Suprathreshold contrast perception across differences in mean luminance: effects of stimulus size, dichoptic presentation, and length of adaptation

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Contrast constancy across changes in mean luminance was reported to hold over a wide range of luminances in a few studies and to be limited to approximately 1 log unit in another. The studies reporting contrast constancy over a wide luminance range used extended grating stimuli presented dichoptically (bright stimulus to one eye and dim stimulus to the other) with long adaptation periods. The study reporting only limited constancy used narrow (1-octave-wide) Gabor patches presented side by side to both eyes with only a short (up to 5 s) period of adaptation. The current study was designed to determine whether differences in stimulus bandwidth, presentation format, or adaptation time could account for the different results reported. It was found that increasing stimulus size had no effect on the results. Dichoptic presentation with either a filter in front of one eye or calibrated screen luminance could account for the differences between the studies. When dichoptic presentation was combined with short adaptation periods (of a few seconds) an intermediate deviation from constancy was demonstrated. This effect suggests that the deviations from constancy demonstrated under free viewing are due to a lack of fast local adaptation and not to long-distance interactions across the retina.

INTRODUCTION

Contrast is considered to be an invariant perceptual attribute.[1] Indeed, two suprathreshold patterns generally match in apparent contrast when their physical contrasts are equal, even when there are large differences in the contrast thresholds for the two patterns.[2] This phenomenon, termed contrast constancy, has been shown to hold over a wide range of spatial frequencies[2,3] and retinal eccentricities.[4] When the test and the standard (of different spatial frequencies) have equal mean luminances, contrasts are matched with near constancy whether they are presented dichoptically[3] or side by side to both eyes together.[2,4]

The extent of constancy found over changes in mean luminance (for stimuli of the same spatial frequency), however, appears to depend significantly and substantially on the mode of presentation. Contrast constancy held across large changes in mean luminance when measured dichoptically[2,3] with long periods of adaptation (1 h and 5 min, respectively, in the studies reported in Refs. 2 and 3). In both studies, one eye was dark adapted and the grating seen with this eye was matched to a grating of the same frequency and different mean luminance presented to the other eye. Using a similar paradigm of dichoptic presentation and long adaptation, Hess[5] recently reported similar results. However, with lower contrast levels (less than 0.1), very low luminance levels (less than 0.02 cd/m^2), and higher spatial frequencies (10 cycles/deg), his results showed substantial deviations from contrast constancy. Nevertheless, even these changes were remarkably small compared with changes in contrast detection thresholds under similar changes in luminance and spatial frequency. The results of these three studies have commonly been considered strong evidence of contrast constancy across changes in mean luminance.

The data described in the previous paragraph were obtained with dichoptic presentation. They do not necessarily apply to more natural viewing conditions in which the two eyes view the same scene and therefore have similar levels of adaptation. Peli *et al.*[6] studied the effects of luminance on contrast constancy under more natural viewing conditions. In their study, bright and dim targets were presented to both eyes side by side, and an observer could move his or her eyes freely between them. Using 1-octave-wide Gabor patch stimuli of the same frequency and different mean luminance, they found a stronger effect of luminance on contrast perception than previously reported. Contrast constancy held only down to a mean luminance of 8 cd/m^2. At lower mean luminances the perceived contrast of the dim grating patch fell gradually, down by as much as a factor of 2 at 0.75 cd/m^2, when compared with the same stimulus with a luminance of 37.5 cd/m^2. The same effects were noted when both contrast matching and contrast estimation paradigms were used.

The results of Peli *et al.*[6] suggest that under more natural viewing conditions, contrast constancy is maintained over a limited range of approximately 1 log unit of luminance on a CRT display. Outside this range the dimmer pattern seems to have less contrast than the brighter pattern. These results suggest that an object in the light can appear to have higher contrast than the same object seen in a deep shadow, which agrees with our daily experience.

Reasons for the luminance effect found by Peli *et al.*[6] and the difference between their results and those of previous investigators[2,3,5] were proposed but not tested

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by Peli *et al.*[6] The current study was designed to determine which of the factors and parameters that Peli *et al.*[6] postulated resulted in these differences.

One possible explanation for the different results may be related to the different spatial extent of the stimuli. The stimuli used by Peli *et al.*[6] were small localized patches (approximately 1 deg). The other studies used extended grating stimuli (2×4 deg in one case[3] and 8×8 deg in the other[2]). These stimuli spanned peripheral retinal areas, and thus more rods were involved, which may have caused increased sensitivity at lower luminances. Hess[5] also used grating patches (of unspecified width but fixed number of cycles), and his data (his Fig. 9) show better contrast constancy with decreased spatial frequency. This effect was possibly due to the wider spatial extent of the lower spatial frequencies required for maintaining the same number of cycles.

