Suprathreshold Contrast Matching in Maculopathy

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PURPOSE. To compare suprathreshold contrast perception among three groups of participants with maculopathy (atrophic age-related macular degeneration [ARMD], exudative ARMD, and juvenile macular dystrophy [JMD]) and to compare suprathreshold contrast matching between controls and subjects with maculopathy.

METHODS. Three groups of subjects with macular disorders (13 atrophic ARMD, 14 exudative ARMD, and 8 JMD) and one group of control subjects (15 subjects 50 years and older) participated. Contrast sensitivity (CS) up to 8.53 cycles per degree (cpd) was measured with a temporal two-alternative forced-choice staircase procedure. Suprathreshold contrast matching was measured using a method of limits. A 0.58 cpd sine-wave grating was the standard; the subject was asked to match the contrast of gratings of different spatial frequencies.

RESULTS. Subjects with maculopathy showed marked deficits of contrast threshold. Suprathreshold contrast constancy was shown, though deficits were observed in absolute matches compared with control subjects. The slopes of matched contrast against standard contrast for the subjects with maculopathy were significantly different from those for the controls, and these differences were in the direction that implies compensation for differences in thresholds. There were no significant differences among the three groups of subjects with maculopathy.

CONCLUSIONS. In this study, the authors observed a degree of contrast constancy in subjects with maculopathy, though there were still deficits compared with control subjects. This is discussed in terms of gain of the visual system adjusting to compensate for CS losses (though incompletely) or contrast overconstancy, present in normal peripheral vision, which helps to compensate for CS loss. (Invest Ophthalmol Vis Sci. 2007;48:3419–3424) DOI:10.1167/iovs.06-0731

A ge-related macular degeneration (ARMD) is the leading cause of visual impairment in Western developed countries. The later stages of ARMD are categorized into atrophic ARMD and exudative ARMD.1 Both conditions involve loss of central vision, including loss of contrast sensitivity and visual acuity. In juvenile macular dystrophy (JMD), such as Stargardt disease and Best disease, a similar loss of visual function occurs. Studies have shown that contrast threshold measurement is a better predictor of functions such as reading speed, mobility performance, and recognition of targets (e.g., faces) than visual acuity.2–6 However, most of our daily visual function happens at suprathreshold contrast levels. Little is known about how suprathreshold contrast perception is affected by maculopathy and whether suprathreshold perception might have a greater or lesser influence on visual disability than threshold measurements.

Studies on normal vision have suggested that suprathreshold contrast perception is different from threshold detection in that it is less dependent on spatial frequency and exhibits constancy at higher contrasts.7–9 Thus, at higher contrasts, gratings of equal contrast but different spatial frequency are perceived as having similar contrast despite large differences in contrast threshold. Several studies have investigated contrast matching between the fovea and eccentric retinal areas.7,10–11 This is of interest in studies of maculopathy, because an eccentric location (the preferred retinal locus [PRL])12–15, rather than the nonfunctional anatomic fovea, is used for fixation. These studies showed that subjects could make fairly accurate matches between the two retinal locations despite large differences in threshold. They suggested that the gain functions of peripheral channels are adjusted to compensate for the neural blur at each retinal locus. However, there was a consistent tendency to perceive an eccentric grating to be of higher contrast than the standard grating at the fovea.7 This was called contrast overconstancy.14 Overconstancy also seemed to occur when gratings of different spatial frequencies, presented at the same retinal eccentricity, were matched—higher spatial frequencies appeared to have more contrast than lower spatial frequencies.14

A few studies have examined contrast matching in people with visual impairment caused by a variety of disorders, namely nystagmus,15 amblyopia,16 and demyelinating disease.17 All these studies showed normal or lower deficit in suprathreshold contrast perception compared with contrast sensitivity. Maculopathy is different from these eye diseases in that a PRL is developed and used instead of the anatomic fovea. A study by Leat and Millodot18 using contrast discrimination (CD) in four subjects with maculopathy, found that CD was significantly poorer for the maculopathy group than for the group with normal vision at all spatial frequencies (0.25–3.0 cycles per degree [cpd]). However, this measure of suprathreshold contrast perception was less affected by maculopathy than were contrast thresholds.

This study aimed to compare suprathreshold contrast perception studied with contrast matching among three groups of subjects with maculopathy—atrophic ARMD, exudative ARMD, and JMD—and to compare suprathreshold contrast matching between controls and subjects with maculopathy. Our hypothesis was that suprathreshold function in maculopathy is less affected than contrast thresholds. Additionally, we sought to determine whether there is evidence of contrast overconstancy in maculopathy.

