Contrast perception across changes in luminance and spatial frequency

Eli Peli

The Schepens Eye Research Institute, Harvard Medical School, Boston, Massachusetts 02114

Lawrence Arend

David Sarnoff Research Center, Princeton, New Jersey 08543

Angela T. Labianca

The Schepens Eye Research Institute, Harvard Medical School, Boston, Massachusetts 02114

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The interaction of the effects of luminance and spatial frequency on perception of suprathreshold contrast was studied with use of a contrast-matching paradigm. Four subjects matched the appearance of Gabor patches at different luminances and spatial frequencies. The contrast of a 1-octave Gabor test patch at one of five frequencies [1–16 cycles/degree (c/deg) in 1-octave steps] and at one of seven mean luminance levels (0.5–50 cd/m^2 in 1/3-log-unit steps) was matched, by the method of adjustment to a standard patch of 3 c/deg at 50 cd/m^2 at a nominal contrast of 0.3. For each block of trials the spatial frequency of the test patch was randomly changed (three repetitions at each frequency per block) while the luminance was fixed. The subject regularly shifted fixation between the two targets in response to a metronome tone every 1.5 s. Contrast constancy was demonstrated across the entire luminance range tested for all but the two highest frequencies. For 8 c/deg the perceived test contrast was reduced only when the luminance was less than 2 cd/m^2. For 16 c/deg, perceived contrast decreased linearly (with a slope of $-1/2$ on a log scale) with decreases in luminance across the entire luminance range. As at threshold, reduction in luminance across the levels commonly available on a CRT display has only minimal effects on low-frequency suprathreshold contrast perception. However, the apparent contrast of high-frequency features, in binocular free-viewing conditions, is rapidly reduced with a local reduction in screen luminance. This effect has important implications for visual models used in image-quality analysis. © 1996 Optical Society of America.

1. INTRODUCTION

Contrast is considered to be a primary and invariant perceptual attribute.[1] Although contrast sensitivity (i.e., the contrast-detection threshold) has been demonstrated to vary considerably with changes in observation conditions, the apparent contrast of a suprathreshold stimulus is much less affected by such changes. 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.[1] This phenomenon, termed contrast constancy, has been shown to hold over a wide range of spatial frequencies[1,2] and retinal eccentricities.[3] When the test and the standard (of different spatial frequencies) have equal mean luminances, contrasts are matched with near constancy.

The degree of constancy found over changes in mean luminance (for stimuli of the same spatial frequency), however, appears to depend significantly and substantially on the viewing conditions. Contrast constancy did hold across changes in mean luminance when it was measured dichoptically.[1,2] In both of these 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 that was presented to the other eye. Using a similar paradigm of dichoptic presentation and long adaptation, Hess[4] reported similar results, although for lower contrast levels (less than 0.1), very low luminance levels (less than 0.02 cd/m^2), and higher spatial frequencies [10 cycles/degree (c/deg)] his results show substantial deviations from contrast constancy. Nevertheless, even these changes were remarkably small when compared with changes in contrast-detection thresholds under similar changes in luminance. The results of these three studies commonly have been held to demonstrate contrast constancy across changes in mean luminance.

Peli *et al.*[5] studied the effects of luminance on contrast constancy under more natural viewing conditions. In their study, bright and dim targets were presented side by side to both eyes, and an observer could move his or her eyes freely between them. Using 1-octave-wide Gabor patch stimuli of the same frequency (2 c/deg for both test and standard) and different mean luminance, they found a stronger effect of luminance on contrast perception than had been previously reported. That is, contrast constancy held only down to a mean luminance of 8 cd/m^2. At lower mean luminances the perceived contrast of the dim patch fell gradually, down by as much as a factor of 2 at 0.75 cd/m^2. The same effects were noted when either a contrast-matching or a contrast-estimation paradigm was

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used. Burkhardt *et al.*[6] noted a similar drop in perceived contrast when a negative contrast of rectangular profile bars with reduced luminance of background was tested. They used the transitivity of contrast perception to estimate the change in perceived contrast over a wide range of luminances (4 log units) by using only a small difference (factor of 3) in each experiment. Their results show better constancy over the range measured by Peli *et al.*[5]; however their stimulus size corresponded to a much lower frequency.

