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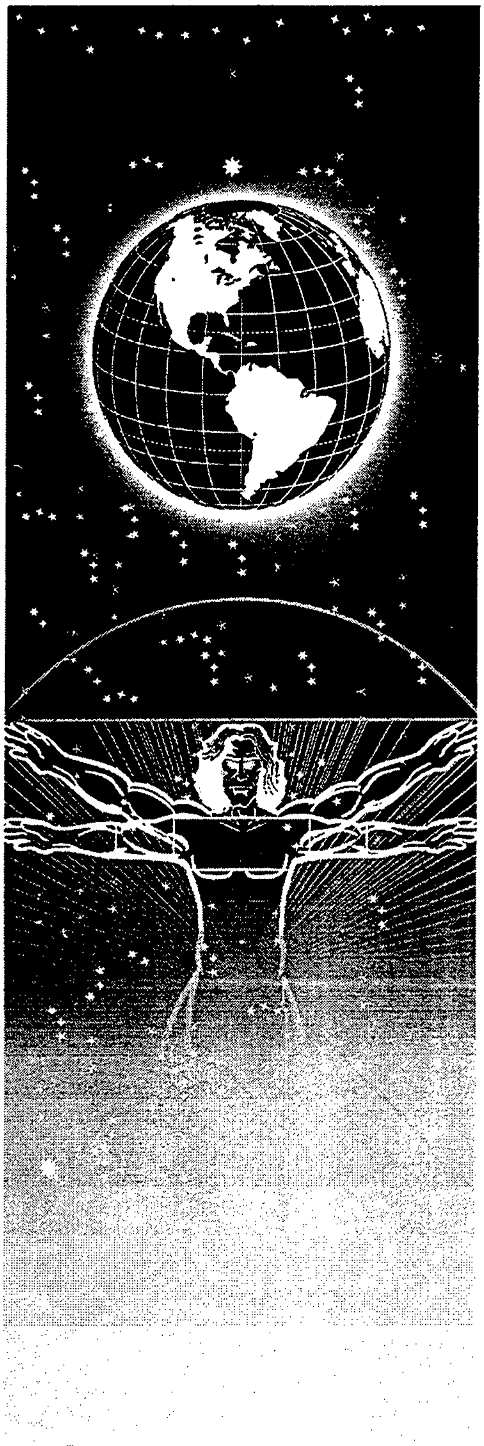

UNITED STATES AIR FORCE
ARMSTRONG LABORATORY

An Examination of the Validity of the Equivalent Background Principle for Predicting Optical Radiation Flashblindness Effects

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We reviewed the light adaptation literature in an attempt to reconcile conflicting reports about the validity of the equivalent background principle (EBP) as a means of characterizing the adaptive state of the retina. The flashblindness model of the AL/OEO Integrated Personnel Effects Model (ILPEM), effectively a dark adaptation function, relies on the EBP to relate the afterimage from an intense light exposure to a hypothetical "background" of uniform luminance that fades with time.
This relationship, if true, makes it convenient to estimate the recovery of visual sensitivity after optical radiation exposure. However, this review found that the data do not support the validity of the EBP, especially for photopic vision. A test of the ILPEM flashblindness model showed weakness in its predictive validity as well. Using the flashblindness model to quantitatively fit two sets of dark adaptation data, we found significant deviations between the predicted and actual recovery times to visual targets. An alternative model was found to be more accurate in predicting the results of the two data sets.

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BACKGROUND

The equivalent background principle (EBP) was first introduced to quantify the effects of glare on foveal vision.[1] The idea was to equate the effect of a non-uniform glare source to that of a uniform background that raised the foveal threshold by the same amount. Crawford,[2] extended this concept to the process of dark adaptation. In one of the first tests of this principle, he attempted to equate the adaptive state of the retina at one point in time during dark adaptation to the adaptation level caused by a hypothetical adapting background, an equivalent luminance background. He showed that the change in sensitivity after exposure to a bright flash of light was equivalent to the change in sensitivity while viewing an external background field of decreasing luminance. By measuring dark adaptation increment thresholds and equating them to luminance detection thresholds over a range of background adaptation luminances, he was able to predict how long it took to recover visibility of a target after bright light exposure at any light adaptation level. Thus, the equivalent background luminance (EBP) was potentially a way of characterizing the adaptive state of the retina by a single variable.

The advantage of EBP resides in its independence from target and task conditions.[3] If adaptation can be characterized by a single variable, the process of adaptation will be the same regardless of the prevailing target or task conditions. If true, such a principle could greatly simplify a practical model of dark adaptation.

The AL/OEO Integrated Personnel Effects Model (ILPEM) hosts a group of submodels which predict recovery of visual sensitivity after exposure to a flashblinding optical source. Given a set of exposure parameters, the model predicts the time it takes to recover visibility of a specific target. The flashblindness model, which is crucial for estimating the rate of visual sensitivity recovery, depends on the EBP for its validity.[4] If the EBP is not supported for different types of task and targets, then the ILPEM flashblindness model would be greatly restricted in its ability to solve operational problems of visual recovery to flashblinding optical radiation.

OBJECTIVE

The objective of this project was to evaluate the validity of the EBP based on a critical review of the experimental literature and by testing an empirical flashblindness recovery model developed from EBP. As a result of this evaluation the report concludes that a photopic EBP is not supported by the data and, consequently, recommends replacing the AL/OEO dark adaptation model with a another model that does not depend on the EBP for its validity.

TECHNICAL APPROACH

We reviewed the visual adaptation literature in order to assess the support (or lack of support) for the EBP. The Defense Technical Information Center database and the Medline database were searched for reports that evaluated the EBP. Seventeen papers were found. These papers were examined and compared in a search for common experimental conditions that either supported or refuted the principle. In addition, the validity of the EBP was empirically evaluated in a test of the ILPEM flashblindness submodel. This submodel was tested against an alternative dark adaptation model which did not rely on the EBP for its validity. The two models were evaluated against two sets of flashblindness recovery (dark adaptation) data to determine which model best fit the data.

This review is organized around the rod and cone systems because most studies tested the EBP in either the rod or cone system. One would expect that tests of the EBP would attempt to isolate one photoreceptor type because each type would be expected to have its own adaptation process.* However, this convention was not always followed. Some studies, intentionally or unintentionally, crossed the border between rods and

---

* Although the EBP is conceived as a single variable that specifies the adaptive state of the retina, it is really a shorthand reference for describing the combined effects of one rod and three cone mechanisms. If the spectral composition of the equivalent background is considered, then four variables would be required.

cones, which, made it more difficult to draw conclusions about the validity of the EBP in one or the other system.