A likely cause of the different results is the difference between the adaptation levels associated with the dichoptic presentation used in previous studies and the adaptation levels used in the natural viewing conditions used by Peli *et al.*[6] Extending the adaptation period to 5 s in this paradigm[6] did not change the results, suggesting longer adaptation (on the order of minutes) and the dichoptic presentation as the most plausible explanations for the discrepancy between the previous studies' results and our findings. The long period of dark adaptation afforded by the dichoptic presentation permits the local gain in the retina viewing the dark target to be stabilized and to reach the same gain as that of the retina seeing the bright target. This equal gain associated with complete adaptation is the presumed cause of the equal perception of apparent contrast for stimuli of equal physical contrast presented at different mean luminance levels.

GENERAL METHODS

The stimuli to be matched were presented on a 19-in., 60-Hz, noninterlaced monochrome video monitor (U.S. Pixel, Framingham, Massachusetts) at a viewing distance of 80 in. (200 cm), in a completely dark room. At this distance the whole screen spanned 8 deg. The spatial inhomogeneity across the screen was 5% at mean luminance. Linearity of the display response was obtained with a 10-bit lookup table. The calibrated screen provided a linear response over 3 log units, and stimuli were limited to that range of luminances. The stimuli, two Gabor patches of different mean luminance, were separated by 4 deg from center to center. The background luminance changed abruptly halfway between the patches. The screen appeared white.

The luminance distribution of each Gabor patch can be written as

$$g_i(x, y) = L_i(1 + m_i \exp\{-[(x - x_i)^2 + (y - y_i)^2]/\sigma^2\} \times \cos 2\pi f(y - y_i)), \quad (1)$$

where the subscript i can be 1 or 2, with 1 representing the standard patch and 2 the test patch. L and m are the mean luminance and the nominal physical contrast of the pattern, respectively. The coordinates (x_i, y_i) are the center position of the two patches. In these experiments the patches were side by side; therefore $y_1 = y_2$. The distance between the centers of the patches, $x_1 - x_2$, was 4 deg. The mean spatial frequency f was set at 2 cycles/deg for both patches.

In experiments 2 and 3 the bandwidth $1/e$ of both the test and the standard in the spatial-frequency domain was set to 1 octave. This was done by setting σ in Eq. (1) to[7]

$$\sigma = \frac{3}{\pi f} = 0.477. \quad (2)$$

For experiment 1, bandwidths of 0.7, 0.5, and 0.3 octave (Fig. 1) were obtained by setting σ to 0.668, 0.923, and 1.528 deg, respectively, in addition to the 1.0-octave-wide stimuli.

Physical contrast of test targets is commonly measured with either the Michelson formula or the Weber fraction. The nominal contrast m, as defined in Eq. (1), was used to measure the contrast of Gabor patch targets. The Michelson contrast of a patch approaches the value of m asymptotically for narrow-bandwidth patches (multiple cycles). On the other hand, for wideband, spatially narrow Gabor patches, the values of m and the Weber contrast coincide. All these measurements of contrast maintain a fixed ratio between their values when the bandwidth is fixed.[8] Because all our data were obtained with test and standard patches of equal bandwidth, m is a consistent measure of contrast.

In experiments 2 and 3 the standard and the test patterns were displayed dichoptically, one to each eye. The dichoptic presentation was achieved with the use of a modification of Morgan's infinity balance technique.[9] This method (Fig. 2) uses a bar septum placed between

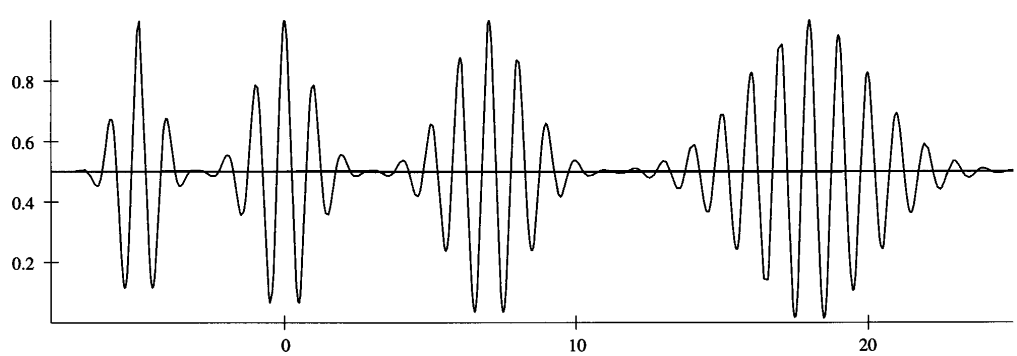

Fig. 1. Luminance profile through the center of the stimuli used in experiment 1. Gabor patches of bandwidth 1, 0.7, 0.5, and 0.3 octave are illustrated. Standard and test stimuli had the same bandwidth in every trial.

