

# Lack of Covariation of the Effects of Luminance and Eccentricity on Contrast Sensitivity

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**ABSTRACT:** *Background and purpose.* Qualitative individual differences in visual processing along various stimulus dimensions have been previously documented. For instance, as compared to the foveal contrast sensitivity function (CSF), the peripheral CSF of some subjects shifts toward lower frequencies, but it scales down for others; also, sensitivity to low spatial frequencies increases monotonically with luminance in some subjects, but it displays a decline at high luminances in others. Although these qualitatively distinct eccentricity- and luminance-related patterns have been thoroughly described separately, their joint occurrence has never been studied. This study aimed at determining whether there is covariation between the effects of luminance and eccentricity on contrast sensitivity, i.e., whether each eccentricity-related pattern occurs with one and only one of the luminance-related patterns. *Methods.* We have measured contrast sensitivity to sine-wave grating patches as a function of luminance and eccentricity in a sample of 18 subjects. *Results.* We found positive evidence of lack of covariation between the effects of eccentricity and luminance: we found subjects who show the same eccentricity-related pattern but differ as to their luminance-related patterns, and we have also found a subject who, unlike the rest, shows qualitatively distinct luminance-related patterns at different eccentricities. *Conclusion.* The dependence of contrast sensitivity on eccentricity and luminance is subject to qualitative variations both across and within individuals, suggesting that meaningful conclusions on the effects of luminance and eccentricity on contrast sensitivity cannot be drawn when the data from all available subjects are aggregated. (*Optom Vis Sci* 1999;76:63-67)

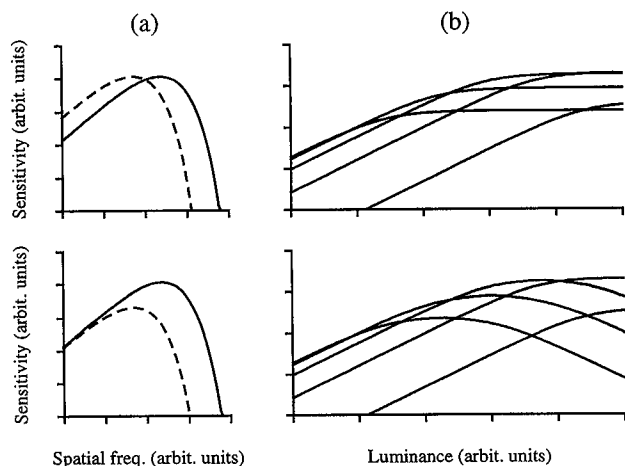
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Contrast sensitivity for sine-waves usually decreases as eccentricity increases<sup>1-3</sup> and increases with increasing luminance.<sup>4,5</sup> Yet, qualitatively distinct patterns of variation in sensitivity with either eccentricity or luminance have been described. García-Pérez and Sierra-Vázquez<sup>6</sup> compiled evidence indicating that some subjects are more sensitive to low frequencies in the periphery, thus disconfirming the rule that sensitivity decreases as eccentricity increases. Also, García-Pérez and Peli<sup>7</sup> compiled evidence that sensitivity to low frequencies decreases at high luminances in some subjects, thus disconfirming the rule that sensitivity increases with luminance. Fig. 1 summarizes graphically the two documented forms in which the sine-wave contrast sensitivity function (CSF) may vary from fovea to periphery, and also the two forms that the relationship of sine-wave contrast sensitivity may have to luminance.

Because different subjects participated in the original studies where these qualitatively distinct patterns were observed, it is not known whether they covary, i.e., whether or not all subjects showing one of the qualitative forms of dependence of sensitivity with

eccentricity always show one and only one of the qualitative forms for the dependence of sensitivity with luminance. Furthermore, in none of those studies were the joint effects of luminance and eccentricity measured in the same subjects and, therefore, it also remains unknown whether there are within-subject variations in these dependencies, e.g., whether or not a subject who shows one of the qualitative forms of dependence of sensitivity with eccentricity at some given luminance also shows the same form of dependence at all other luminances; likewise, whether or not a subject who shows one of the qualitative forms of dependence of sensitivity with luminance at a given eccentricity also shows the same form of dependence at all other eccentricities. Interest in these questions arises because covariation of these qualitatively distinct patterns along the two (clearly independent) dimensions of eccentricity and luminance might indicate a common source for the effects of luminance and eccentricity on contrast sensitivity.