We focused on three major factors: 1) the bleaching light, 2) the adapting background light, and 3) the test target, and the ways they were used in the visual tasks. We wanted to determine if differences in the quantity or type of these factors could account for the conflicting findings of the research reports. Consequently, we examined the size, intensity, retinal location, duration, and spectral content of the bleaching and adapting lights, as well as the size, location, duration, spectral bandwidth, and spatial structure of the test stimuli. We begin with examining the relevant cones studies followed by the rod studies.

RESULTS

Tests of the EBP in the Cone System

We examined twelve studies that looked for evidence for the EBP in the cone system. Six of the twelve studies found evidence in favor of the EBP. Our general finding was that no factor or combination of factors could distinguish between evidence for or against the EBP. We found considerable overlap in the experimental values chosen for the three major parameters: the bleaching light, the adapting light, and the test stimulus. Bleaching field sizes could be small or large, foveal or extra-foveal, white or colored, with either short or long bleach durations. Backgrounds could be colored or white, or have large or small spatial extents. Similarly, test stimuli overlapped in dimensions of size, duration, color, and retinal location. Table 1 summarizes the parameter values used in the cone studies. As can be seen, no set of conditions appears to distinguish between studies that support or reject the EBP.

TABLE 1. STIMULUS CONDITIONS USED IN CONE STUDIES TO TEST THE EBP

	Size	Duration	Location	Band
Test				
For	3.5-40', 7°	25-500 ms	F, F-7°, F-16°	W, 655 nm
Against	3-45'	5-50 ms, 1 s	F, F-5°	W, R, G
Bleach				
For	14', 5°, 7°, 14°	.5, 30 s, 2, 24 min	F, F-7°, F-16°	W, R, G
Against	31', 2-8°	26 s, 2-5 min	F, F-5°, F-8°	W, 490, 512 nm
Background				
For	5-14°	Steady	F, F-7°	W, 657 nm
Against	13.5', 30', 2-8°	Steady, .5, 1, 26 s,	F, F-5°	W, R, G

Key: F = fovea, W = white, R = red, G = green

One reason for finding no clear-cut distinctions between studies for or against the EBP may be attributable to some methodological shortcomings. As will be seen, there is considerable evidence that the rod and cone systems have different adapting mechanisms. However, the EBP studies did not always select stimulus conditions to isolate the system of interest. For example few cone studies used stimuli to which the cone system is optimally sensitive. Spots of white light were often used instead of spatially structured, chromatic, or high temporal frequency stimuli. In addition, only a few studies attempted to actively suppress the rod system in the course of studying the cone system, or vice versa.

Finding no set of common conditions that discriminated between studies for or against the EBP, we turned our attention to the individual reports. The reports were reviewed with regard to the type of task used to test the EBP. Several studies used spatial summation tasks. Geisler[5] presented white test lights of 3.5', 10', and 50' in diameter centered on the fovea after brief exposure to an intense bleaching field 5° in diameter. The increment threshold curves for the three test sizes were similar to dark the adaptation curves, suggesting that at least for these stimulus sizes and retinal location, the EBP was found to hold. Miller[6] tested the EBP using different sized (28.7' and 16.3') Sloan-Snellen acuity letters and different bleaching energies (7.5, 7.1, and 6.7 log td-s). The log recovery times of the two targets were linearly related to log equivalent field luminance at each flash intensity, suggesting that spatial summation held and that a single background luminance parameter was sufficient to predict threshold identification for the letters. However, because Miller used relatively large targets at a low luminance of 0.07 mL, it was unclear whether cones were selectively isolated. Rather, recovery probably involved a mixture of rods and cones. Crawford[2] tested the EBP over a wider range of retinal area. He examined spatial summation with white test spots 0.18° to 5.7° in diameter. Again, the EBP was found to hold for spatial summation. However, the bleaches and adapting backgrounds ranged from scotopic to photopic levels and the data supported the EBP more at scotopic adaptation levels than at photopic levels.

In their review of the EBP, Hood and Finkelstein[7] criticized the Geisler[5] report because of the restricted range over which spatial summation was tested. Geisler's dark-adaptation and increment threshold curves were parallel, indicating no change in spatial summation over the retinal area tested. Hood and Finkelstein[7] argued that if test stimuli are within the limits of spatial or temporal summation then the EBP necessarily has to hold. A similar criticism can be leveled at the Miller[6] report. As a result, the evidence from these two studies can not be used to confirm EBP validity for photopic viewing.

Nevertheless, other studies found evidence for a photopic EBP using different tasks. Bauer, Frumkes, and Holstein[8] found that the EBP was valid for differences in rod masking illuminances (thresholds) when masks were less than 1° in diameter. For masks greater than 1° the EBP did not hold, however. They found that as rod dark adaptation proceeded, i.e. as rods recovered, the cone threshold gradually increased. It appeared that rods inhibited cone thresholds during rod dark adaptation. This result indicated an equivalence between dark and light adaptation at least for small retinal areas. The contradictory results for the different sized masks suggested that differences between the inhibitory and excitatory mechanisms existed in the channel mediating rod-cone interactions. Beyond 1° rod signals were apparently channeled into a much larger inhibitory spatial summator.

Miller[9], using an afterimage brightness matching technique, found that the fading positive afterimage could be matched by an adjustable real background light over a period of two minutes after an adapting light flash. These results suggested that the fading afterimage during dark adaptation was equivalent to a real background light in controlling the sensitivity of the retina.

Other studies found evidence against the EBP. These studies, though not all methodologically sound, appear to have collected sufficient evidence to reject the validity of a general photopic EBP. Some studies found that dark adaptation results matched light adaptation results qualitatively but not quantitatively. For example, Geisler[10] found that increment thresholds were not equivalent when measured during dark adaptation and against steady backgrounds of various intensities. However, dark adaptation and background adaptation results did coincide if the effect of a subtractive inhibitory process was eliminated. More recently, Hahn and Geisler[11] confirmed Geisler's[10] earlier findings using spatially limited sine-wave patterns. Again, they found non-equivalence of bleaching and background adaptation mechanisms. They concluded that bleaching adaptation was local and multiplicative, but that background adaptation was not completely local and likely involved more than one mechanism.