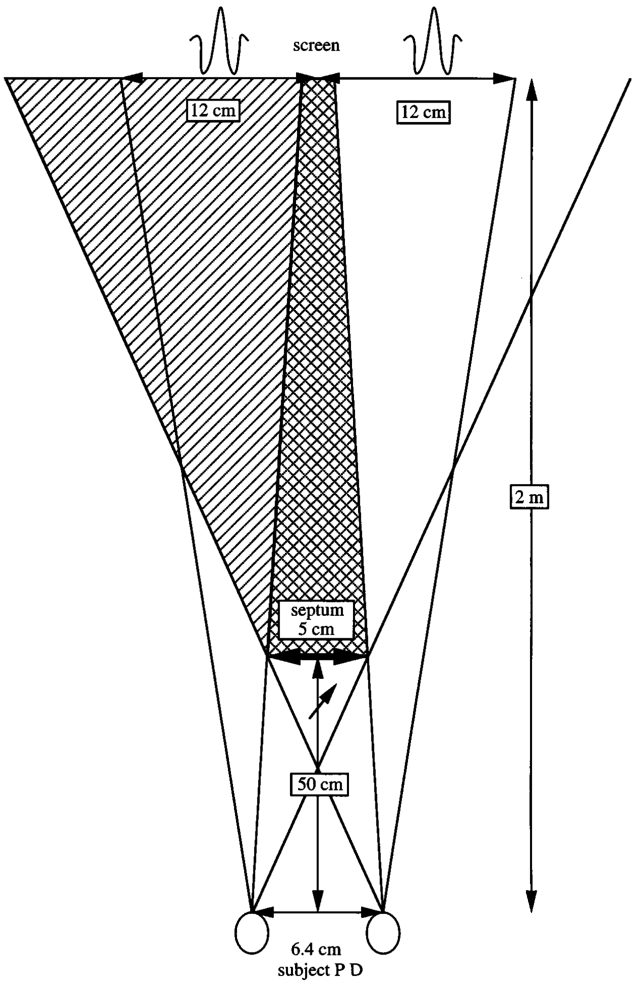

Fig. 2. Schematic illustration of the septum arrangement used for dichoptic presentation. The shaded area illustrates that part of the display that was not visible to the observer's right eye. Symmetrically, the right-hand part of the display is occluded from the left eye.

the subject and the screen. The septum size can be calculated with Morgan's formula,[10] and the septum position is adjusted (with the use of an X–Y manipulator)to ensure separation of the two eyes' views (Fig. 3). Since the occluded areas may overlap in the middle without harm (as illustrated in Fig. 2), a different septum size is not needed for subjects with different interpupillary distances. None of the subjects reported any difficulties in maintaining the two eyes' views separated (unfused) with this display.

The standard mean luminance L_1 was fixed at 37.5 cd/m^2 throughout the experiments. The standard contrast m_1 was set at one of three levels (0.1, 0.3, or 0.6). Contrast levels for the test were changed in steps of 0.02 log unit. For each standard contrast, matches were obtained at four levels of L_2, the mean luminance of the test patch (0.76, 1.10, 3.78, and 18.7 cd/m^2 for experiment 1 and 0.76, 1.10, 2.29, and 6.78 cd/m^2 for experiment 3). Only luminance levels below 8 cd/m^2 were used in most cases because deviations from contrast constancy were noted only for such low levels of luminance.[6] Four test luminance levels or three contrast levels were randomly interleaved, depending on the experiment. Test contrast was always the variable adjusted by the subject's response. In a forced-choice paradigm, subjects were asked to decide which side had lower contrast, ignoring any luminance differences. All the subjects reported understanding the concept of contrast.

The psychophysical procedure was a hybrid method consisting of three steps described more fully by Peli *et al.*[11] The first step was a staircase procedure. After the second reversal of direction, data were collected and analyzed on line with the parameter estimation by the sequential testing (PEST) method.[12] During this second phase, stimulus presentation was still controlled by the staircase. When an initial threshold estimate was determined within a confidence interval of 40%, stimulus control was switched to PEST. This modification prevented long random walks that occur occasionally at the beginning of a PEST routine.[13] After termination, a psychometric function (Weibull) was fitted to the data to produce matching contrasts, and the PROBIT analysis provided a sampling statistic that is comparable to the standard error of the mean.