The results of Peli *et al.*[5] suggest that under more natural viewing conditions, contrast constancy is maintained over a limited range of ~1 log unit of luminance. For larger luminance differences the suprathreshold contrast of the lower mean luminance pattern is perceived to be lower than that of the higher mean luminance 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. The reader can confirm this by looking at the same object held under high illumination and in a deep shadow.

In the current study we investigated whether, under natural viewing conditions, deviations from contrast constancy at low luminance follow the spatial frequency dependence found for contrast thresholds. The previous studies addressed the effects of frequency and mean luminance on suprathreshold contrast perception separately. A strong interaction of these two factors was demonstrated for contrast sensitivity (thresholds) by van Nes and Bouman.[7] They found, as had others before them, that contrast thresholds remain constant over a range of luminances. This result is consistent with the Weber-law expression of contrast. For lower luminances the contrast thresholds increased following the square-root law (slope of $-1/2$ on a log-contrast-versus-log-luminance graph, also known as the de Vries–Rose range). The point of transition, from the Weber-law range (horizontal line) to the square-root-law range, shifted to higher luminances for higher spatial frequencies. The square-root law is usually considered to be a result of photon noise becoming significant at low luminance levels. This effect should be found for suprathreshold as well as for threshold levels.

We are interested in the effects of local luminance on contrast perception both at threshold and at suprathreshold levels, because such effects have to be incorporated into vision models. Peli *et al.*[5] have demonstrated the effect of reduced contrast on separate spatial frequency bands used in such models. Most of these models assume contrast constancy above the threshold[8] and use a single contrast sensitivity function for the whole image.[9] Local luminance effects that have been studied can have a large impact on the result of calculations that use such models.

2. METHODS

The stimuli to be matched were presented on a 19-in., 117-Hz, noninterlaced monochrome video monitor (Image Systems, M21Max; phosphor: DP-104) of the VisionWorks™ system at a viewing distance of 2 m. Linearity of the display response was obtained by using a resistor net to combine the output of the three channels' digital-to-analog converters and by creating an appropriate lookup table. The calibrated screen (with use of the calibrating system provided by VisionWorks) provided a linear response over 3 log units, and stimuli were limited to that range of luminances.

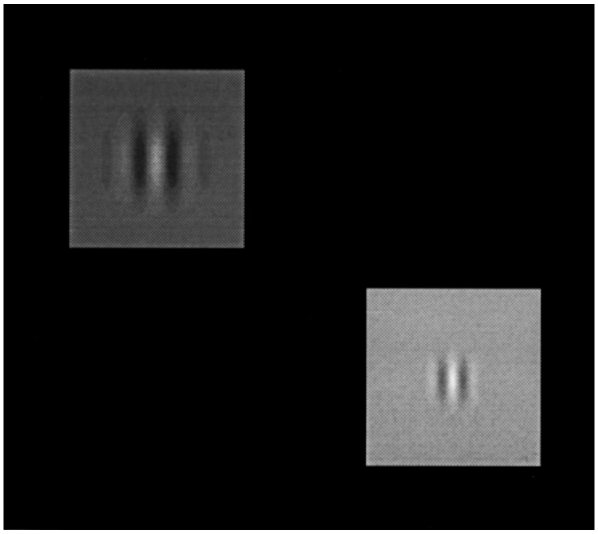

Fig. 1. Illustration of the display used in the contrast-matching study. Two Gabor patches at different luminance levels and spatial frequencies are matched by the subject for equal apparent contrast.

