Interactions between flicker thresholds and luminance pedestals

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Abstract

We investigated the interactions between flicker thresholds and luminance pedestals using threshold versus contrast (TvC) and method of constant stimuli paradigms. High amplitude luminance pedestals were found to elevate flicker thresholds, but low amplitude luminance pedestals were unable to reduce flicker thresholds. Luminance pedestals elevated flicker thresholds more at low temporal frequencies. A simple model based on local light adaptation was able to capture the general form of the TvC functions. Our results suggest that flicker thresholds derived in the presence of a luminance pedestal (luminance-pedestal flicker) may vary from those obtained by modulating about a mean luminance (mean-modulated flicker). © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Contrast discrimination functions; Light adaptation; Luminance pedestal flicker; Masking; Facilitation

1. Introduction

Investigations into the temporal responsiveness of the visual system use two types of flickering stimuli, namely mean-modulated and luminance-pedestal flicker (Fig. 1). Mean-modulated stimuli vary luminance about a background level and so effect no change in the time-averaged luminance. Luminance-pedestal flicker is achieved by modulating a luminance increment over time, resulting in both a flickering component and a change in the time-averaged luminance (a luminance pedestal). At some temporal frequencies, the onset and offset of the luminance pedestal is more detectable than is the flickering component (Vingrys, Demirel & Kallo- niatis, 1995).

One issue that needs to be considered is whether luminance-pedestal flicker thresholds are equivalent to mean-modulated flicker thresholds. The two thresholds will be equivalent only if the luminance pedestal has no effect on threshold outcomes. This seems unlikely, given recent work that suggests that luminance pedestals can alter flicker thresholds (Eisner, 1995; Eis-
static transducer. Bodis-Wollner and Hendley (1979) presented 8 Hz flickering gratings upon static grating pedestals, but their study had insufficient power to determine the presence of facilitory effects. Pantle (1983) also presented flickering gratings upon static grating pedestals and failed to show facilitation at low pedestal amplitudes. However, as his study used test and masking gratings of differing spatial frequency, the absence of facilitation could be due to this spatial discrepancy. Consistent with this possibility, his static gratings on static pedestals show no facilitation either (Fig. 3; Pantle, 1983). Georgeson and Georgeson (1987) found that the facilitory effect present with static gratings (1 c/deg) disappeared when the test grating was presented as a single cycle of 40 Hz flicker, although threshold elevation at high pedestal amplitudes remained. This finding implies that static luminous contrast is unable to directly excite the flicker contrast transducer for grating stimuli, but can elevate flicker thresholds. Given that certain aspects of contrast discrimination in low spatial frequency gratings can be predicted from local luminance responses (Kingdom & Whittle, 1996), it may be expected that luminous-contrast/flicker-contrast interactions for small spot targets would show a similar pattern to those found for gratings. It is not clear, however, what effect temporal frequency has on these interactions.

We investigated the interactions between luminance pedestals and flicker thresholds over a range of temporal frequencies for spot targets using a Tvc paradigm and by establishing psychometric functions. We present a model, based on local light adaptation, that describes the main effects found in our data.

2. General methods

2.1. Subjects

Six subjects (20–30 years) participated in the experiments; five in Experiment 1 and four in Experiment 2. All had best corrected visual acuities of 6/6 or better and no history of ocular disease or migraine (McKendrick, Badcock, Heywood & Vingrys, 1998). All subjects wore their habitual spectacle correction for testing and used monocular viewing with natural pupils. For eccentric targets (15°) only nasal locations were tested. The study complied with the tenets of the Declaration of Helsinki, with subjects giving written informed consent prior to participation.

2.2. Apparatus and procedure

Stimuli were generated using a Cambridge Research Systems VSG 2/3 graphics card (Cambridge Research Systems Ltd., Kent, UK) and displayed on a gamma corrected Hitachi™ HM-47231-D colour monitor (mean luminance 25 cd/m²; frame rate 120 Hz). The visible area of the monitor subtended 19.3° × 13.7° (w × h) at 1 m, and was surrounded by a 4 cd/m² square white background that subtended 53° horizontally. Spatial variations in the output of the monitor (Metha, Vingrys & Badcock, 1993) were avoided by having subjects alter their fixation for eccentrically presented targets.