Seven subjects with normal or corrected-to-normal vision, ages 20–35 years, participated in the experiments. One subject, GY, had practiced for many sessions and was aware of the purpose of testing; the other subjects were paid volunteers and were naïve to the objectives of the experiment. Two of the subjects (JY and EF) had also participated in our previous study.[6] (The remaining subjects were tested also with the contrast matching paradigm, with 1.0-octave-wide patches and the luminance levels used in the previous study.)

Each session in experiment 1 started with 2 min of dark adaptation followed by 1 min of light adaptation to a uniform field with the mean luminance of the standard. Before each trial two uniform backgrounds of different

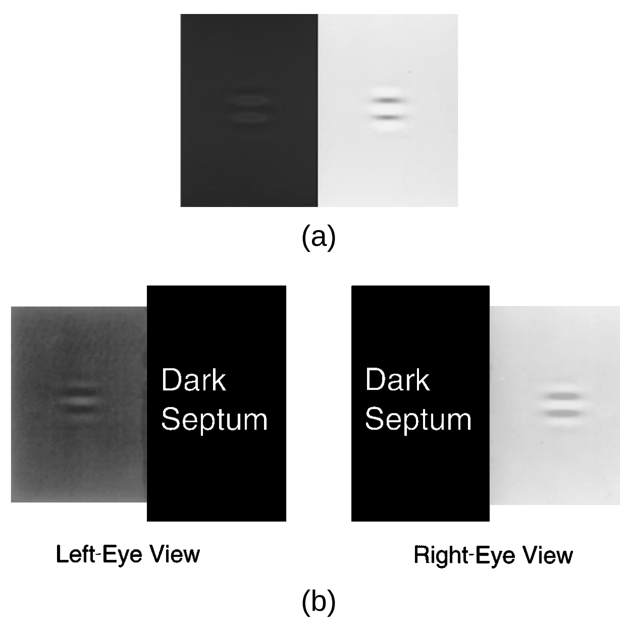

Fig. 3. Appearance of the screen for each eye in the different experiments. (a) In experiment 1, both eyes were presented with both patches of gratings simultaneously; (b) in experiments 2 and 3, one eye saw the bright standard and the septum while the other saw the dark test patch and the septum. In experiment 2 the standard was always seen by the right eye, whereas in experiment 3 the eye seeing the standard was selected randomly from trial to trial.

luminances appeared on the screen. When a subject pressed the ready button, the patches emerged abruptly from the backgrounds without change of mean luminance and remained on. Following a response both patches disappeared and two different uniform backgrounds appeared on the screen at the intensity levels of the next trial. The subject could take as long as he or she wanted to adapt to the new levels before pressing the ready button. Usually subjects did not wait more than a few seconds, even following a large change in luminance. The standard and the test grating patches were presented randomly on the right or left side of the screen. In experiments 2 and 3, in which dichoptic presentation was used, the adaptation and presentation procedures were necessarily different and are described below.

EXPERIMENT 1: EFFECT OF STIMULUS SIZE

Methods

Peli *et al.*[6] postulated that the larger stimuli that Kulikowski[3] and Georgeson and Sullivan[2] used (4×2 deg and 8×8 deg, respectively) may account for the difference between their results and those of the previous researchers. To determine the effect of target extent, in experiment 1 we repeated the contrast-matching-in-free-viewing experiment of Peli *et al.*[6] [see Fig. 3(a)], using 0.7-, 0.5-, and 0.3-octave Gabor patch gratings (see Fig. 1) in addition to the 1.0-octave grating previously used. The 0.3-octave patch was the largest that could be included in the display for the same spatial frequency of 2 cycles/deg. Except for the change in stimulus size, these experiments were carried out under the same conditions as those reported by Peli *et al.*[6]

Results

The results for two observers are presented in Fig. 4. Each set of data (one symbol type, i.e. triangle, square, or circle) represents the mean matches to one standard contrast level (0.1, 0.3, or 0.6, respectively). As in the study by Peli *et al.*,[6] the nominal contrast of the test target that was needed to achieve perceived contrast match with the standard increased with reduced mean luminance of the test. However, no systematic effect of stimulus size was noted. Even for the largest target (0.3 octave), which spanned ~ 4 deg, each individual's results were essentially the same as the results obtained with the smaller, foveal stimuli. The average results for all seven subjects are presented in Fig. 5, and they are compared with the results of the same subjects obtained with 1.0-octave patches at the luminance levels used by Peli *et al.*[6] These results illustrate the same absence of effect of stimulus size on contrast matching of targets of differing mean luminance. These results reject the hypothesis that the difference in the spatial extent of the stimuli can account for the differences between the results of Peli *et al.*[6] and those of previous studies.[2,3,5]

EXPERIMENT 2: DICHOPTIC PRESENTATION WITH LONG ADAPTATION

This experiment replicates the experiments of Kulikowski[3] and Georgesonb and Sullivan.[2] Its aim was to establish whether results similar to theirs can be obtained through use of the psychophysical paradigm and stimuli used by Peli *et al.*[6] but with dichoptic presentation and long adaptation periods.