Buss, Hayhoe, and Stromeyer[12] measured very small test targets (2') on small backgrounds of 5',13',19', and 31' in diameter. They examined the EBP in the context of spatial summation and found that if a large field was added to a small bleached patch, the patch did not lower the threshold as much as it would have when added to an equivalent small background. This result suggested that bleaches and backgrounds which produced equal threshold elevations did not have equal inputs to the spatially opponent site. The bleached condition apparently produced much stronger opponent signals than the background condition. Consequently, thresholds were higher in the bleached condition than in the background condition. The authors concluded that the sensitivity loss caused by bleaches and backgrounds could not be simply explained on the basis of one adaptation mechanism. Rather, sensitivity was controlled by more than one variable, for example, a gain change in the receptors together with a change in receptor membrane potential that could affect sensitivity by response compression, with background and bleaches affecting these variables somewhat differently.

Bowen and Hood[13] used temporal resolution and threshold detection tasks to test the EBP. They found that the results qualitatively but not quantitatively supported the EBP. Findings such as this raise the question of whether the lack of quantitative evidence in support of the EBP could be due to experimental error or other uncontrolled factors, such as the precision of calibration or the effects of eye movement and light scatter. One factor of some importance seems to be stabilizing the background adapting field on the retina. When the background is not stabilized this condition does not conform to the effect of a brief bleaching light. Eye movements could change the spatial relationship between the test stimulus and the adapting field, especially if small adapting fields are used. Two studies have suggested that this factor may be responsible for some of the differences between dark adaptation and background adaptation results[14,15].

Stewart[16] employed a temporal summation task to test the usefulness of the EBP in describing recovery early in dark adaptation. She used test lights 0.005 s and 0.2 s in duration. Weak adapting (0.62 and 1.38 log mL) and bleaching flashes were used to test temporal summation during the first 22 s of dark adaptation. Stewart found significant differences in the adapting background luminance for the two temporal stimuli at a given stage in dark adaptation. Compared to the level of sensitivity indicated by the short test flash, the thresholds for the long test flash showed less temporal summation for the equivalent background of dark adaptation than for a real background. However, it is difficult to ascribe the failure of the EBP to either the rod or the cone system since the longer stimulus probably stimulated both rods and cones and the shorter stimulus stimulated only cones. In addition, the bleaching light flash of 240 mL was probably not intense enough to completely saturate the rods. Thus, the differences in temporal summation may have been due to adaptation differences between rods and cones.

Rinalducci, Higgins, and Kramer[17] isolated individual cone mechanisms in a spatial summation task. Red or green tests spots 8'and 20' in diameter were presented for 20 ms on the fovea. Test spots were presented on either a red or green adapting background and visual recovery was measured after exposure to a 4.17 log td adapting flash. Both the homochromatic and heterochromatic conditions produced failures of the EBP. The researchers reasoned that the EBP failed because each cone mechanism had independent excitatory and inhibitory adaptation mechanisms. They suggested that the large area test spot stimulated both excitatory and inhibitory mechanisms but the small spot stimulated only the excitatory mechanism. Alternatively, it has been suggested that changes in spatial summation take place during dark adaptation and that these changes are mostly accompanied by the reorganization of receptive fields and the gradual cessation of inhibition.[18] Thus, these results argue against an EBP in the photopic system.

Cone Adaptation Mechanisms

Several researchers[1,7,10,19-21] have proposed that light and dark adaptation consists of multiplicative and subtractive mechanisms that operate very early in the visual pathways. Multiplicative adaptation mechanisms include pupillary constriction, photopigment bleaching, changes in temporal and spatial summation, as well as other, as yet unidentified, factors.[7,10,19] The subtractive process appears to occur through lateral inhibitory effects[13,22] and may work in the following way. A bipolar cell receives direct input from the photoreceptor and indirect input from neighboring photoreceptors via the horizontal cell. Direct inputs are excitatory and indirect inputs are inhibitory. The result is a subtractive process in which much of the direct excitatory activity is canceled by the indirect input from neighboring photoreceptors. This center-surround inhibitory arrangement contributes to the visual system's ability to maintain responsiveness with increasing levels of ambient illumination by effectively canceling much of the background intensity.

If the location of these mechanisms turns out to be at the receptor level, then it may be concluded that light adaptation is largely complete by the time the signal reaches the bipolar cell. This conclusion is consistent with the observation that bipolar cell responses would otherwise saturate at much lower light levels than they normally do, producing the so-called response saturation effect.[20,23] Because of the early adaptation mechanisms, however, the strength of the incoming signal remains within the response range of the bipolar cell.

Geisler[10] suggested that the subtraction mechanisms may also be responsible for the differences between bleaching and background adaptation. He suggested that the equivalent background hypothesis does not hold for the cone system because the additional absorbed quanta from the background are driving the visual system part of the way up its intensity-response function. As a result steady backgrounds produce lower thresholds, compared to the dark adapted state, because of the inclusion of the subtractive mechanism. Thus, thresholds will be lower under conditions of steady backgrounds whenever lateral inhibitory mechanisms have a chance to work. However, the backgrounds must be relatively large for lateral inhibition to work this way. Indeed, very small backgrounds have the opposite effect, actually raising thresholds because they presumably produce more response compression.[22] To more fully understand how background size affects adaptation, it would be helpful to determine the spatial extent of the antagonistic surround and how it varies with adaptation level and retinal location. If the antagonistic surround varies as a function of retinal location and adaptation level, it may account for the way in which spatial channels change thresholds in the presence of changing adapting background levels.

These results led Kortum and Geisler[24] to conclude that bleaching adaptation is local and multiplicative in nature but background adaptation is more complicated, possibly involving one or more subtractive mechanisms in addition to a multiplicative mechanism.[21,25] Whether or not the center-surround antagonism arrangement of the cones and horizontal cells are solely responsible for the failure of the equivalent background hypothesis in the cone system will be decided by future investigation.

Tests of the EBP in the Rod System

Four out of five rod studies found evidence in support of the EBP. The EBP was found to be valid for brightness matching of stabilized images[14,15] and spatial summation,[2,26] but not temporal resolution.[27] Studies by Barlow and Sparrock[14] and Rushton and McLeod[15] matched the brightness of the afterimage of a circular field bleached by a white light flash with a continuously presented white annulus, stabilized on the retina. Brightness matching took place over a 4-6 log unit range which spanned rod and cone sensitivity. These researchers found the decaying afterimage could be matched by a real background image when the background was stabilized on the retina just as the afterimage was. Because they stabilized backgrounds these studies were able to track the afterimage brightness in its positive and negative phases. The researchers concluded that Crawford's[2] "equivalent background light" during dark adaptation was, in fact, the flashed afterimage fixed on the retina and that it functioned like a real background image in setting the adaptation level of the retina for scotopic vision. The afterimage was an equivalent background which effectively could be added to a real background, so that the threshold was simply the increment threshold of the combined backgrounds. Because Barlow and Sparrock[14] found equivalence between dark adaptation thresholds and increment thresholds obtained on stabilized backgrounds, it leads to the question of whether or not some failures of the EBP is because the adapting background is not stabilized on the retina as the flashed background normally is. The consequences of using non-stabilized backgrounds may be particularly problematic when using small very small backgrounds and test stimuli.