In Experiment 1, thresholds were measured using a two-interval forced choice paradigm and a ZEST procedure (King-Smith, Grigsby, Vingrys, Benes & Supowit, 1994) of 30 trials, allowing thresholds falling outside the realisable gamut to be predicted. Stimuli were presented in a pseudo-random order and thresholds were determined from an average of two estimates (log threshold) made at different times. In Experiment 2, a two-interval forced choice method of constant stimuli with 100 trials per intensity was used to determine psychometric functions. Preliminary investigations suggested that eight intensities, separated by 0.23 log units, adequately described the psychometric function. A suprathreshold trial (maximum intensity) was included to determine false negative rates. In all experiments, the beginning of each interval was indicated by an auditory tone, and auditory feedback was provided after each trial.

All stimuli and pedestals were 0.5° diameter white (1931 CIE, x = 0.283, y = 0.319) sharp-edged spots, presented at either 0 or 15° eccentricity. Square wave flicker was used at temporal frequencies of 4, 7.5, 12 and 20 Hz, with thresholds given as mean-to-peak amplitudes. Flickering stimuli were presented with their positive going phase at onset. All luminance pedestals were presented at the same time as the flickering stimu-
lus. For all experiments, three stimulus-pedestal combinations were used: luminance increment stimuli on luminance pedestals, flickering stimuli on flickering pedestals and flickering stimuli on luminance pedestals, the latter being termed the luminance-pedestal flicker condition. For stimuli presented on luminance pedestals, a 4 cd/m² background was used to maximise the range of pedestals that could be investigated. In contrast, as flicker requires both incremental and decremental luminance excursions, a higher background (27 cd/m²) was used for flickering pedestals (see Table 1). All luminances were constrained to lie above the lower 5% of the monitor’s range, to avoid the ‘dark-light’ of the monitor (Metha et al., 1993).

2.3. Stimulus timing

The effects of stimulus duration and inter-stimulus interval (ISI) were determined by empirical investigation. For luminance increment stimuli, durations of 8.3 ms (1 frame) to 1000 ms (120 frames) were investigated. For flickering stimuli, durations ranged from a single cycle up to 2000 ms, with all durations giving an integer of flicker cycles. Only the extremes of temporal frequency (4 and 20 Hz) and pedestal magnitude were investigated.

The effect of stimulus duration is shown in Fig. 2. As expected, the data for the luminance increment detection task (filled circles) shows a characteristic Bloch’s law response (Hart, 1987) with constant thresholds beyond 100 ms. However, thresholds for a luminance increment presented on a luminance pedestal (unfilled circles) are largely unaffected by duration. This suggests that luminance discrimination is achieved when the stimulus is a fixed proportion greater than the pedestal, regardless of duration. The results obtained at 15° eccentricity (not shown) were of a similar form to the centrally collected data. We decided to use a 200 ms stimulus for all subsequent investigations involving luminance increments.

The 4 and 20 Hz luminance-pedestal flicker thresholds (squares and triangles, respectively) both decrease up to a critical duration (∼ 700–800 ms). These changes in threshold are larger than would be expected from probability summation over time (Watson, 1979) and suggest that the luminance pedestal raises thresholds initially but that its effect is redressed over time. The results for a flickering stimulus presented on a flickering pedestal of the same frequency (not plotted) gave a flat response as seen with the luminance discrimination task (Fig. 2, unfilled circles). Trends were the same for both central and eccentric data sets. We decided to use a stimulus duration of 750 ms for all flicker investigations, except for the 7.5 Hz stimulus where the longer duration of 800 ms was used. These durations allowed an integer of flicker cycles to be presented in all cases.