This work set out to explore the covariation of the effects of eccentricity and luminance on contrast sensitivity by measuring contrast sensitivity to sine-wave grating patches at various eccen-



**FIGURE 1.**

(a) Two forms in which sine-wave CSFs have been reported to change with eccentricity. At the top, peripheral CSFs (dashed curve) are similar to the foveal CSF (continuous curve) except for a shift toward lower frequencies, which results in the peripheral retina being more sensitive to low frequencies than the fovea; at the bottom, peripheral CSFs fall below the foveal CSF so that the fovea is more sensitive than the periphery at all frequencies. (b) Two forms in which sine-wave contrast sensitivity has been reported to change with luminance. Each curve pertains to a different spatial frequency. At the top, sensitivity increases monotonically with luminance at all spatial frequencies; at the bottom, it displays a nonmonotonic dependence at some frequencies.

tricies and luminance levels in a sufficiently large sample of subjects. However, our goal is not to describe or document well-known forms of dependence of sensitivity with luminance (or eccentricity, for that matter), nor is it to provide normative data or large-sample statistics. Rather, we aim at searching for empirical evidence bearing on the covariation between the eccentricity-related sensitivity patterns in Fig. 1(a) and the luminance-related sensitivity patterns in Fig. 1(b). In other words, we are interested in studying whether the effects of eccentricity covary with the effects of luminance, however dissimilar the isolated effects of either variable are.

Given the exploratory nature of this study, our results must remain inconclusive for they merely reflect the characteristics of the subjects in our sample, thus potentially failing to reveal sensitivity patterns that are less prevalent in the population. Nevertheless, our main goal of searching for positive evidence of lack of covariation was attained: we found subjects who show the same eccentricity-related pattern but different luminance-related patterns, and also subjects who show qualitatively distinct luminance-related patterns at different eccentricities.

## METHODS

### Stimuli and apparatus

Stimuli were horizontal, even-symmetric Gabor patches of frequencies between 0.05 and 3.2 cpd, in octave steps. Only low spatial frequencies were used because it is in this range where qualitative individual differences have been reported.<sup>6,7</sup> There were four cycles of the sinusoid between  $1/e$  points of the circular Gaussian envelope (but the Gabor patch was not spatially truncated), which results in a perceived size (at threshold contrast) such that

peripherally presented patches did not significantly cover central retinal locations.<sup>8</sup> To prevent the peripheral Troxler effect, contrast was linearly ramped on and off over 100 ms before and after a 300-ms flat-contrast presentation period.

Stimuli were displayed on an Image Systems M21L monitor (DP-104 phosphor) at a frame rate of 117 Hz. The monitor response was linearized by gamma correction. Mean luminance on the screen was 66 cd/m<sup>2</sup>, and it did not change over the course of the experiments. For measurements at lower luminances, subjects wore over-the-glasses goggles fitted with Kodak neutral density filters. All experimental events were under control by an 80486 PC equipped with VisionWorks<sup>9</sup> (Vision Research Graphics Inc., Durham, NH) hardware and software.

The screen was surrounded with a large (1×1.2 m) piece of translucent white foamboard whose surface was vertically curved to describe a 90° arc above the 1024×512-pixel (27×21-cm) image area in order for all (vertically aligned) fixation points to lie at the same viewing distance. The foamboard was illuminated from the back so its front side was approximately matched in luminance to the screen, and the room was otherwise dark.

Viewing was binocular and a viewing distance of 45 cm was ensured with a head- and chin-rest. All peripheral measurements were carried out on the inferior visual field by directing subjects' fixations to the appropriate locations along an imaginary vertical line running up from the center of the image area. Small dots on the screen or on the foamboard served as fixation aids. Eccentricity was defined as the distance between the fixation point and the center of the Gabor patch.

## Procedure

Natural pupils and accommodation were always used and subjects adapted to the screen/surround luminance for 5 to 10 min before any session began, whether wearing goggles or not.