Blakemore and Rushton[26,28] found evidence for the EBP in the rod system by using a rod monochromat as a subject. They showed equivalence between dark adaptation and steady backgrounds for spots of light and for gratings of different sizes. Moreover, consistent with the above studies,[14,15] they found that real backgrounds and after-images were additive. After-images acted like actual backgrounds in their ability to affect adaptation level, and hence, thresholds. Assuming that similar results could be obtained in individuals with a full complement of photoreceptors, the results indicated that adaptation mechanisms are simpler in the rod system and may be accounted for by a single variable.

Although some support the rod EBP has been found, other studies have rejected it in other tasks. Ernst[27] measured the rod critical fusion frequency (CFF) against real background lights and an afterimage after an 8.5 log td-s adapting flash. When test lights were well above threshold, he found that CFF thresholds measured against a real background light were higher than during dark adaptation.. However, when test lights were near threshold the EBP was confirmed. These results suggested that the rod system has at least two adaptation mechanisms, but that one mechanism may dominate at threshold levels of sensitivity. Similar conclusions have been reported by Teller and Gestrin[29] and by Adelson.[30]

CRITIQUE OF MODELS

The second part of this project concerned an evaluation of the ILPEM dark adaptation model. Besides the question of its theoretical validity as discussed above, the ILPEM model has exhibited several other problems and limitations. First, the model was based on data from only one study,[6] using a single target, which limits its generalizability. Second, the dark adapted threshold for the test stimulus had to be estimated because it was not reported in the original paper. The dark adapted threshold is crucial because it estimates the absolute sensitivity of the retina. Inaccurate estimation of the dark adapted threshold can cause all other thresholds during dark adaptation to be misjudged. Because of the linear fitting procedures used, the model is not analytical as recovery time approaches zero. The equivalent background approaches infinity as the recovery time approaches zero which is not possible. This problem renders the model invalid for estimating very short recovery times, such as the recovery of visibility between pulses of multiple pulse lasers.

Alternative models reported in the literature offer several advantages over the current model. In a pair of reports Geisler and colleagues[11,24] presented models of light and dark adaptation. These models are not based on an equivalent background, which avoids the validity problems of the EBP. The dark adaptation model is analytical for very short post-exposure times and is based on a set of targets varying in spatial frequency. These features give the dark adaptation model greater validity and extends its utility over more target conditions than the current model.

Description of the Models

The ILPEM flashblindness model[4] specifies the brightness of a hypothetical background that fades in brightness as a function of time after a bleaching light exposure. The equivalent background depends only on the retinal illuminance of the initial light exposure and time after the exposure and has the form:

$$\log(\mathrm{EBL}) = -3\log(t) + 1.75\mathrm{E} - 6.33$$

where t is in seconds, the integrated retinal illumiance of the adapting light, E, is in log troland seconds, and EBL is given in cd/m.[2] This model is based on data from Miller.[6] However, a critical assumption was made regarding the model derivation. It was assumed that the dark-adapted threshold contrast of a Snellen-Sloan letter with a critical angle of 3.3' was 7%. This threshold may have been underestimated. Other research indicates that the threshold contrast for similar letters is between 9% and 13% for a background luminance of 1 mL.[31] As a result of this assumption, the function relating the log intensity of the bleaching light and the log time at which the equivalent background faded to 1 mL could be approximated by a linear function. This function is shown in

Figure 1, but is plotted instead on linear-log coordinates. It can be seen that the function is linear over a range of bleaching energies and recovery times. However, it is clear that the equivalent background luminance continues to increase as recovery time approaches zero. This result is impossible since the equivalent background cannot be brighter than the initial light exposure. The equation is problematic at the other extreme, as well, because the EBL never reaches zero, as one would expect after a sufficient time in the dark.

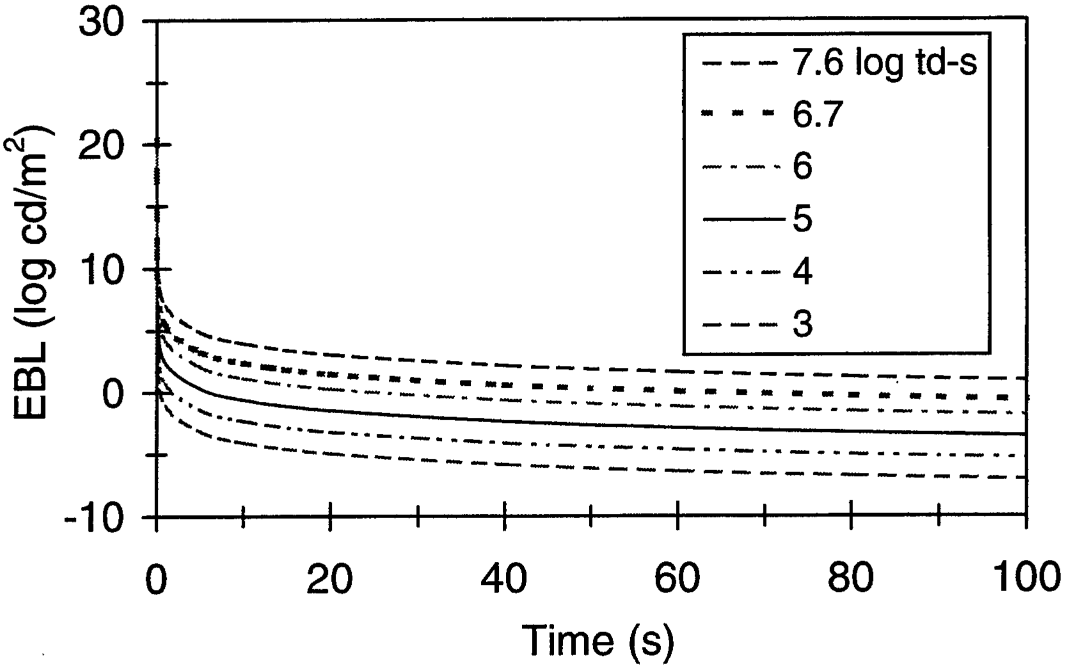

Figure 1. An illustration of the ILPEM dark adaptation model showing the relationship between the equivalent background luminance and recovery time for various integrated retinal illuminance exposures. Note that the equivalent background luminance (erroneously) continues to increase as recovery time approaches zero and continues to decrease indefinitely with increasing time.