Methods

Only one luminance level for the test patch was used for each session, while three contrast levels were interleaved. The standard was presented to the right side (eye) and the test to the left side (eye) throughout the experimental session [Fig. 3(b)]. Subjects adapted each eye for 5 min to the mean luminance level of its target after 3 min of dark adaptation. Since in all previous experiments[2,3,6] contrast constancy was found for the higher mean luminance levels of the test, we tested only the two lowest luminance levels used in experiment 1. The subject initiated each trial by pressing the ready button; then the patches emerged abruptly on both sides. The patterns

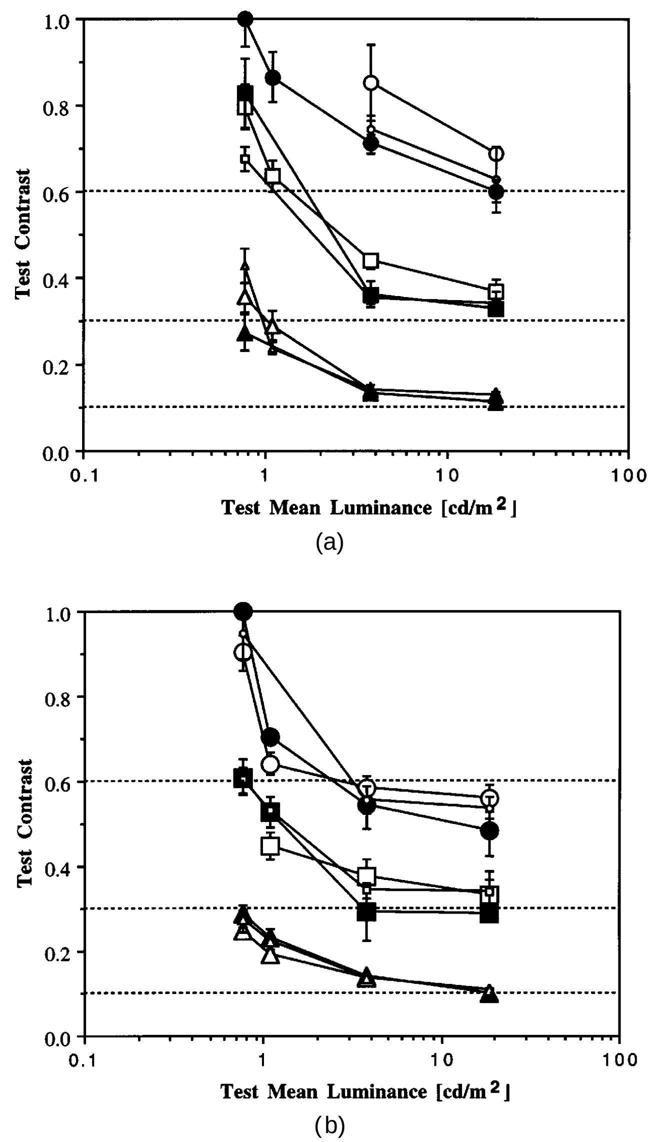

Fig. 4. Comparison of contrast matching results with the use of stimuli of varying size or spatial extent illustrated for two subjects [(a) and (b)]. Results obtained with Gabor patches of 0.7, 0.5, and 0.3 octave are illustrated by filled, small open, and large open symbols, respectively. Each symbol type (triangle, square, or circle) represents the test contrast matches to one standard contrast level (0.1, 0.3, or 0.6, respectively).