The method of adjustment (MOA) was used to obtain 6 to 8 threshold estimates per condition, and reported data are arithmetic means of those thresholds.<sup>a</sup> Contrast was defined in decibels, with the origin of the scale at  $m = 1$ , where  $m$  is the Michelson contrast of the underlying sinusoid. Each MOA trial consisted of a 500-ms presentation (signalled by an audible tone) and requested an adjustment move from the subject. At the beginning of each MOA trial, the stimulus appeared with a random contrast chosen from a uniform distribution between -10 and -30 dB, and subjects used controls to change contrast in 1-dB steps up or down until the stimulus was just visible.

## Design

Measurements were taken in separate experimental sessions, each devoted to a given pairing of luminance and eccentricity levels. Each subject went through these sessions in a newly randomized order, and the order of spatial frequency presentations in

<sup>a</sup> A pilot study revealed that MOA thresholds are less variable than those obtained with a 10-reversal, 3-down/1-up 2AFC staircase using a down-step size of 0.4 log units and an up-step size of 0.516 log units, which represent near-optimal settings for convergence around the 82%-correct point.<sup>9,10</sup> Also, CSFs obtained with either method were very similar, and eight MOA thresholds could be obtained in about the time required to complete a single staircase.

CSF measurements was also newly randomized within each session. Including the adaptation periods, complete measurements under all conditions relevant to this study required several hours of observing throughout several days, something that limited the number of subjects that could contribute data under all the conditions of this study.

## Subjects

Consistent with our goals, we kept testing subjects until data were obtained that provided positive evidence of lack of covariation. Overall, 18 subjects (25- to 61-years-old) with normal or corrected-to-normal vision participated in the study, although not all of them served in all conditions. All subjects had 20/20 or better acuity, and most of them were pre-presbyopes.<sup>b</sup> Except for the authors, subjects were naïve as to the purpose of the experiment, and three of them had no previous experience in psychophysical experiments.

## RESULTS

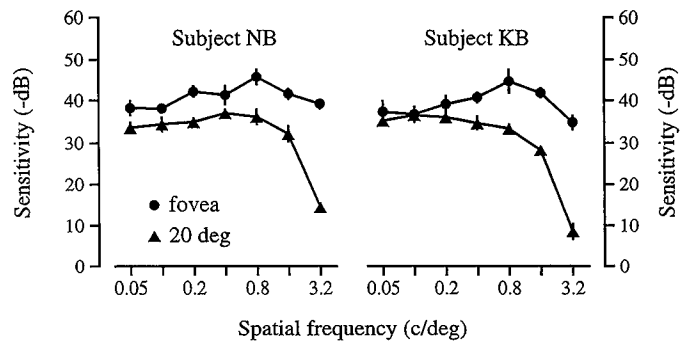
Fig. 2 shows data from the two subjects whose foveal vs. peripheral CSFs differed most in relative shape at 66 cd/m<sup>2</sup>. Yet in both cases, sensitivity is higher at the fovea for all frequencies, although in subject KB the foveal and 20-deg eccentric CSFs converge at low frequencies, while they follow separate paths in subject NB.

Other measurements all indicated higher sensitivities at the fovea for all frequencies, and progressively lower sensitivities as eccentricity increased. These additional measurements were taken from 6 subjects at the same eccentricities of 0° and 20° at each of 2 luminances (66 and 6.6 cd/m<sup>2</sup>), from 1 subject at 3 eccentricities (0, 20, and 40°) at each of 3 luminances (66, 6.6, and 0.66 cd/m<sup>2</sup>), and from 1 subject at the additional eccentricities of 10, 30 and 40° at each of 4 luminances (66, 6.6, 0.66, and 0.066 cd/m<sup>2</sup>), in all cases using the same 7 spatial frequencies for which data from 2 subjects are shown in Fig. 2. In search of the elusive higher sensitivity to low frequencies in the periphery, a quick screening test was carried out on 9 additional subjects by measuring sensitivity to the 0.4 cpd patch at the fovea and 20° into the periphery, but all 9 subjects proved more sensitive to the low frequency patch at the fovea.