Using the stimulus durations determined above, the effect of ISI (8.3 ms (1 frame) to 1000 ms) was investi-

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Table 1
Average ± SEM threshold (λ) and slope (β) of the best fitting Weibull functions for different types of stimulus–pedestal and background luminance

<table>
<thead>
<tr>
<th>Stimulus–pedestal type and background luminance</th>
<th>Pedestal luminance (cd/m²)</th>
<th>λ</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static–static 4 (cd/m²)</td>
<td>0</td>
<td>0.18 ± 0.03</td>
<td>2.39 ± 0.30</td>
</tr>
<tr>
<td>Static–static 0.1</td>
<td>0.09 ± 0.02</td>
<td>1.50 ± 0.12*</td>
<td></td>
</tr>
<tr>
<td>Static–static 2.15</td>
<td>0.72 ± 0.10*</td>
<td>1.13 ± 0.03*</td>
<td></td>
</tr>
<tr>
<td>Static–static 21.54</td>
<td>3.82 ± 0.23*</td>
<td>1.09 ± 0.12*</td>
<td></td>
</tr>
<tr>
<td>Flicker–static 0.46</td>
<td>0.09 ± 0.02</td>
<td>3.18 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>Flicker–static 21.54</td>
<td>0.71 ± 0.07*</td>
<td>3.04 ± 0.56</td>
<td></td>
</tr>
<tr>
<td>Flicker–flicker 27 (cd/m²)</td>
<td>0.38 ± 0.05</td>
<td>3.52 ± 0.70</td>
<td></td>
</tr>
<tr>
<td>Flicker–flicker 0.46</td>
<td>0.22 ± 0.04</td>
<td>1.25 ± 0.10*</td>
<td></td>
</tr>
<tr>
<td>Flicker–flicker 10</td>
<td>1.71 ± 0.15*</td>
<td>1.43 ± 0.14*</td>
<td></td>
</tr>
</tbody>
</table>

* Denotes that the parameter is significantly different (P < 0.05) from the zero pedestal condition.
Fig. 3. Effect of inter-stimulus interval (ISI) on threshold for a 20 Hz luminance-pedestal flicker stimulus (squares), a 4 Hz luminance-pedestal flicker stimulus (triangles), and a luminance increment presented on a luminance pedestal (circles). All luminance pedestals were 21.54 cd/m², and all data were collected with central fixation. Data points give the mean of five observers ± SEM.

Fig. 4. TvC for a luminance increment presented on a luminance pedestal. Data points give the mean of five observers ± SEM and were collected with central fixation. The horizontal dashed line and filled symbol gives the average threshold for the baseline (no pedestal) condition, which has been plotted on the abscissa at 2.

Fig. 5. Effect of ISI on threshold for flickering stimuli presented on a flickering pedestal. Data points give the mean of five observers ± SEM.

3. Experiment 1: luminance and flicker TvCs

3.1. Aims and methods

The main purpose of this experiment was to consider the effect of a luminance pedestal on flicker detection, using a TvC paradigm. We also wished to confirm the existence of a dipper-shaped TvC function for both luminance-on-luminance and flicker-on-flicker conditions. It should be noted that amplitude, rather than contrast, is plotted in all our TvC functions and so our curves are strictly amplitude discrimination functions, as described by Yang and Makous (1995). For simplicity, we will refer to the curves as TvC functions as our curves would be exactly the same shape if plotted as contrast values, given the constant background luminance.

3.2. Results and discussion

Fig. 4 shows the TvC for a luminance increment presented on a luminance pedestal. It should be noted that in this, and other TvC curves, low pedestal amplitudes significantly decreased luminance increment thresholds (facilitation), whereas high pedestal amplitudes significantly increased luminance increment thresholds, giving a characteristic dipper-shaped TvC consistent with previous work (Cornsweet & Pinsker, 1965; Whittle, 1986). The results obtained eccentrically (not shown) were similar in form, but had elevated thresholds and an increased upward slope to the TvC.

The results for flickering stimuli presented on flickering pedestals can be seen in Fig. 5. A dipper-shaped TvC is present at both temporal frequencies investigated, with significant facilitation evident. Similarly shaped functions were obtained eccentrically (not shown). These results are consistent with those that have been obtained for flickering (Boynton & Foley, 1999) or moving (Stromeyer, Kronauer, Madsen & Klein, 1984) gratings. The existence of a dipper-shaped TvC for both luminance and flicker discrimination is consistent with an S-shaped transducer function under-
lying both forms of contrast processing. Therefore, is it possible for a luminance pedestal to directly excite the flicker contrast transducer and so produce a similar dipper-shaped TvC?