SUBJECTS, MATERIALS, AND METHODS

Apparatus

A computer (Macintosh 6100/66; Apple, Cupertino, CA) was used to generate stimuli with Morphophone 3.5 software.19 Stimuli were displayed on a high-resolution 21-inch monitor (Trinitron; Sony, Tokyo, Japan) with a mean luminance of 60 cd/m2. A hardboard surround with luminance of 60 cd/m2 was placed around the monitor to provide a constant level of light adaptation. The luminance was measured with a

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photometer (LS-100; Minolta, Tokyo, Japan). The display area measured 30.3° horizontally and 28.5° vertically at a viewing distance of 57 cm.

Stimuli
The stimuli were vertical cosine gratings of at least four cycles in width with a circular vignette envelope. Contrast thresholds were measured for spatial frequencies of 0.26, 0.58, 1.11, 2.17, 4.29, and 8.53 cpd. The viewing distance for 4.29 cpd and lower was 57 cm, and for 8.53 cpd it was 114 cm. The duration of the stimulus was 1.053 seconds, and the interstimulus interval was 583 ms.

For suprathreshold contrast matching, two horizontally separated gratings were presented. The standard grating, with a fixed spatial frequency of 0.58 cpd, was on the right of the display screen and was presented at seven contrast levels: 1.7%, 3.6%, 7.2%, 13.7%, 27.9%, 57.9%, and 114.8%. The test grating, with varying spatial frequency of 0.26, 0.58, 1.11, 2.17, 4.29, or 8.53 cpd, was presented on the left.

Subjects
Subjects with normal vision or maculopathy were recruited from the Optometry Clinic at the School of Optometry, University of Waterloo, and the Canadian National Institute for the Blind (CNIB). Given that our previous findings showed no main effect of age for suprathreshold contrast matching and most of the maculopathy subjects (30 of 36) were older than 50 years, one control group was used in this study (15 subjects aged 50 and older). There were three groups of subjects with maculopathy (13 subjects with atrophic ARMD, 14 with exudative ARM, and 8 with JMD). Average ages of the groups were as follows: control group, 70 ± 11 years; atrophic ARM group, 81 ± 5 years; exudative ARM group, 81 ± 8 years; and JMD group, 47 ± 14 years. All subjects gave written informed consent for participation in the study, which was approved by the Office of Research Ethics at the University of Waterloo. All subjects were treated in accordance with the Declaration of Helsinki.

Procedure
Subjects' refractive errors were checked by subjective refraction. If there was no improvement in visual acuity, they wore their spectacles plus a working distance lens, was worn in a trial frame. Monocular visual acuity of the preferred eye was measured with the University of Waterloo logMAR chart. Five minutes of light adaptation was allowed beforehand. For contrast threshold measurement, a temporal two-alternative forced-choice (2-AFC) staircase method was used.

For suprathreshold contrast matching, a method of adjustment, under experimenter control, was used. Subjects, looking freely between the standard and the test grating with the preferred eye, compared the contrast between the standard grating (0.58 cpd) and the test grating (with varying spatial frequency) and told the experimenter to increase or decrease the contrast of the test grating to match the contrast of the standard grating. To minimize any pattern adaptation, subjects were instructed not to look at the standard grating for too long.

The number of contrast matches each subject could make was limited because of fatigue and level of vision; for instance, some subjects could not detect the lowest contrasts at some spatial frequencies to make a match. Therefore, the aim was to complete matching across all spatial frequencies at 5.6% and 27.9% contrast so as to get as full a data set as possible for these parameters and to undertake as many other contrast matches as possible for the other contrast levels, including the highest spatial frequency and the lowest contrast that each subject could detect. Only a few subjects could undertake matches for 8.53 cpd (1 at 5.6% and 5 at 27.9%); therefore, 8.53 cpd was not included in the ANOVA statistical analysis for the contrast matching.

Statistical Analysis
ANOVA in Systat was used to analyze the contrast thresholds for 0.26 to 8.53 cpd and the contrast matching (3.6% and 27.9%) for 0.26 to 4.29 cpd. Given that some data were missing for both contrast thresholds and contrast matches, we assumed sphericity and repeated the ANOVAs according to Winer, a method that uses all the data. To analyze the slopes of the contrast-matching curves, all data that were available for each subject were included.