The Hahn-Geisler[11] dark adaptation model is a four parameter model of the form:

$$\log \mathrm{Amp}(t) = \alpha(e^{-t/t_o}) + \beta$$

where Amp(t) is the amplitude threshold at time t in seconds, α is the initial increase in threshold due to bleaching adaptation, t_o is the time constant of recovery, and β is the dark-adapted threshold. The amplitude parameter is used as a substitute measure of contrast for increment-Gabor patch stimuli presented against a black background. Nevertheless, the equation is equally suitable for more traditional measures of sensitivity, such as increment contrast thresholds. The behavior of this model for a hypothetical bleaching condition is shown in Figure 2. The Hahn-Geisler model is analytical at very short recovery times; the amplitude reaches an asymptote when $t = 0$. Furthermore, the amplitude threshold approaches the dark-adapted threshold as t increases toward infinity.

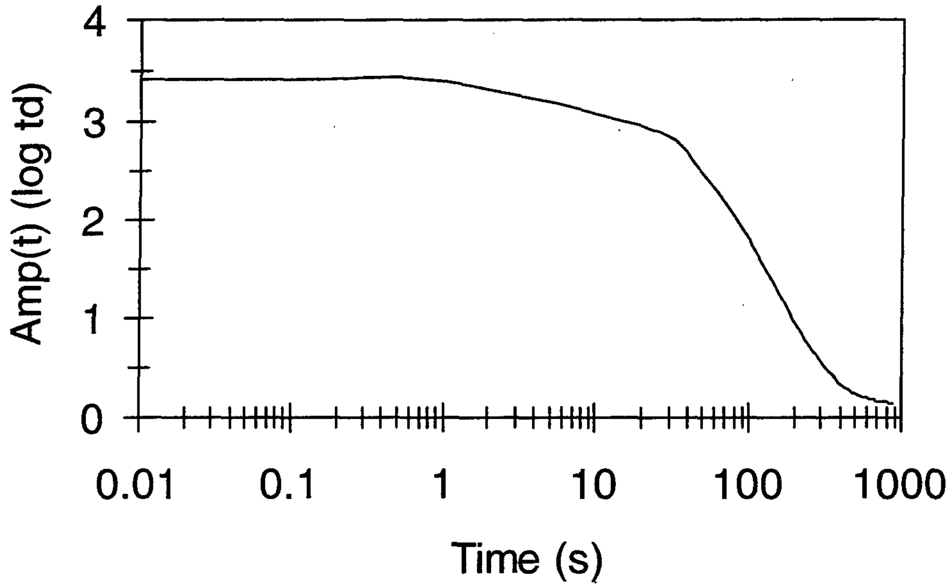

Figure 2. An illustration of the Hahn-Geisler dark adaptation model showing that the amplitude threshold asymptotes as time approaches zero and with extended viewing time.

Comparison of the Two Models

The ILPEM flashblindness model and the Hahn-Geisler model were tested against two data sets: one set from Geisler's lab[11] and one set collected by Menendez and Garcia[32] at AL/OEO. The Hahn and Geisler[11] data consisted of dark adaptation thresholds from two observers measured on Gabor patches with center frequencies of 1, 3, 7, 10, and 15 cycles per degree (cpd). Amplitude thresholds were obtained against a dark background for approximately 15 minutes after offset of a 7.85 log td-s bleaching flash. The Menendez and Garcia[32] data were composed of dark adaptation contrast thresholds. Sine-wave gratings with spatial frequencies of 1, 4, 8, 12, and 24 cpd at a mean luminance of 10 cd/m^2 were collected from four observers. Grating contrasts ranged from 100% to 1.28%. Recovery times were measured over a period of about 120 s.

To directly compare the two data sets, the data were converted to log amplitude thresholds for the Hahn-Geisler model. For the ILPEM model the data were transformed into log equivalent background luminances. Non-linear regression techniques from the Systat statistical package and the Excel and Sigmaplot spreadsheets were used to evaluate the models.

Figures 3 and 4 show the results of the fit of the Hahn-Geisler model to the Hahn and Geisler[11] data and the Menendez and Garcia[32] data, respectively. It can be seen that the Hahn-Geisler model fit both sets of data to a high degree of accuracy, with R-squared regression coefficients greater than 0.99. The parameter estimates of the two data sets are shown in Table 2.