The TvCs for luminance-pedestal flicker presented centrally are shown in Fig. 6. The most obvious difference between these TvCs and those of Figs. 4 and 5 is the absence of facilitation at low pedestal amplitudes. Only two points (marked with asterisks) showed significant facilitation, being the $-0.66 \log$ pedestal condition at 7.5 Hz and the $-0.33 \log$ pedestal condition at 12 Hz, and the magnitude of this facilitation was approximately one half to one third of that found in the luminance-on-luminance or flicker-on-flicker condition. Correcting for multiple comparisons within the ANOVA (Dunnett’s Method) also gave significant results. The absence of a consistent facilitatory effect is not due to low power in the ANOVA: for an effect of 0.167 log units (smaller than those seen in Figs. 4 and 5), power exceeded 0.80 for all temporal frequencies. The results for luminance-pedestal flicker presented eccentrically are given in Fig. 7. No significant facilitation is evident at low pedestal amplitudes, and the TvC upward slopes are increased eccentrically when compared with those obtained with central fixation (Fig. 7 vs. Fig. 6). For both the central and eccentric data, the upward slopes of the TvCs reduce as temporal frequency increases.

These results suggest that the luminance pedestal present in luminance-pedestal flicker is not able to excite the flicker transducer (Ross & Speed, 1991; Boynton & Foley, 1999), but can influence the flicker mechanism in a way that produces threshold elevation, possibly via an adaptational process (Ross & Speed, 1991). As temporal frequency increases, the upward slopes of the luminance-pedestal flicker TvCs decrease, which is consistent with increased linearity of the flicker mechanism as temporal frequency increases (DeLange, 1958; Kelly, 1961; Roufs, 1972). Therefore, it seems that local light adaptation (i.e. background plus pedestal) may be involved in the effect exerted by the luminance pedestal. It should be noted that, because the TvC slope changes with temporal frequency, nor-

![Fig. 6. Centrally collected TvCs for flickering stimuli presented on a luminance pedestal for four temporal frequencies. Points marked with asterisks show significant facilitation when compared to baseline. The solid line gives the best fitting form of the light adaptation model described in the text ($Q$-statistics are $<0.001$, $<0.001$, $<0.001$ and 0.93 for the 4, 7.5, 12 and 20 Hz conditions, respectively). The dotted line gives the locus of stimuli that can be produced by square-wave modulation of a luminance pedestal with a 50% duty cycle. Other details as per Fig. 4.](image)
malising the Tvc axes to detection thresholds will not result in a common detection template as has sometimes been found in the spatial domain (Yang & Makous, 1995).

4. Experiment 2: psychometric functions

4.1. Aims and methods

To more fully quantify the threshold changes seen in the TvcS above, psychometric functions were determined on four observers for important pedestal amplitudes (Table 1). For luminance increments presented on luminance pedestals, functions were determined with no pedestal, with a facilitatory pedestal (0.1 cd/m²), and two pedestals that raised thresholds (2.15 and 21.54 cd/m²). For luminance-pedestal flicker stimuli, functions were determined with no pedestal, a low pedestal (0.46 cd/m²) and a high pedestal (21.54 cd/m²). For flickering stimuli presented on flickering pedestals, functions were determined on no pedestal, a facilitatory pedestal (0.46 cd/m²) and a high pedestal (10 cd/m²). All investigations were performed with central fixation, and all flickering stimuli were 4 Hz.

Data from each observer were fitted, using a $\chi^2$ minimisation technique, with a Weibull function of the form:

$$\psi(x) = 0.5 + (0.5 - \lambda)(1 - e^{-((x/a)\beta)})$$

where 0.5 gives the probability of guessing in the forced choice paradigm, $x$ the threshold, $\beta$ the slope, and $\lambda$ the lapsing probability (false negative rate, as a probability). Consistent with King-Smith et al. (1994) we found low lapsing probabilities that never exceeded 0.03.

We wished to determine whether significant differences existed between the psychometric function parameters under various experimental conditions. Although bootstrap techniques can be used, and have the advantage of making no assumptions regarding the distribution of the data (Maloney, 1990), our sample size was insufficient to implement such techniques. Therefore, we determined mean values from the individual coefficients of each observer, as described by Anastasi and co-workers (Anastasi, Brai, Lauricella & Geracitano, 1993).