In sum, none of the 18 subjects showed any indication of higher sensitivity to low frequencies in the periphery. That is, they all showed the pattern sketched in the bottom panel of Fig. 1(a). All of these data thus support what García-Pérez and Sierra-Vázquez<sup>6</sup> called a declining gain function. Failure to find evidence of qualitatively different eccentricity-related patterns may simply reflect a prevalence of the declining function,<sup>6</sup> but it did not adversely affect our investigation because individual differences in luminance-related patterns were found, as described next.

The CSF of 6 subjects was measured in at least two luminances (66 and 6.6 cd/m<sup>2</sup>) at several eccentricities. Five of them showed similar or lower sensitivities at the lower luminance, and further

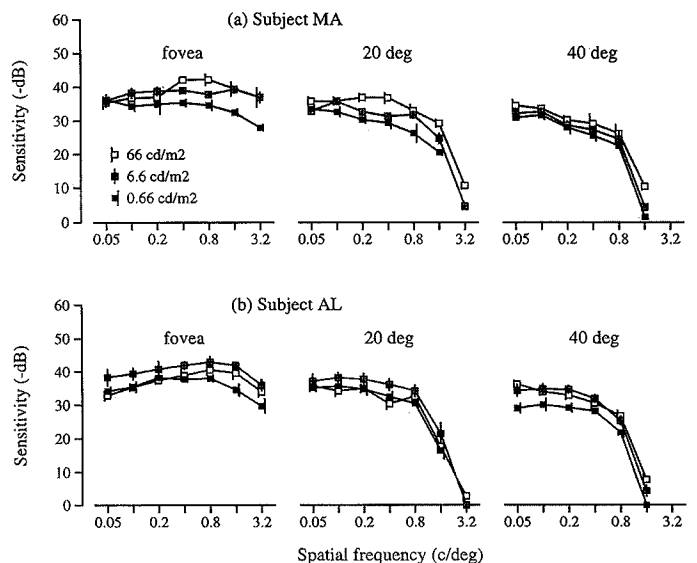
<sup>b</sup> We are not reporting data from the presbyopic subjects in our figures, although they did not show any pattern of sensitivity that was qualitatively different from the rest of our pre-presbyopes. Indeed, blur caused by improper accommodation will be very small given our low-frequency stimuli, and it will nevertheless be the same across eccentricity and luminance.



**FIGURE 2.**

Foveal and 20° eccentric CSFs for two subjects. Data are arithmetic means of 8 MOA thresholds. Error bars indicate 95% confidence intervals. The CSFs show low frequency convergence for subject KB but not for subject NB.

measurements with one of them at a still lower luminance (0.66 cd/m<sup>2</sup>) confirmed this trend [subject MA; see Fig. 3(a)]. Thus, these data were in agreement with the DeVries-Rose to Weber transition sketched in the top panel of Fig. 1(b). However, the sixth subject systematically showed higher sensitivities at the lower luminance, but further measurements at a still lower luminance (0.66 cd/m<sup>2</sup>) reversed the trend and resulted in a drop in sensitivity [subject AL; see Fig. 3(b)]. This characteristic shows clear evidence of nonmonotonicity in the relationship between sensitivity and luminance and, thus, provides evidence against the DeVries-Rose to Weber transition, as sketched in the bottom panel of Fig. 1(b). Incidentally, subject AL had participated in previous foveal studies, where she also showed a nonmonotonic pattern.<sup>11</sup> However, her peripheral performance had never been measured before.



**FIGURE 3.**

Foveal and peripheral CSFs at each of three luminances for two subjects. Data are arithmetic means of 6 to 8 MOA thresholds. Error bars indicate 95% confidence intervals. Note that sensitivity decreases with decreasing luminance at most frequencies and eccentricities for one subject (a), whereas the other subject (b) was approximately equally sensitive at the two extreme luminances (open and solid squares) but was more sensitive to all frequencies at the intermediate luminance (gray squares) at the fovea and at 20° eccentricity.