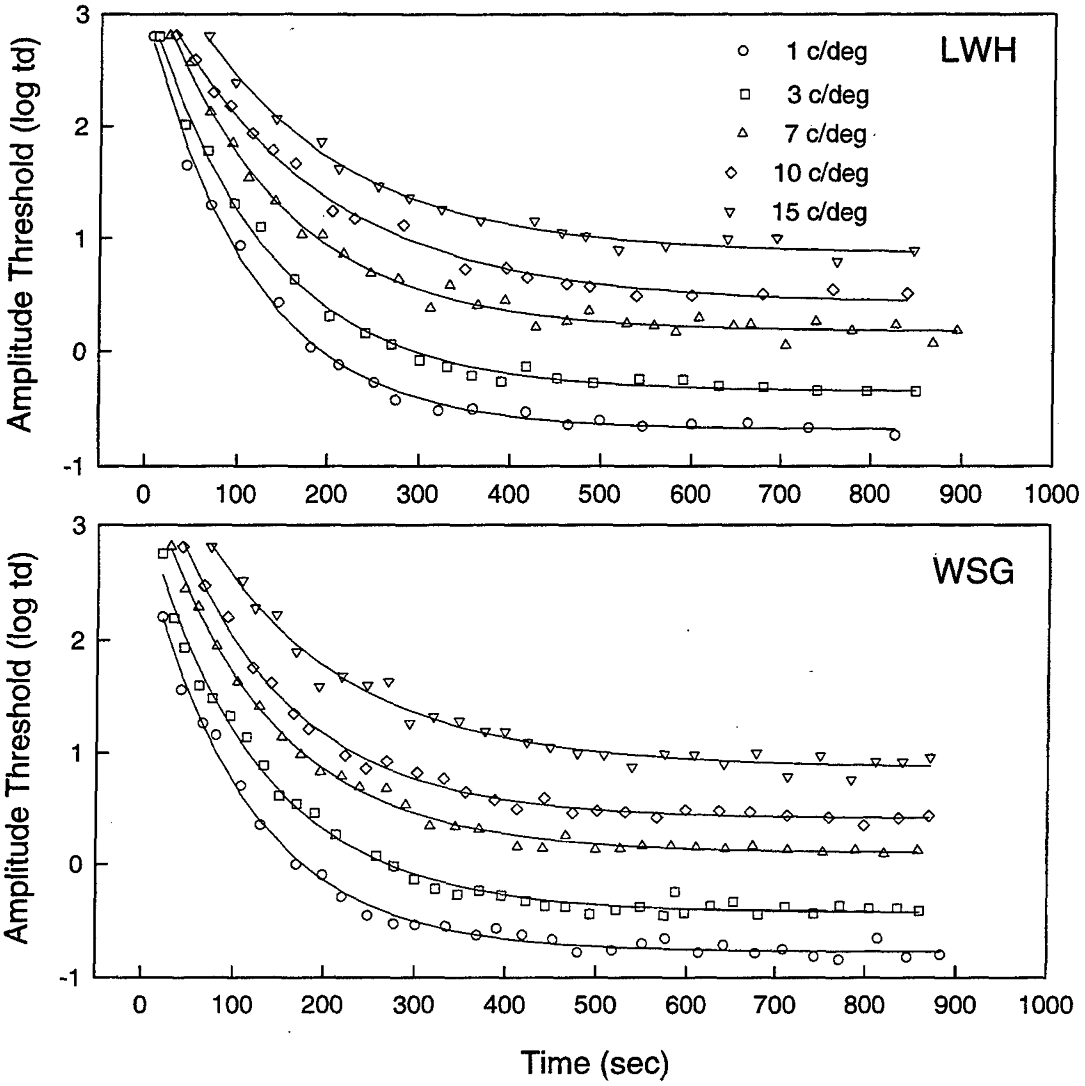

Figure 3. The Hahn and Geisler[11] dark adaptation data for two observers and five spatial frequencies fit with the Hahn-Geisler model.

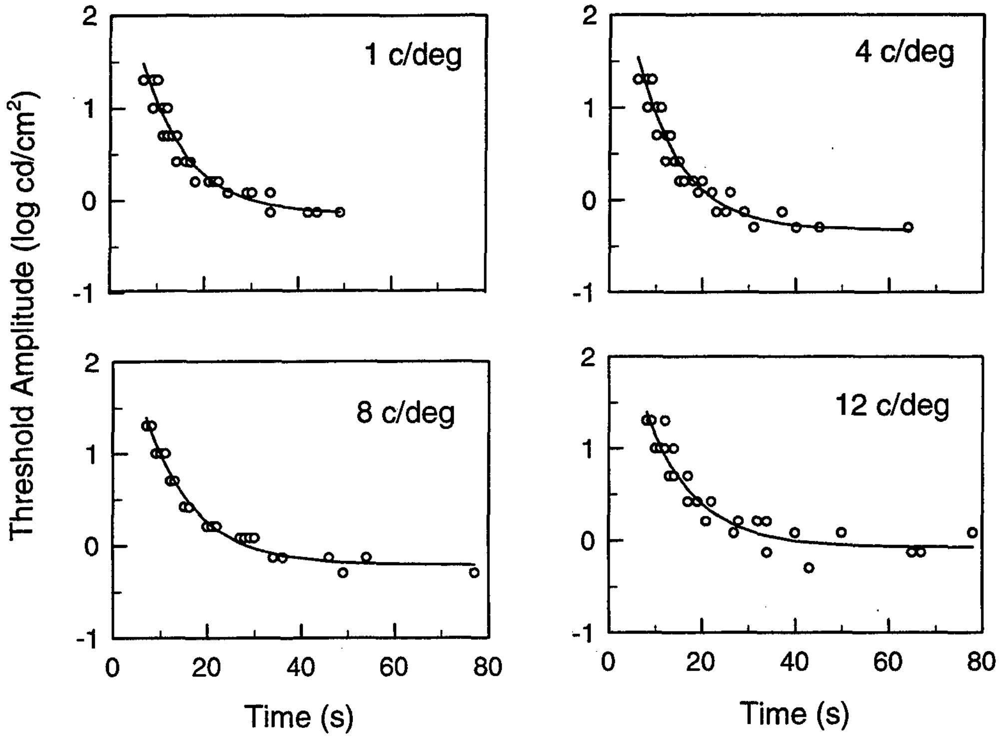

Figure 4. The Menendez and Garcia[32] flashblindness recovery data for four observers and for four spatial frequencies fit with the Hahn-Geisler model.

TABLE 2. THE HAHN-GEISLER MODEL PARAMETER ESTIMATES OF THE MENENDEZ AND GARCIA[32] DATA AND THE HAHN AND GEISLER[11] DATA

		Spatial Frequency (c/deg)				
Menendez-Garcia	Parameter	**1**	**4**	**8**	**12**	**24**
	α	3.383	3.491	3.116	3.316	2.142
	β	0.104	0.104	0.095	0.095	0.101
	t_o	-0.146	-0.328	-0.212	-0.075	0.158
Hahn-Geisler		**1**	**3**	**7**	**10**	**15**
	α	3.627	3.482	3.284	3.098	2.936
	β	0.009	0.008	0.007	0.007	0.006
	t_o	-0.742	-0.404	0.139	0.411	0.865

The ILPEM model fits are shown in Figures 5 and 6 for the Hahn and Geisler[11] data and the Menendez and Garcia[32] data, respectively. The ILPEM model did not fit either data set as well as the Hahn and Geisler model. The ILPEM model consistently underestimated recovery time (i.e. predicted shorter recovery times than were actually observed) for recovery times longer than 20 s.