4.2. Results and discussion

Psychometric functions, derived from the average parameters listed in Table 1, are plotted in Fig. 8. For luminance increment stimuli (Panel a), the introduction of a small pedestal produces a leftward shift in the curve, as well as a significant shallowing of the slope (Table 1) consistent with the facilitation shift in the TvC function (Fig. 4). Such slope change has been reported previously (Nachmias & Sansbury, 1974) and can be predicted by assuming an accelerating transducer function encoding contrast. At higher pedestal amplitudes, the psychometric functions show significant shifts to the right, consistent with the raised thresholds.
found in the TvC data. A similar pattern is seen for the flickering stimulus presented on a flickering pedestal (Panel c).

The results for the luminance-pedestal flicker stimulus are given in Panel b. As expected from the absence of a facilitory effect in the TvC, the presence of a small pedestal (thin solid line) has no significant effect on the shape or position of the psychometric function. At the higher pedestal, the curve shifts rightward, as expected. No significant difference was found between the slopes of the psychometric functions of Panel b, indicating that the slope does not alter in the presence of a luminance pedestal.

5. Discussion

The results from Experiment 1 suggest that independent S-shaped transducer functions exists for both luminance and flickering contrasts. This is evident from the fact that luminance and flicker pedestals can excite their own transducers, causing facilitation, but a luminance pedestal is unable to exert an excitatory effect on the flicker transducer. Nevertheless, the luminance pedestal is able to elevate flicker thresholds. This latter finding is consistent with the work of Eisner (1997) who found that a luminance pedestal suppressed flicker sensitivity. The dependence on temporal frequency of the TvC’s upward slope is suggestive of light adaptation and the following section explores how well a model of local light adaptation can predict these TvC functions.

5.1. A light adaptation model for luminance-pedestal flicker

If mean-modulated flicker thresholds are determined at two different background luminances, the adaptation characteristic of the flicker response can be described by the following equation,

\[
A = \log\left(\frac{T_2}{T_1}\right) \log\left(\frac{B_2}{B_1}\right)
\]

where \(B_2\) and \(B_1\) are the higher and lower backgrounds, respectively, and \(T_2\) and \(T_1\) are the flicker thresholds obtained at these backgrounds. The adaptation characteristic, \(A\), is equivalent to unity under Weberian adaptation. In luminance-pedestal flicker, we propose that the local luminance (i.e. background plus pedestal) is important in setting the level of adaptation of the flicker mechanism. A similar argument has been successfully applied to chromatic stimuli presented on intense luminance pedestals (Cole, Stromeyer & Kronauer, 1990). The following equation results:

\[
A = \log\left(\frac{T_{\text{ped}}}{T_{\text{mean}}}\right) \log\left(\frac{B + P}{B}\right)
\]

where \(T_{\text{ped}}\) and \(T_{\text{mean}}\) are the flicker thresholds under luminance-pedestal and mean-modulated conditions respectively, \(B\) is the background luminance, and \(P\) is the luminance pedestal. Solving for \(T_{\text{ped}}\) gives:

\[
T_{\text{ped}} = T_{\text{mean}} \times 10^{(A \times \log(B + P/B))}
\]

Eq. (4) was fitted to the data in Figs. 6 and 7 by minimising the \(\chi^2\) statistic, and is shown by the solid curves. As the parameter \(T_{\text{mean}}\) was set to the mean-modulated flicker threshold, the equation had only one free parameter, \(A\). It is apparent that this model can capture the general form of the experimental data. Fig. 9 shows how parameters \(A\) and \(T_{\text{mean}}\) change with temporal frequency. The adaptation characteristic, \(A\), declines as temporal frequency increases, and is of
Fig. 9. Parameters $A$ and $T_{\text{mean}}$ from the fitted curves in Fig. 6 (circles, central) and Fig. 7 (squares, 15° peripheral). See text for details.

Consistently higher magnitude for the data presented eccentrically. The curve for $T_{\text{mean}}$ returns the temporal sensitivity function to a mean-modulated stimulus.

Given these results, it seems that the luminance pedestal in luminance-pedestal flicker raises flicker thresholds primarily through a process of light adaptation, as determined by stimulus onset asynchrony paradigms (e.g. Crawford, 1947). Likewise, the capacity of a luminance pedestal to raise thresholds is increased for eccentric stimuli (Fig. 9, upper panel). This most likely reflects the stimulus appearing physiologically smaller in the periphery, due to increased receptive field dimensions with eccentricity (Hubel & Wiesel, 1974), as it is known that small stimuli can defeat adaptational processes and cause saturating responses (Buss, Hayhoe & Stromeyer, 1982; Tyler & Liu, 1996).