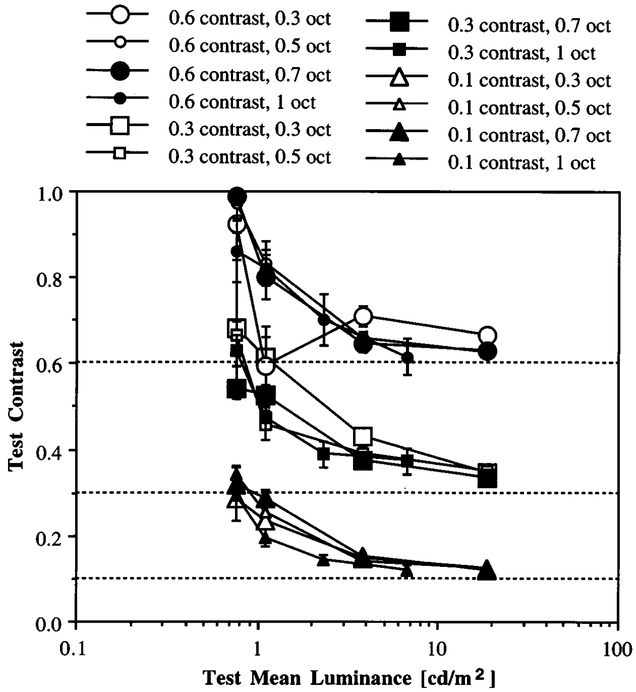

Fig. 5. Average results of contrast matching with varying stimulus size for the seven subjects. The symbol notation is the same as in Fig. 4, with the addition of results with 1-octave-wide patches illustrated by small filled symbols. There is no systematic effect of stimulus size. Error bars represent standard errors of the mean. The single point at a bandwidth of 0.3 octave, contrast of 0.6, and mean luminance of 1.1 cd/m^2 that appears to deviate from the general pattern may be a chance outcome.

remained on until the subject responded, and then the patches disappeared abruptly, leaving the background luminance unchanged.

This experiment differs from those of Kulikowski[3] and Georgeson and Sullivan[2] mainly by the use of a calibrated screen rather than the application of a filter in front of the dark-adapted eye. To account for this difference we also ran a control experiment, using the same procedure except that both sides of the screen were set to equal mean luminance and a neutral density filter was placed in front of one eye. In addition to providing a duplication of the experiments of Kulikowski[3] and of Georgeson and Sullivan,[2] this control experiment also served to check our calibration by comparing the filtered and the nonfiltered experimental results and to reject the possibility that the light scatter in the room might have an effect in our paradigm.

Results

Mean matching results for all seven subjects and for both display conditions are shown in Fig. 6 (open symbols). Large open symbols represent results for the calibrated-screen condition and small open symbols the results of the control, filter condition. Each set of data (one symbol type, i.e. square, triangle, or circle) represents the mean matches to one standard contrast level. The data obtained in both experiments overlap completely, indicating that there is no difference between the matchings obtained with use of the filters and the results obtained by controlling the display luminance.

The results of both experiments are also in good agreement with the results of Kulikowski[3] (dashed curves) and with the results of a similar experiment recently reported by Hess[5] (dotted curves). These results are significantly different from the results illustrated by large filled symbols, which are from the seven subjects in the same 1-octave condition of experiment 1 with natural viewing.

The solid curves drawn through the data are tracings of Stiles's threshold-versus-intensity (TVI) curves.[14] We transformed the TVI curves, $\Delta I = A(B + I)$, to our format by defining Weber contrast c as $c = \Delta I/I$. Successively higher curves correspond to higher standard contrast matches. The Weber range of the curve was shifted to the corresponding standard contrast. Then, to give the best fit, the curves were moved parallel to the luminance axis. The curves presented here are those fitted to the data from the same experiment reported by Peli *et al.*[6] As can be seen, the current data were well fitted by the same TVI curves. These data differ substantially from the results obtained with dichoptic presentation and a long adaptation period.