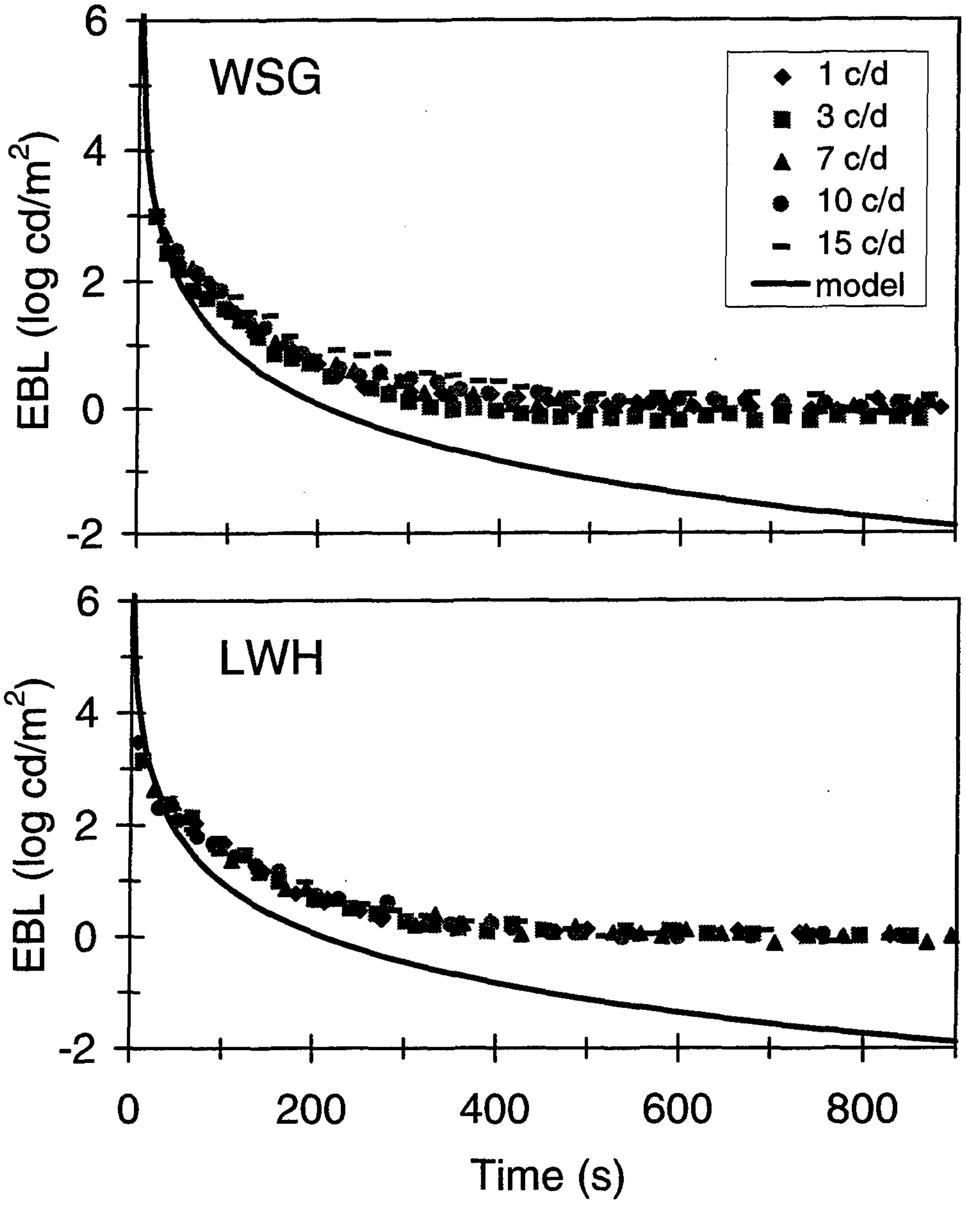

Figure 5. The Hahn and Geisler[11] data fit with the ILPEM model. Amplitude thresholds were converted to equivalent background luminances. A) observer LWH, B) observer WSG.

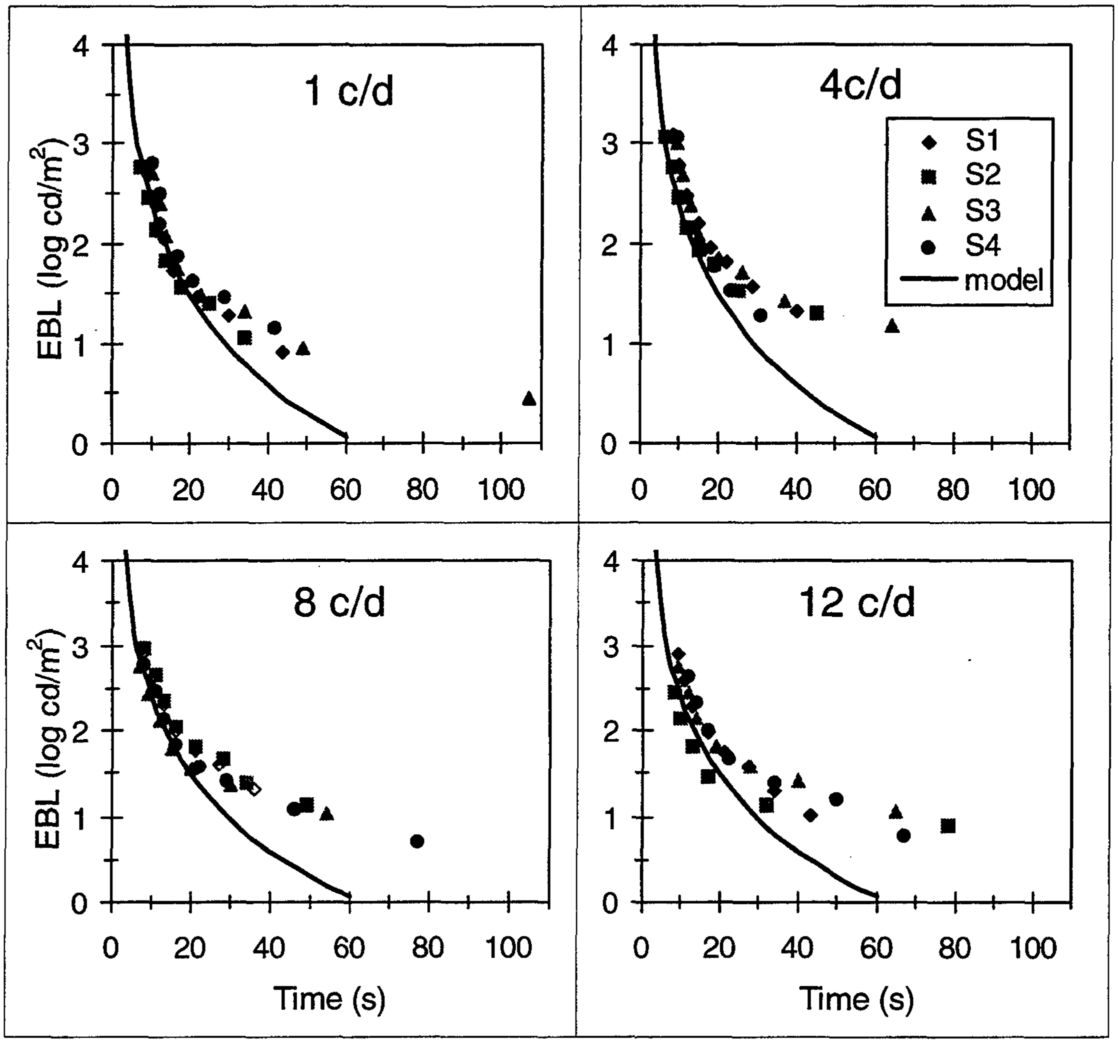

Figure 6. The Menendez and Garcia[32] data fit with the ILPEM model. Each plot represents data from four observers.