Results
ANOVA showed an age difference between the ARMD group and the control group (F = 19.53; P < 0.01). This occurred because it was difficult to recruit subjects with normal vision according to our criteria (no age-related maculopathy [ARM], no cataract within the pupil area, no diabetes, good general health) of the same age as some of the older subjects with ARMD. Average VAs were logMAR −0.03 ± 0.10 for control subjects, 0.88 ± 0.09 for atrophic ARM, 1.06 ± 0.04 for exudative ARM, and 1.06 ± 0.05 for JMD. ANOVA showed there was no significant difference in VA among the three maculopathy groups (F = 2.05; P = 0.146).

First, the contrast threshold results are considered. Figure 1 shows the individual contrast thresholds of the three groups and the 95% range of the control subjects. As expected, most subjects with maculopathy showed some deficit of contrast sensitivity, especially at high spatial frequencies. To compare the performance of the three maculopathy groups, mixed ANOVA (three maculopathy groups/six spatial frequencies) was applied. There was no effect of diagnosis (F = 0.43; P = 0.658) and no interaction between spatial frequency and diagnosis (F = 2.074; P = 0.102). Because the three groups showed similar contrast sensitivity, they were pooled for comparison with the normal control data. Mixed ANOVA (two
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Contrast matching of 3.6% and 27.9% for all subjects is shown in Figure 2, together with the 95% range of normal. Fifty of 175 data points were missing at 3.6%, and 10 of 175 at 27.9%. To compare the performance of the three maculopathy groups, mixed ANOVA (three groups/five spatial frequencies/two contrast levels [excluding contrast threshold]) was undertaken but showed no main effect of diagnosis (F = 0.891; P = 0.413) and no higher interactions based on diagnosis.

Given that no effect of diagnosis was found, the three groups were pooled into one larger maculopathy group for final analysis. Mixed ANOVA (two groups/five spatial frequencies/two contrast levels [excluding contrast threshold]) showed a main effect of the presence of maculopathy (F = 49.34; P < 0.001) and main effects of contrast (F = 4500; P < 0.001) and spatial frequency (F = 76.30; P < 0.001). Interactions occurred between contrast and group (F = 16.81; P < 0.001), spatial frequency and group (F = 23.15; P < 0.001), contrast and spatial frequency (F = 23.7; P < 0.001), and group, contrast, and spatial frequency (F = 11.70; P < 0.001).

Interactions occurred between macular health and spatial frequency and between macular health and contrast that were explored further by post hoc mixed ANOVAs with respect to spatial frequency and contrast. Mixed ANOVA at each contrast level showed effects of macular health at both 3.6% (F = 45.64; P < 0.001) and 27.9% (F = 17.86; P < 0.001), which indicates that maculopathy affects suprathreshold contrast perception at low and medium contrast levels. Interactions occurred between macular health and spatial frequency at both contrast levels (both P < 0.001). All our ANOVA results were confirmed with those determined by the method according to Winer.23,24

Post hoc t-tests with Bonferroni correction (the new P value for significance is 0.05/5 = 0.01, treating each ANOVA as a separate group of t-tests) showed an effect of macular health at 3.6% and 27.9% at spatial frequencies of 1.11 cpd and higher (P < 0.01). Thus, at higher spatial frequencies, subjects with maculopathy needed higher contrast than did controls to make a match. At higher contrasts, however, contrast-matching

Figure 2. Contrast threshold and suprathreshold contrast-matching curves for three subjects with atrophic ARMD, exudative ARMD, and JMD. Top curve represents the contrast threshold. Lower curves represent the contrast-matching curves at six contrast levels. None could match certain contrast levels at 4 and 8 cpd. Arrows show spatial frequency of the standard grating.

Figure 3. Contrast matching at 3.6% and 27.9% for three groups. Dashed lines show 95% confidence limits of older control subjects (1.96 × SD). The solid curves contrast matches of individual subjects with maculopathy. Arrows show spatial frequency of the standard grating.
curves become flatter and more data points were within the normal range (Fig. 3).