The stimuli, two Gabor patches of different mean luminance, were separated by 4.25 deg horizontally and were located above and below the midline. The background luminance surrounding each Gabor patch (2.5 deg × 2.5 deg) changed abruptly from the overall screen background, which was black (Fig. 1). The two Gabor patches were of 1-octave bandwidth. The standard patch was always presented at a mean luminance of 50 cd/m^2, spatial frequency of 3 c/deg, and nominal contrast of 30% for the contrast matching. (Nominal contrast for a Gabor patch is defined as the Michelson contrast of the underlying sinusoid.[10]) The test patch contrast was adjustable. The test mean luminance was fixed in each block at one of seven values between 0.5 and 50 cd/m^2 in 1/3-log-unit steps. Within each block, five spatial frequencies of the test patch were interleaved, covering the range of 0.5–16 c/deg (1-octave steps). Each frequency was presented three times per block in random order. The complete procedure was repeated in a separate session.

The subject viewed the screen binocularly in a dark room. Testing began following 15 min of adaptation to the screen luminance. Subjects shifted fixation regularly between the two targets in response to a metronome tone every 1.5 s. In a recent study Peli[11] demonstrated that even short adaptation (of a few seconds) provided increased constancy in comparison with free viewing. The metronome control was implemented to ensure regular shift of foveal adaptation between the test and the standard, simulating the effect on the observer of scanning a scene with a wide luminance range. While shifting fixation, the subjects used the method of adjustment to match the apparent contrast of the test to that of the standard. The initial contrast of the test was randomized within 10% contrast range above and below the 30% level of the standard. Adjustment was done in 1% steps by use of the up and down arrow keys of a computer keyboard. Each subject provided six settings for each luminance and frequency combination.

Four subjects with normal corrected vision completed the study. All were familiar with the concept of contrast as used in vision science. They were asked to set the test contrast to the same apparent contrast as the standard.

The same method was used for the threshold sensitivity measure. The standard contrast was set to zero, but the mean luminance remained the same. The subjects performed the same eye movement task while adjusting the test contrast to a just-visible level.

3. RESULTS

A. Threshold

Lines with slopes of −0.5 and 0 were fitted by eye to the threshold data, similar to the method of van Nes and Bouman.[7] As seen in Fig. 2, our data replicated their results for the range of luminances we tested. The high luminance data could be fitted with a line of slope 0 (Weber range). At low luminances for most spatial frequencies the slope changes to −0.5. The transition from the Weber range to the de Vries–Rose range occurred at lower luminances for lower frequencies. The results are replotted in Fig. 3 in the more common format presenting contrast-detection threshold as a function of spatial frequency, with luminance as a parameter. Seen in this way, the data replicate the general finding of many other studies of the effects of luminance on contrast sensitivity,[12] where sensitivity is reduced with reduced luminance and the curve's shape changes from bandpass to low pass. Comparison of Figs. 2 and 3 suggests that the transition to the de Vries–Rose range at higher luminance levels for higher spatial frequencies is the reason for the apparent gradual change of the contrast sensitivity function from bandpass to low pass with decreasing