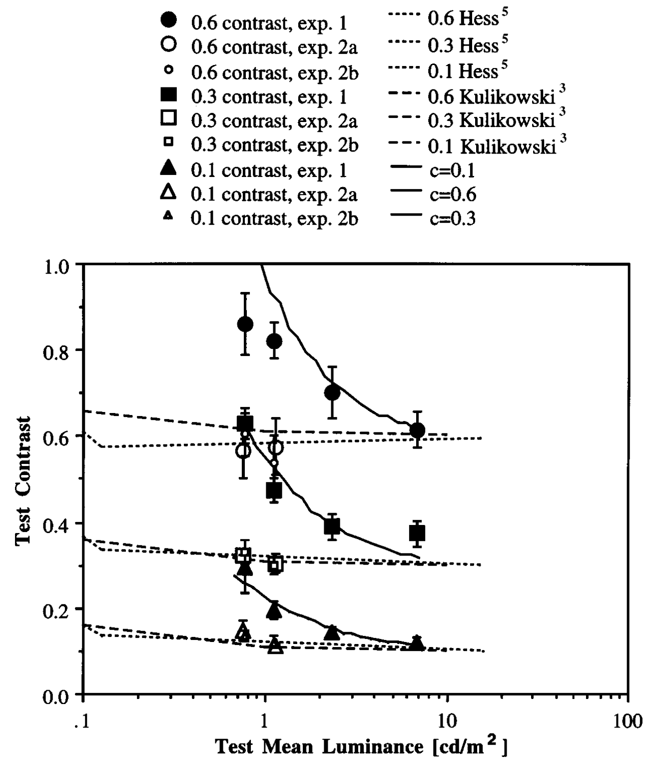

Fig. 6. Comparison of contrast matching results obtained under natural (side-by-side) viewing conditions with the matching obtained with dichoptic presentation and long periods of adaptation. Each symbol type (triangle, square, or circle) represents the test contrast matches to one standard contrast level (0.1, 0.3, or 0.6, respectively). Average results for seven observers under natural viewing conditions (filled large symbols) replicate our previous results for the same condition (solid curves).[6] Average results for the same subjects in dichoptic presentation with long adaptation periods are represented by open symbols. These results do not differ from the results of two other studies: dashed curves from Kulikowski[3] and dotted curves from Hess.[5] Data from these two studies were obtained with dichoptic presentation and long periods of adaptation (more than 5 min). The standard patch was always presented with a mean luminance of 37.5 cd/m^2. Error bars represent standard errors of the mean.

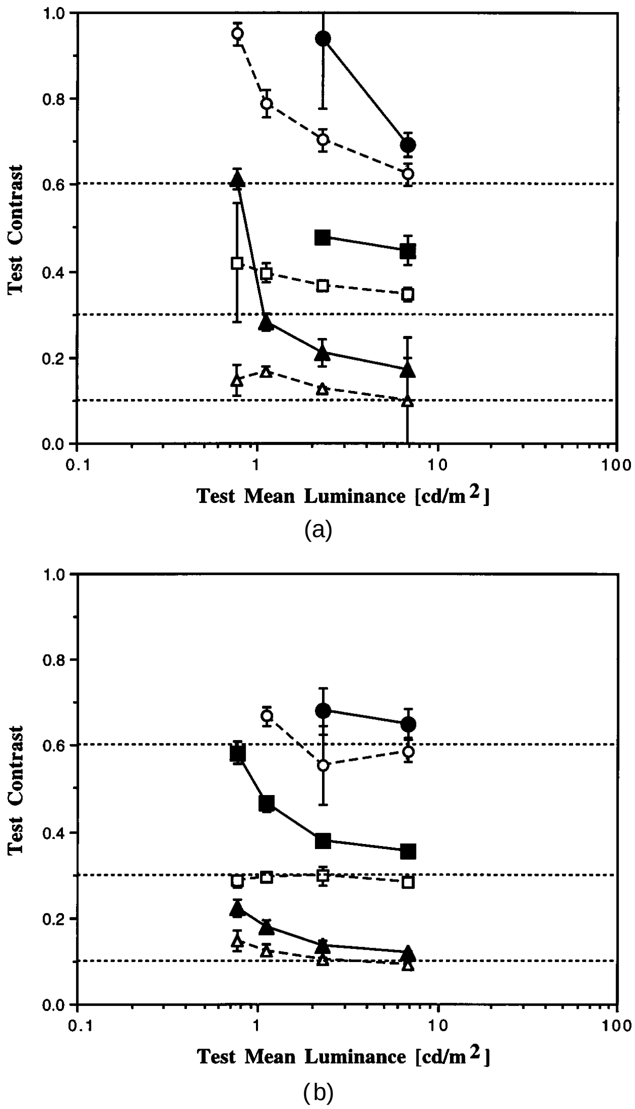

Fig. 7. Comparison of contrast matching results in the dichoptic presentation with short adaptation (open symbols) to the matchings obtained in binocular free viewing (filled symbols) for two subjects [one each in Figs. 7(a) and 7(b)]. Although the results in dichoptic presentation deviate from constancy, the deviation is smaller than that exhibited under the binocular free-viewing condition.

EXPERIMENT 3: DICHOPTIC PRESENTATION WITH SHORT ADAPTATION

Methods

This experiment repeats the dichoptic contrast matching experiment (experiment 2), with a different temporal sequence. Unlike experiment 2, in which the right eye viewed the bright standard target and the left eye viewed only the dark target [Fig. 3(b)], here the position of the bright standard patch was selected randomly to the right or the left side of the screen and thus to the right or the left eye on each trial. This resulted in rapid (a few seconds) changes in the adaptation levels of both eyes. In each session the standard patch luminance and contrast were fixed, and the four test luminance levels were randomly interleaved. The test patch contrast was matched by the subjects, as described in the General Methods section. Following the subject's response, the next test luminance level and eye of presentation were selected randomly and the next stimuli were abruptly presented. Subjects responded at their own rates but were encouraged to respond rapidly. The psychophysical paradigm required numerous responses, and all subjects were trained in the procedure and usually responded in less than 2 s (frequently within 1 s).

Results

The results of two observers are presented in Fig. 7 (open symbols). The filled symbols represent the results of the same subjects under the same presentation conditions but without the septum separation (a replication of the conditions in experiment 1 of Ref. 6). There are individual differences in the magnitude of the effects of luminance. However, in all cases the matching results in the dichoptic condition with short adaptation showed more contrast constancy than in the free-viewing condition and less than in the long-adaptation condition (experiment 2). The few missing data points represent conditions under which the subjects attempted to match the standard with a test contrast higher than 1.0. These conditions occur only for high-contrast, low-luminance matchings.

