the paper, in most cases the spectral content of the luminance environments can be assumed to be fairly constant. For example, installing different numbers of similar indirect luminaires in the same space will result in different uniformity ratios and luminance levels, but will not change the luminous spectral composition.

### *To Yukio Akashi*

Mr. Akashi's question regarding brightness perception and beam edge can best be discussed by imagining a spotlight aimed at a wall. Assuming the wall is lit with a certain background luminance, the brightness of the spot (assumed to be brighter than the background) will be affected by the gradient of the edge. The sharper the gradient of the edge, the brighter the perception of the center. The size of the spot will also affect brightness perception. We can see that when the spot becomes larger and larger and eventually occupies the entire visual field, this will make the spot luminance and its background indistinguishable. In this case, the perception of the spot brightness will be less than before. Will luminous gradient (edge) affect brightness and discomfort glare? Yes, I believe so. A good practical example is an installation of two-x-four lensed troffers. The edge brightness difference (or the gradient) between the ceiling and the luminaires is very high. Discomfort can be reduced if additional luminance is introduced on the ceiling around the edge of the luminaires.

In a very large space with a perfectly diffused ceiling, due to increase in angular frequency, the ceiling at the far end will look a bit brighter than the one that is closer to the observer. In practice, this phenomenon may be either exaggerated or diminished due to the nature of the ceiling tiles. Some types of ceiling tiles, because of their smooth texture, exhibit a more specular nature at high-incident angle. Therefore, due to the luminaires at the far end, a strong reflected brightness can be created. This will exaggerate the brightness of the tiles at a distance. Other tiles with different textures tend to help diminish the situation. Therefore the phenomenon has more to do with the nature of the bi-directional reflective distribution function of the ceiling tile than the distribution of the luminaires. What constitutes presentness of a luminous environment is outside the scope of this paper. It is, however, definitely related to the luminance gradient function.

### *To David L. DiLaura*

Mr. DiLaura's comments center on whether the applications have input values that exceed the functional limit of Haubner's Equation, and that the phenomena that the paper predicted are beyond the fineness of the detail from the basic experiments. The detail of Haubner's Equation can be found in the references cited by this paper and need not be repeated here.

The intent of the paper is to use Haubner's equation (Equation 2) to explain conceptually and qualitatively some of the brightness phenomena in dealing with real-world indirect and indirect/direct lighting systems.

There are three obvious areas to examine: size, uniformity of luminance, and range of luminance.

This paper assumes two general, basic luminous conditions as described in the beginning of the paper. One condition is when the change of luminance is relatively smooth and gentle. Evaluation is done with **Equation 3**, which was derived from the condition when the target luminance is indistinguishable from its surround. In this case the size of the target is out of the equation. In the real world of indirect and indirect/direct lighting, the ceiling is seldom perfectly uniform in luminance. (We do not prefer it either.) But for each localized area of visual fixation, the change is gentle. The liberty that the author took is to assume that it is uniform. To the extent of the intent of this paper, this is justified. Remember also that the cube root (0.3 power) that translates luminance to brightness is very forgiving.

The other condition is for surfaces with abrupt variations in luminance such as localized striations on the ceiling. In this case, **Equation 2** is used. Usually, striation subtends a very small visual angle, which is within the boundary of Haubner's Equation. There will be situations where the target size is greater, such as in the case of brightness transfer and angular frequency, but within the context of the intent of this paper, **Equation 2** is applicable to the extent that it illustrates qualitatively how brightness behaves.

Another question is, of course, what background luminance one should assign (**Figure 2**). The answer is that the sharper the gradient, the more different the background and target luminance. Hence, for equal target luminance, the steeper the luminance gradient, the higher the brightness. Current understanding does not allow us to predict quantitatively the precise numeric value of brightness under these two conditions (brightness evaluation of target luminance with gradient). But again, as in the case of size, lack of a precise quantitative model does not change the outcome of the situation. That is, for equal target luminance, steeper gradient will create higher target brightness. This is, of course, what the author wants to bring out.

As for the range of luminance of target and background, it is well within range.

***To Dawn De Grazio***

The author believes that, within limits, we can apply some of the conclusions to lighting calculations. In addition, we should also begin taking steps toward making recommendations that are based on brightness perception rather than simple luminance values. For example, should different luminance uniformity be recommended for different general luminance levels? Should uniformity be specified with a certain frequency?