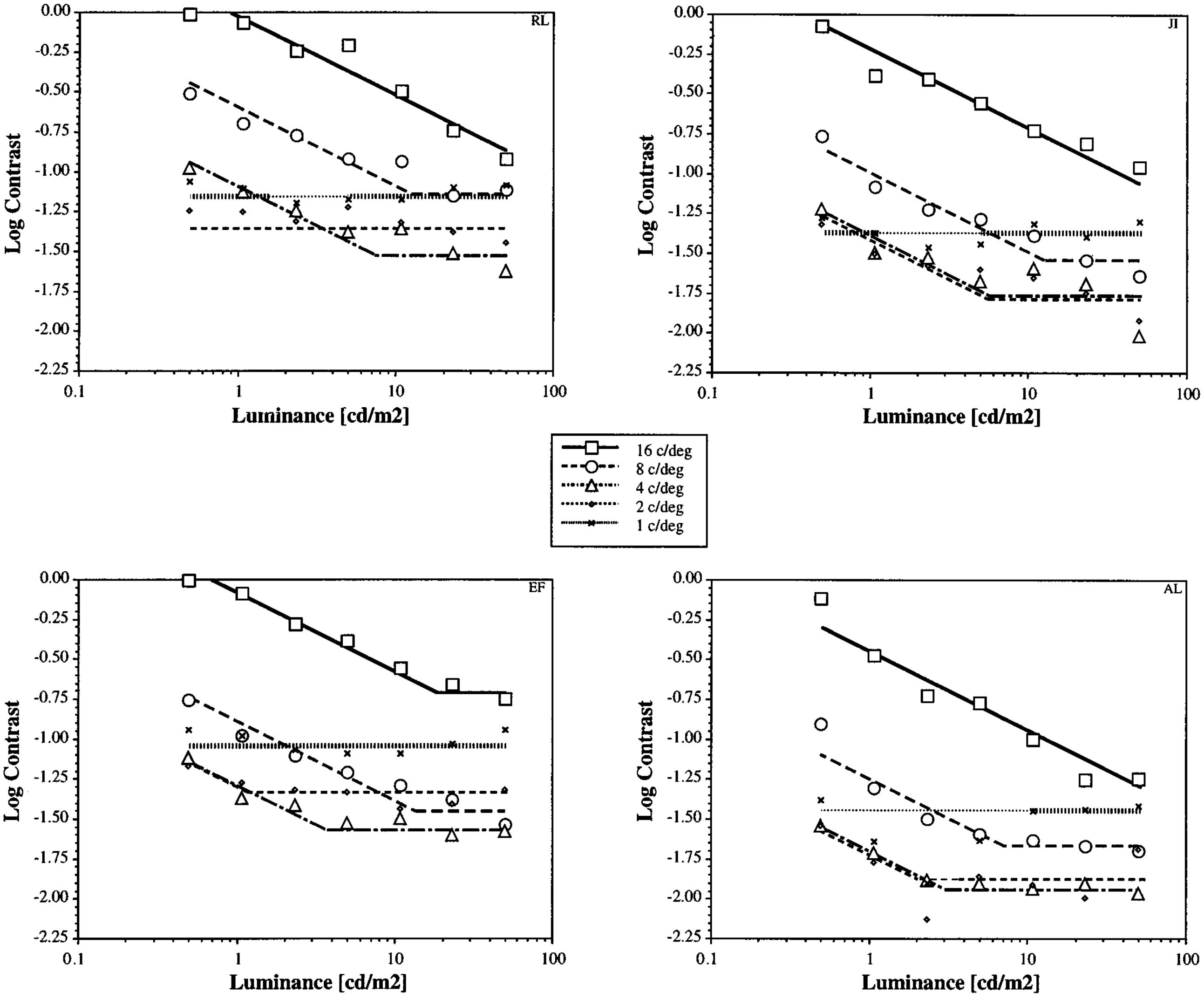

Fig. 2. Contrast-detection-threshold data at different spatial frequencies as a function of luminance, for the four subjects, are plotted in the same way as by van Nes and Bouman,[7] illustrating the interaction between spatial frequency and luminance effects. Note the increased sensitivity near the transition point from the Weber (flat section) to the de Vries–Rose range (slope = −0.5) for low frequencies, particularly for subjects AL, JI, and RL (thin dotted-line segment for the 1-c/deg condition).