However, the adaptation model appears to over-estimate thresholds at moderate pedestal amplitudes. This is reflected in the $Q$-statistics for the model (see figure legends), which are sufficiently low in some cases ($< 0.001$; Press et al., 1992) to suggest that other determinants of luminance pedestal-flicker interactions need to be sought. The failure of local light adaptation to fully explain the data can also be seen in the psychometric functions of Fig. 8. In the high pedestal condition of Panel b, the local luminance was 25.54 cd/m² whereas in the zero pedestal condition of Panel c it was 27 cd/m². Given these luminances, a local adaptation model would predict similar thresholds. However the data of Table 1 shows that, although the slopes of the psychometric functions are not different (3.04 vs. 3.52, $P = 0.57$), the threshold parameter $\alpha$ is significantly higher (0.71 vs. 0.38, $P = 0.05$) in the luminance-pedestal condition, contrary to model predictions. It seems that other factors influence luminance-pedestal flicker thresholds, and these may relate to the loss of surround matching (Spehar & Zaidi, 1997) or inhibitory effects from surrounding photoreceptors (e.g. Goldberg, Frumkes & Nygaard, 1983; Alexander & Fishman, 1984; Coletta & Adams, 1984).

5.2. Determining flicker thresholds

Some psychophysical investigations generate luminance-pedestal flicker by ‘chopping’ a luminance increment, using a 50% duty cycle (for example, Alexander & Fishman, 1984; Coletta & Adams, 1984). The resultant flicker has a modulation amplitude of 100% and a time averaged luminance pedestal equivalent to the mean-to-peak amplitude of the flicker signal (for example, Fig. 1, lower panel). If the flicker amplitude is plotted against the pedestal amplitude, the dotted lines on Figs. 6 and 7 result. The thresholds for these stimuli can be determined from the intersection of these dotted lines and the TVC functions. As these lines intersect at thresholds similar to the mean-modulated thresholds, this suggests that modulation amplitude thresholds are roughly equivalent for mean-modulated and luminance-pedestal (50% duty cycle) stimuli. The only investigation to concurrently determine flicker thresholds using mean-modulated and luminance-pedestal stimuli (Frumkes, Lange, Denny & Beczkowska, 1992) found similar thresholds and data patterns for each type of flicker, consistent with our prediction.

Presenting stimuli at eccentricities greater than 15° or at very high temporal frequencies would be expected to move the intersection point progressively onto the upward slope of the TVC function, producing luminance-pedestal flicker thresholds that are elevated when compared with mean-modulated thresholds. However, of greater importance is the use of luminance-pedestal flicker in the investigation of ocular disease. Luminance-pedestal flicker thresholds have been shown to be reduced in cases of ocular disease and migraine even in the presence of normal increment thresholds (McKendrick et al., 1998; Phipps, Guymer & Vingrys, 1999; Vingrys & Pesudovs, 1999). Depending upon how ocular disease affects the shape or position of the TVC, it is possible that sensitivity losses to luminance-pedestal flicker could be greater than to mean-modulated flicker, allowing earlier detection of disease processes.
5.3. The origin of facilitation

The absence of a facilitatory effect in the luminance-pedestal flicker TVCs provides information about the origin of the facilitary effect seen in the flicker-on-flicker and luminance-on-luminance conditions. Facilitation has been attributed by some authors, notably Pelli (1985), to a reduction in spatial or temporal uncertainty effected by the presence of the pedestal. If this were true, it would be expected that the pedestal should reduce uncertainty under all conditions including luminance-pedestal flicker. However, this was not the case (Figs. 6 and 7). It is possible that the increased duration of the luminance pedestal in Fig. 6 (750 vs. 200 ms for Fig. 4) resulted in an increase in temporal uncertainty, thereby negating any facilitory effect. However, this is not likely as an extended pedestal (750 ms) was able to produce significant facilitation (Fig. 5). It is more likely that facilitation results from an S-shaped transducer encoding contrast within the visual system.

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References