Fig. 3 shows further evidence of a declining function for both subjects at all luminances: as eccentricity increases (i.e., left to right within each row of panels) the CSFs slide down along the sensitivity axis. This trend occurred at every luminance level for both subjects, despite the qualitatively distinct (i.e., monotonic vs. non-monotonic) luminance-related pattern displayed by each subject. Fig. 3 also indicates that the effects of luminance may change with eccentricity. Specifically, in subject MA's data, sensitivity increases monotonically with increasing luminance for all frequencies at all eccentricities. Yet, from subject AL's data, nonmonotonicity holds at the fovea and 20° into the periphery, but monotonicity seems to hold at 40°.

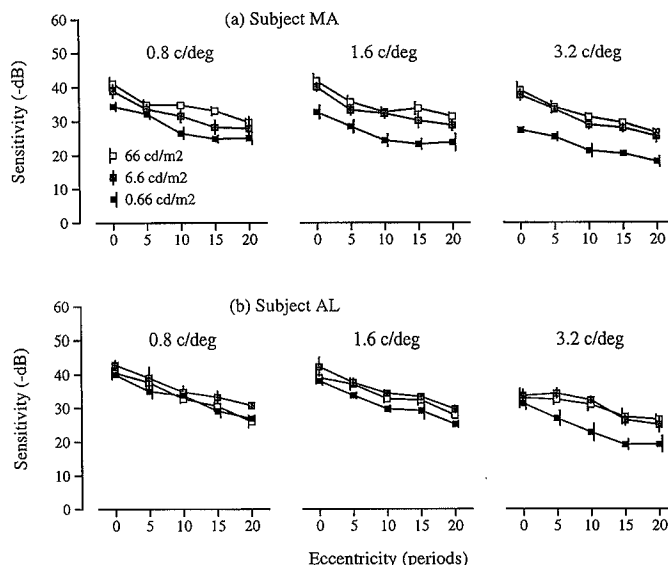
Moreover, subject MA's data indicate that quantitative aspects of the effects of luminance may change from fovea to periphery: CSFs at the three luminances are closer together at 40° than they are at the fovea or at 20° [see Fig. 3(a)], as if the three luminances were closer to the Weber range in the far periphery than they are in the fovea or a nearer eccentricity. This characteristic seems to contradict earlier claims<sup>12</sup> that the DeVries-Rose to Weber transition occurs at the same luminance at all eccentricities.<sup>7</sup>

In summary, these data show clear evidence of qualitative individual differences in the effects of luminance on sensitivity, as well as within-subject changes in these effects with eccentricity. Importantly, Fig. 3 indicates that the effects of eccentricity and luminance do not covary: sensitivity changes with eccentricity in the same way for both subjects (it declines at all frequencies) and yet variations with luminance describe a different pattern in each subject (monotonic vs. nonmonotonic); in addition, sensitivity changes with luminance in the same way (monotonically) at all luminances for subject MA, but this luminance-related pattern changes from nonmonotonic to monotonic toward the periphery in subject AL.

To explore whether this lack of covariation was also observed when eccentricity is defined in relative rather than absolute units, the contrast sensitivity gradients<sup>1-3</sup> were measured in these subjects at 66, 6.6, and 0.66 cd/m<sup>2</sup>. Only patches of the three highest spatial frequencies (0.8, 1.6, and 3.2 cpd) were used in order to be able to determine contrast sensitivity at five relative eccentricities (0 to 20 periods of the sinusoid, in 5-period steps) without the peripheral patches reaching the fovea and, at the same time, yielding practicable eccentricities.

Fig. 4 shows the results, revealing similar declines at all luminances. As luminance changes, only overall sensitivity seems to change in a manner that is consistent with the luminance characteristic of each observer: for subject MA [Fig. 4(a)] the curves slide down toward lower sensitivities as luminance decreases, whereas for subject AL [Fig. 4(b)] the curves slide up toward higher sensitivities when luminance decreases from 66 to 6.6 cd/m<sup>2</sup> and then slide back down when luminance decreases further from 6.6 to 0.66 cd/m<sup>2</sup>.

Note that the largest absolute eccentricity implied in these measurements is 25° (corresponding to a 0.8 cpd patch located 20 periods away from the fovea). Thus, according to the data displayed in Fig. 3(b), these measurements were carried out within the range of absolute eccentricities where nonmonotonicity holds for subject AL. Thus, these data further corroborate that the effects of eccentricity on sensitivity do not covary with those of luminance.