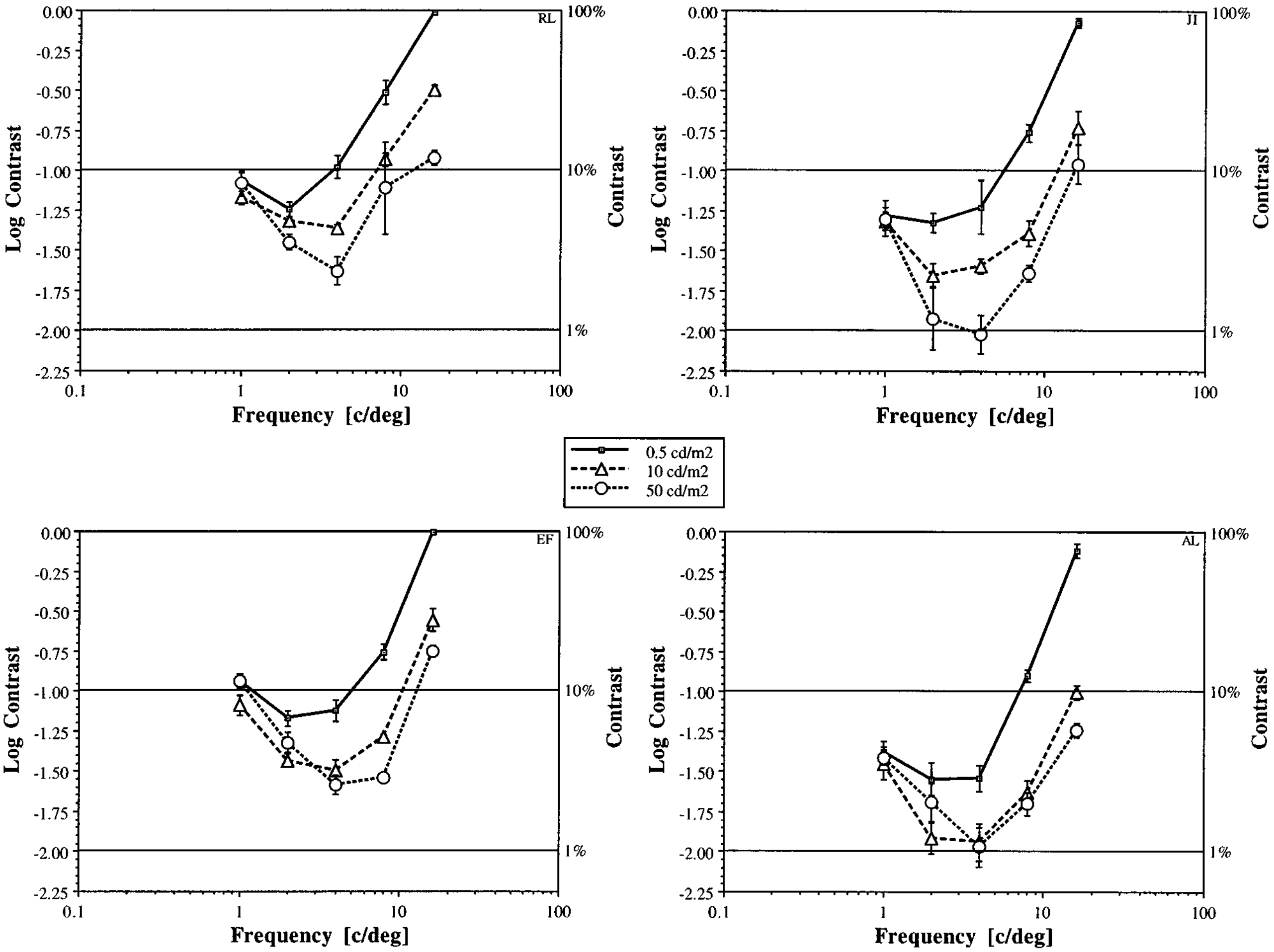

Fig. 3. Data from Fig. 2 replotted as a function of frequency, with luminance as a parameter, illustrating the typical transition from bandpass to low-pass characteristics at low luminance, with loss of sensitivity limited to moderate and high spatial frequencies.

mean luminance, as seen in Fig. 3. As the luminance is reduced, the high-frequency threshold is affected, while the low-frequency threshold at first remains unchanged, resulting in the reduction of peak sensitivity. This presentation of the data, however, does not explain why different frequencies are affected differently by reduced luminance.

A secondary unexplained result was replicated as well. Van Nes and Bouman[7] found a slight decrease in threshold at 4 c/deg, just at the transition knee between the two straight lines (their Figs. 5 and 6). They did not comment on it but clearly marked it in their graphs. This peak in sensitivity corresponds to the peak noted by Patel[12] in both its spatial frequency and its luminance. We found a similar unexplained drop in threshold just at the transition zone (marked by thin dotted lines in Fig. 2) for the 1-c/deg condition. A similar increase in sensitivity at 4 c/deg was found for the suprathreshold contrast-matching results described below.