CONCLUSIONS

It is clear that the Hahn-Geisler dark adaptation model provided a better fit to the dark adaptation data than the current ILPEM model. However, this takes on somewhat less significance considering that the Hahn-Geisler model has three free parameters compared to none for the ILPEM model. The ILPEM model would benefit from allowing the constant to freely vary, especially since was derived from the dark adapted threshold, which was estimated, not empirically derived. However, the other modeling and theoretical shortcomings noted above do not favor a modification of this model. Thus, the modeling results indicate that the Hahn-Geisler model provided a more accurate method of estimating recovery time to flashblinding optical radiation. We recommend that the Hahn-Geisler model be considered for use in ILPEM.

Although the Hahn-Geisler model more accurately estimated dark adaptation thresholds, the Hahn-Geisler model exhibited some problems and limitations of its own. The model was developed on data from only two subjects, and so lacks generality. A more serious drawback is that it requires estimates of three parameters, which will vary according to adaptation and target parameters. Thus, a user may have difficulty specifying values for these parameters for a particular application. However, it may be possible to replace some of the free parameters with constants if it can be shown that the parameter has little variance across observers and test conditions. For example, the slope parameter, alpha, has been estimated to be about 3.0 under a variety of flash and target conditions. As shown in Table 2, alpha varies little across spatial frequencies and observers. This parameter could be replaced with a constant without sacrificing modeling accuracy.

Two other problems with also limit the Hahn-Geisler model's generalizability. First, the model is limited to the target characteristics similar to the ones used in the experiment. Second, only one level of flash intensity was used and so no parameter is given for flash intensity. In order to produce a more general model, that is, one that is not dependent on the target, one could divide each set of spatial frequency data by its dark adapted threshold. This procedure would, in effect, "normalize" the data across spatial frequency as shown in Figure 5. This figure shows that all the data from the five spatial frequencies fell on one curve after normalization. This relationship suggests, as did the EBL analysis, that the rate of recovery during dark adaptation is the same regardless of the target, and if the target's dark-adapted threshold is known, then recovery time could be predicted from the flash and time constant parameters.

The Hahn-Geisler model is also limited to the recovery of targets in the dark. As reported by Hahn and Geisler,[11] dark adaptation functions cannot be replaced by a set a background adaptation functions. Thus, another model would be needed to predict recovery times for targets against light backgrounds. The companion paper to Hahn and Geisler,[11] provides a model for this situation.[24]

The results of the studies on the EBP point to the notion that the rod system behaves as though bleaching adaptation and background adaptation are equivalent in steady state tasks, but not under other conditions, such as temporal resolution. The rod system appears to have two adaptation mechanisms, but under certain circumstances one mechanism appear to dominate. For the cone system, the EBP generally fails, but it appears to hold under the special case when the subtractive mechanism is bypassed.[10,22] This mechanism is bypassed during bleaching adaptation because the brief flash does not allow the subtractive mechanism sufficient time to operate.[10,21] One could conclude from these findings that the EBP might hold for both the rod and cone systems if the subtractive mechanism is not activated during background adaptation. The larger number of failures associated with the cone EBP could be because the subtractive mechanism operates faster and is organized differently in the cone system.[19,21,33] Because the cone system is tuned for pattern discrimination it may be that the subtractive mechanisms are more localized than in the rod system.

Assuming that all ganglion cells across all spatial channels have the same firing thresholds, one can draw some inferencess about how the different spatial channels response properties change with changes in adaptation level. First, at any particular adaptation level, contrast threshold differences between channels are, in large part, due to spatial summation. Cells with large receptive fields will reach threshold at lower ambient levels than cells with small receptive fields because they receive a larger amount of inputs. Spatial summation studies that take into account receptive field size have shown that the drop off in sensitivity at low spatial frequencies is an artifact of a restricted stimulus field size. Increasing the number of cycles in low spatial frequency stimuli, presumably until the entire receptive fields are covered, results in lower thresholds. When the number of cycles is optimized for lower spatial frequencies, the contrast sensitivity function takes on a low pass form, having a constant slope up to about eight c/deg and then dropping off sharply thereafter (Hoekstra, van der Goot, van den brink, and Bilsen, 1974). Also evident from their study is that the number of cycles needed to optimize contrast sensitivity increases as background luminance increases. This result means that receptive field size increases as background luminance increases. This effect would be expected if additional cells contribute to a spatial channel as the background light level increases. Increasing the background would bring higher threshold cells, such as high spatial frequency cells, closer to threshold, thereby lowering the threshold of the low spatial frequency channel. Such a mechanism implies that low spatial frequency channels receive inputs from high spatial frequency cells at higher adaptation levels.

Thus, two events may account for increased contrast sensitivity as background light level increases. First, cells with smaller receptive fields and fewer inputs approach firing threshold as background light level increases. Second, the higher spatial frequency cells contribute to lower spatial frequency channels, expanding the channel's receptive field and increasing its sensitivity.

A re-examination of the equivalent background problem with respect to the magnocellular and parvocellular divisions of the visual pathways may prove fruitful. The magnocellular pathway receives input from the rods and a portion of the cones, whereas the parvocellular pathway receives input only from cones. It may be that the two systems have separate adaptation mechanisms, the magnocellular system which is consistent with EBP and the parvocellular system, which is not. This hypothesis could be tested in a future AFOSR or ER research project.

TRANSITION POTENTIAL, DUAL-USE

The Hahn-Geisler dark adaptation model could be adapted for use in clinical ophthalmology to diagnose pathologic conditions of dark adaptation or photoreceptor function.

RELEVANCE TO AIR FORCE

From the standpoint of the aircrew member a flashblindness episode represents a window of vulnerability in which the aircrew member is unable or less able to perform his or her duties. In operational terms, it is important to accurately estimate the susceptibility of flashblindness effects both in terms of effects on visual function and on mission performance. A quantitative, validated model will provide more accurate estimates of visual recovery times for specific operational conditions and will help in mission planning, hazard evaluation, and in the assessment of the effectiveness of optical radiation countermeasures.

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