The average results from the seven subjects with the same format are illustrated in Fig. 8. The data obtained with the dichoptic presentation and short adaptation could be fitted with the same TVI curves as the data obtained in the natural viewing condition shifted to the left by 0.4 log unit. Thus the increased adaptation effect in the dichoptic presentation, even for short adaptation periods, is equivalent to changing the mean luminance level by a factor of 2.5.

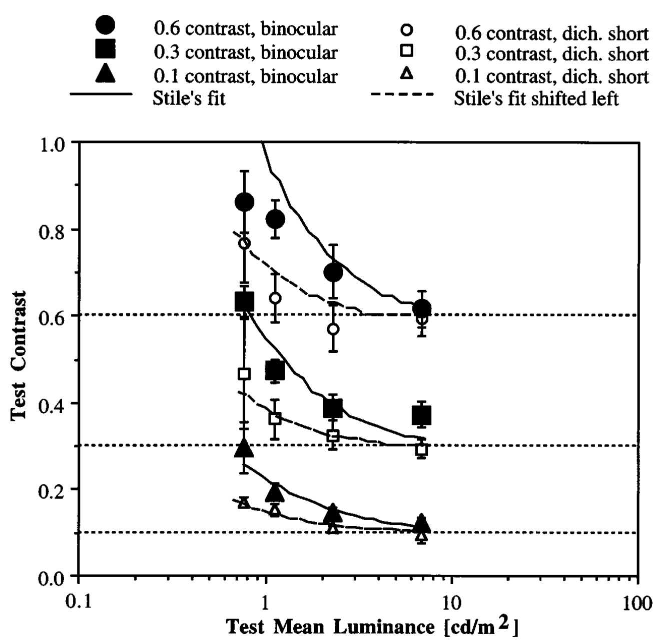

Fig. 8. Average results for seven subjects comparing contrast matches obtained by dichoptic presentations and short periods of adaptation (open symbols) with matchings obtained in free binocular viewing (filled symbols). The curves fitted to the data are tracings of the transformed Stiles TVI curves. The dotted curves are the same curves as the corresponding solid curves shifted to the left by 0.4 log unit.

GENERAL DISCUSSION

The results of experiment 1 rejected the hypothesis presented by Peli *et al.*[6] that the small spatial extent of their stimuli might have resulted in the reduction in contrast constancy at low luminance found in their study. Reducing the stimulus bandwidth and thus increasing the number of cycles and the spatial extent did not change the reduction in perceived contrast of the dim stimuli. This difference in stimuli could not account for the different results obtained in other studies.[2,3,5]

Experiment 2 demonstrated that under dichoptic presentation our subjects, equipment, and psychometric methods yielded contrast constancy similar to that reported by others.[2,3,5] Thus I was able to confirm that when given the time to adapt to the mean luminance level, the visual system indeed is capable of maintaining contrast constancy over the range of mean luminance levels available on a common CRT display. However, this type of adaptation is unlikely to occur in daily activity, and thus the deviations from contrast constancy reported by Peli *et al.*[6] and replicated here represent an actual effect on performance.

Experiment 3 demonstrates that under dichoptic presentation with relatively short (a few seconds) adaptation time, the deviations from contrast constancy are larger than those resulting from dichoptic presentation and longer adaptation time and smaller than those noted under natural viewing conditions and adaptation time. The reduction in contrast constancy in natural viewing (experiment 1) could be a result of long-distance interactions between two targets of differing mean luminance at different retinal positions. However, such interactions are not possible in the dichoptic condition. Furthermore, the role of such spatial interaction was ruled out by the contrast estimation paradigm of Peli *et al.*[6] Thus only the change in the temporal aspect of the presentation remains to account for the intermediate results. This finding may suggest that under natural viewing conditions with displays of varying local luminance levels, extended fixation at a dark portion of the display may recover the constancy of suprathreshold contrast perception even in the presence of brighter images on the screen.

The results of this study confirm and reconcile the report of Peli *et al.*[6] with the different results of Georgeson and Sullivan,[2] Kulikowski,[3] and Hess.[5] It is clear that even for the limited range of luminances available on a CRT display, contrast constancy in natural viewing conditions is only partially maintained. The existence of contrast constancy was included explicitly or implicitly in numerous vision models.[4,11,15] The ramifications of these luminance effects on image perception are not known. In order to interpret these results in terms of image filtering as a function of luminance, we need to determine the dependence of the luminance effects on spatial frequencies. Such work is now in progress.

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