B. Suprathreshold Contrast Matching

The suprathreshold contrast-matching data follow the same general pattern as the threshold data (Fig. 4). For low spatial frequencies we find contrast constancy over the whole range tested. As the frequency is increased to 8 c/deg, the data clearly show a deviation from constancy at low luminance levels, which can be approximated by a slope of -0.5. The transition from the Weber range to the de Vries–Rose range occurs at a higher mean luminance for higher spatial frequencies, such that for the 16-c/deg target, reduced mean luminance results in a drop in apparent contrast over the full range of luminances available on our display. With a slope of -0.5 this decrease accounts for a full-log-unit drop in apparent contrast over the 2-log-unit change in mean luminance available on most CRT's.

If the data are plotted as a function of frequency with mean luminance as a parameter, the matches for moderate to high luminances have the typical flat or shallow bandpass characteristics of contrast constancy (Fig. 5), as reported by others.[1,2] At low luminance levels the apparent contrast is reduced, resulting in a low-pass characteristic for the curve. However, for two of the four subjects (EF and AL) we also found an increase in apparent contrast at high spatial frequencies and for high levels of mean luminance (these data are illustrated in Figs. 4 and

5). This characteristic, which can be described as the high-pass nature of suprathreshold sensitivity (Fig. 5, lower panels) has not to our knowledge been discussed before. Similar peaking of sensitivity at high luminance for high frequencies can, however, be noted in the contrast-estimation data of Biondini and de Mattiello[13] (their Fig. 13), who used a mean luminance as high as 67 cd/m^2. Most previous work in this area used lower mean luminances (10 cd/m^2 for both Georgeson and Sullivan[1] and Kulikowski).[2] It is possible that the high-pass nature is revealed only at such high luminance levels.

C. Effects of Refractive Error and Adaptation

One of the authors, AL, participated in the study, first using her habitual contact lens correction with visual acuity 6/6. Following the completion of that session, she underwent refraction and received spectacle correction, which improved her acuity to 6/4.5. A repeat of the supra-