**FIGURE 4.**

Contrast sensitivity gradient at 0.8, 1.6, and 3.2 cpd at each of three luminances for the subjects in Fig. 3. Data are arithmetic means of 6 MOA thresholds. Error bars indicate 95% confidence intervals. Note the absence of major qualitative differences in the declines.

## DISCUSSION

In a sample of 18 subjects, we have found quantitative individual differences in the effects of eccentricity (Fig. 2), as well as qualitative and quantitative differences in the effects of luminance (Figs. 3 and 4), but we have not found any consistent covariation between how sensitivity changes with eccentricity and how it changes with luminance. In other words, although some of the known forms for the relationship of sensitivity to either eccentricity or luminance (see Fig. 1) seem to be more prevalent than others (see also discussion in ref. 6), our data reveal that both monotonic and nonmonotonic dependencies of sensitivity with luminance can be observed in subjects whose CSFs describe the same pattern of variation with eccentricity. We have also found evidence of within-subject changes in the luminance-related pattern at different eccentricities, which corroborates the lack of covariation between luminance-related and eccentricity-related patterns. In this respect, it is also important to note that nonmonotonic patterns have been reported for some subjects at an eccentricity of 37° (see Fig. 2D of ref. 12), although none of our subjects showed this characteristic.

Undoubtedly, the distinct patterns of variation as well as the breadth of individual differences described in this paper do not cover the entire spectrum of possibilities, as the results of any empirical study of this nature are determined by the characteristics of the visual system held by each available subject. Yet, our results—along with results previously reported in similar conditions—attest to the existence of major qualitative and quantitative individual differences in the effects of eccentricity and luminance on contrast sensitivity. These results also indicate that meaningful conclusions from research on variations of contrast sensitivity with eccentricity and luminance cannot be drawn by averaging data from all available subjects, nor by aggregating data collected from different subjects, each tested at a different eccentricity and/or

luminance. At the same time, these results contradict two tenets of visual science. First, none of the 18 subjects whose CSF was measured at several eccentricities confirmed the shift rule,<sup>13</sup> whereby peripheral CSFs are identical to the foveal CSF except for a shift toward lower frequencies. Second, the DeVries-Rose to Weber transition was disconfirmed by evidence that sensitivity may decrease with increasing luminance at low frequencies.<sup>7</sup>

Of major concern to our understanding of visual processing is what sensitivity measures reveal about visual gain.<sup>14</sup> At present, we can only speculate on the causes of the patterns described in this paper, but there are aspects of the functional organization of the visual system where quantitative individual differences might produce qualitative and/or quantitative differences in empirical functions describing variations of sensitivity with luminance and eccentricity.

As luminance increases, visual processing passes from being mediated by rods through being mediated by both rods and cones to being mediated by cones only.<sup>15, 16</sup> We might assume that visual sensors process a weighted sum of rod-based and cone-based inputs,<sup>17</sup> each of which, in turn, may be differently affected by luminance and eccentricity. Preliminary simulation results with a spatial vision model with these two components indicate that a simple quantitative change, namely, the balance of rod-based and cone-based inputs, produces the various changes in the relationship between contrast sensitivity and luminance that have been reported in this paper and elsewhere in the literature. Specifically, contrast sensitivity at low light levels is determined only by rod-based inputs, whereas it is only determined by cone-based inputs at high light levels. Yet, at intermediate light levels—where both cone-based and rod-based inputs are contributing to each sensor's response—the shape of the predicted relationship between contrast sensitivity and luminance depends only on the balance of these contributions: if cone-based inputs dominate, only DeVries-Rose and Weber behavior occur; if rod-based inputs dominate, an interleaved decreasing range occurs between the DeVries-Rose and Weber ranges. If the balance between rod-based and cone-based inputs changes across the visual field, then the characteristics of the data reported for subject AL in Fig. 3(b) can be reproduced.

Thus, when a gain function (whatever the ultimate source of its form may be) is included in spatial vision models that explicitly incorporate cone-based and rod-based inputs, changes in the form of this function can explain qualitative and quantitative differences in contrast sensitivity as a function of spatial frequency, eccentricity, and luminance.

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