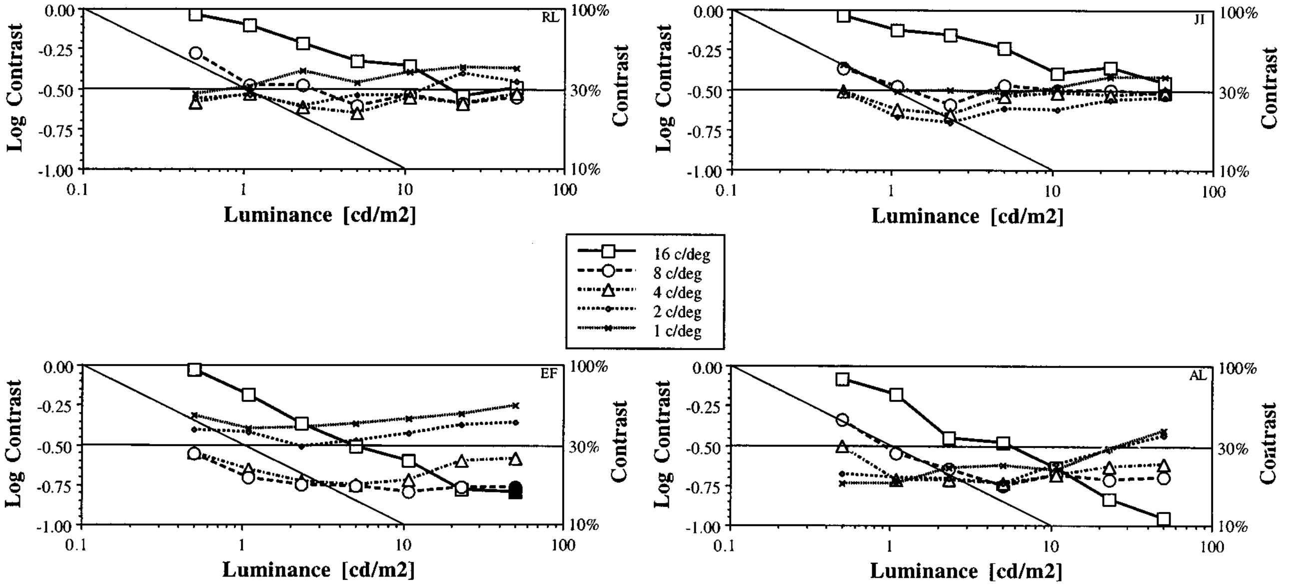

Fig. 4. Suprathreshold contrast-matching data as a function of luminance illustrate effects similar to those found at threshold. The low spatial frequencies (1–4 c/deg) show contrast constancy across the whole luminance range tested. The diagonal line represents a slope of −0.5. The two filled symbols for subject EF represent that these data were obtained from one session only.

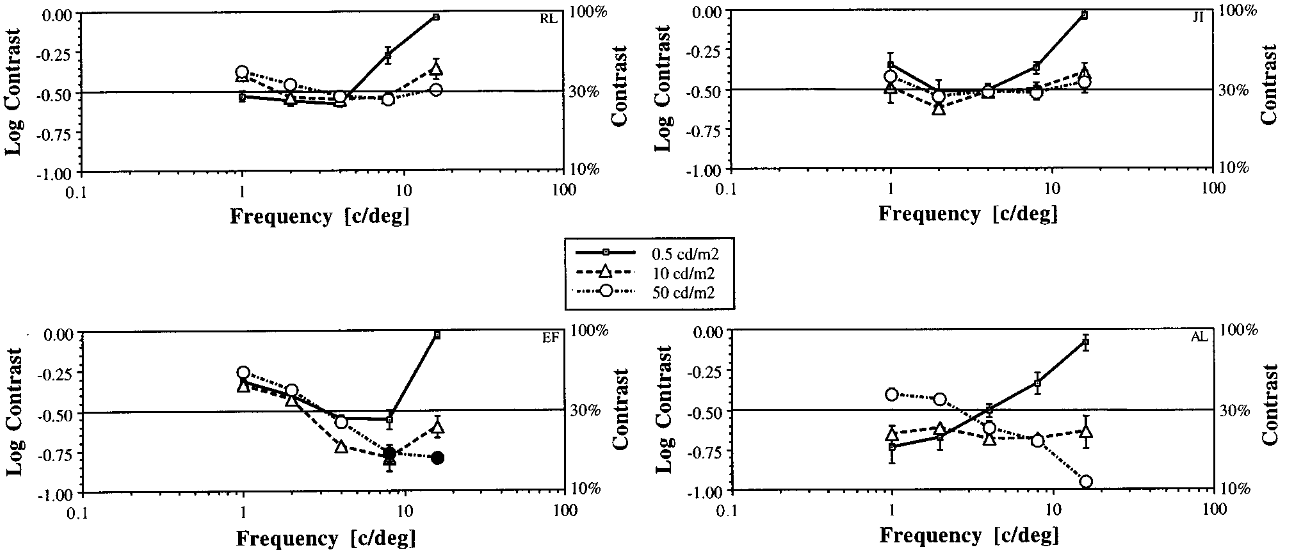

Fig. 5. Data from Fig. 4 replotted as function of frequency. For all subjects the data represent contrast constancy for the 10-cd/m^2 condition (triangles) and a reduction of apparent contrast at high frequencies (low-pass) for the low-luminance [0.5-cd/m^2 (squares)] condition. For the high-luminance condition (circles), two of the four subjects displayed contrast constancy, and two (AL and EF) presented an unexpected high-pass characteristic.

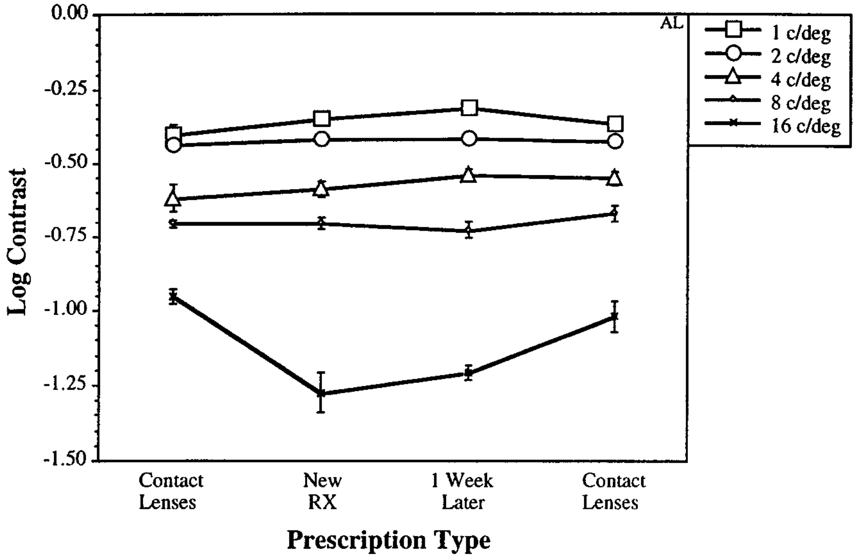

Fig. 6. Changes for one subject in contrast-matching results following change of refraction, adaptation to new refraction, and return to contact lens correction with slightly reduced acuity.

threshold matching experiment with the spectacle correction yielded the expected increase in sensitivities for high frequencies as well as a slight reduction in low frequencies (Fig. 6). The latter effect is expected only because the improved refraction affected the 3-c/deg standard more than it affected the lower spatial frequencies. Following a week of the subject's adaptation to the new spectacles (with constant wear), the measurements showed a relative return to baseline sensitivity, as would be predicted by the theory of contrast recalibration.[14] A return to the contact lens correction resulted in a return of the matching results to their original level. A second subject who was tested first with a new prescription demonstrated the same changes when retested with the previous slightly inferior correction. Similar adaptation to suprathreshold contrast perception is noted for patients with long-term media opacities that are due to cataract or corneal scars.[15] These observers frequently report perceiving the world with a full range of contrasts despite the fact that their scattering optics reduces the maximal possible retinal contrast substantially.

4. CONCLUSIONS

To a first approximation, apparent-contrast matches as a function of luminance at well above threshold follow a pattern analogous to that seen at threshold,[7] but the transition from Weber's law to the square-root law occurred at lower luminances in the suprathreshold task. Only the 8- and 4-c/deg stimuli provide sufficient data for comparison across conditions. These data suggest ~1-log-unit lower luminance for the suprathreshold transition. At high frequencies (8 and 16 c/deg) the transition from Weber's law to the square-root law became evident, even for luminance levels frequently used on a CRT. For lower frequencies the response followed Weber's law (flat) throughout the range of luminances tested here and probably follows the same pattern at lower luminance levels. The effects of local luminance level on both the detection threshold and the apparent contrast of features at 8 c/deg and higher frequencies is substantial. A reduction of 1 log unit is possible across luminance changes commonly found on the display. These effects should be considered in various applications such as image-compression and image-quality measures.

The fact that the apparent contrast is reduced does not necessarily mean that the perception of lightness is changed, nor does it lead to a misidentification of surfaces. Arend and Spehar[16] showed that observers can make separate and consistent judgments when matching either property and that apparent contrast can change without affecting the veridical perception of surface-reflection properties.

We have replicated two phenomena that were identifiable in previous data and remain unexplained. The apparent high-pass characteristics of the contrast-matching function at high luminances found for two of our four subjects is notable in the contrast-estimation data of Biondini and de Mattiello.[13] The increase in sensitivity as a function of luminance at the transition from the Weber to the de Vries–Rose range, which is noted in the threshold data of van Nes and Bouman,[7] was found in our data, and a corresponding change was noted for the suprathreshold data. We currently have no explanation for either phenomenon, but the fact that they were noted in different experiments in different laboratories suggests that a search for an explanation will be worthwhile.

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