To analyze the gain of matched contrasts against reference contrast, the data were plotted as the matched contrast against the test contrast at each spatial frequency for subjects who were able to complete the contrast matching at a range of contrasts (four or more) at each spatial frequency. The numbers of these subjects for each spatial frequency are shown in Table 1. If contrast matching were perfect, all the contrast-matching data points would lie along the diagonal line for equal contrast. Figure 4 shows some examples of this analysis. Generally speaking, the regression slopes of subjects with maculopathy showed larger variability than did those of the control subjects. Some of the contrast-matching points fell out of the 95% confidence limits of control group. At the higher spatial frequencies, there were more contrast matches outside the normal range. Regression lines were calculated for each subject, and the average slopes of each spatial frequency and the 95% confidence limits are shown in Table 1. Regression lines for 0.58 and 1.11 cpd were along the diagonal line; those for 0.26, 2.17 and 4.29 cpd were above the diagonal, with a tendency to flatter slopes. Between the slopes of the control and the maculopathy group, *t*-tests showed significant differences at 1.11 cpd (*P* < 0.001), 2.17 cpd (*P* < 0.001), and 4.29 cpd (*P* < 0.001). It was not possible to analyze the 8.53 cpd data in this way because data were missing for many subjects.

**DISCUSSION**

**Contrast Threshold**

Our results showed that contrast thresholds in subjects with maculopathy were significantly higher than in the 95% range of age-matched control subjects, which is in agreement with previous findings, and that this deficit of contrast sensitivity increased with increasing spatial frequency. Our results also showed that the average contrast threshold was abnormal at all spatial frequencies tested, which is also in agreement with former studies. In all three groups of subjects with maculopathy, the peak of the CSF shifts to lower spatial fre-

![Figure 4](http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933444/)
quencies, to around 0.58 cpd, compared with 1.11 cpd in control subjects. This shift can probably be attributed to two causes: eccentric fixation and photoreceptor dysfunction.

Suprathreshold Contrast Matching

The first finding of this study is that, for subjects with maculopathy who were able to undertake contrast matching at all contrast levels (examples shown in Fig. 1), the suprathreshold contrast-matching results plotted across contrast levels appear similar to previous findings in subjects with normal vision.7–9 At low contrasts, the matching curves resembled the threshold curve, whereas at medium and higher levels, the curves became flatter, demonstrating contrast constancy. All the maculopathy subjects performed contrast matching at 5.6% and 27.9% (shown in Fig. 3), and the matching curves at higher contrast were flatter than those at lower contrast, again demonstrating some degree of contrast constancy. Thus, observers with maculopathy performed similarly to subjects with other visual disorders.15–17 This is particularly interesting because these studies included subjects in whom the disorder was located at the retinal level (maculopathy and albinism), the optic nerve (demyelinating disease), the cortical level (amblyopia), and the motor centers of the brain (congenital nystagmus).

However, there were differences between the control and the maculopathy groups at both levels of contrast. Thus, our results are also in agreement with those of a previous study showing deficits of suprathreshold contrast perception in subjects with maculopathy. As in this previous study, these deficits were not as great as the deficits in contrast threshold; there is some compensation for contrast sensitivity loss. As with contrast threshold, the peaks of the contrast-matching curves shifted to lower spatial frequencies compared with those of the control group. As with the contrast threshold differences, this shift could be attributed to two factors: the attenuation of medium and high spatial frequencies resulting from normal neural changes with eccentricity and the dysfunction of photoreceptors resulting from maculopathy.11,31 A few studies have compared visual function at a given eccentricity between people with ARMD and normal vision and show a loss of function compared with healthy eccentric retina.26,32

As in normal vision, there is a connection between contrast threshold and suprathreshold contrast perception, though these two mechanisms are probably different. Figure 4 and Table 1 show the regression slopes of contrast matching at each spatial frequency compared with the 95% normal ranges, indicating that the threshold differences between the test and the standard spatial frequency determined the position of the regression line relative to the diagonal line. Most subjects with maculopathy had highest contrast sensitivity for spatial frequencies of 0.58 and 1.11 cpd. Correspondingly, the regression line slopes of 0.58 and 1.11 cpd were close to the diagonal, and the other spatial frequencies of 0.26, 2.17, and 4.29 cpd were above the diagonal line and had flatter slopes. These slopes were also significantly different from those of the controls, and these differences were in the direction expected to compensate for differences in thresholds. These findings are in agreement with previous studies suggesting neural compensation by means of a change in gain.15,16,18 Alternatively, the results may be explained according to the model of Brady and Field.35 Accordingly, maculopathy would result in an increase in noise that would result in an increase in threshold, but suprathreshold performance, which depends on average signals rather than the signal-to-noise ratio, would be affected to a lesser extent or not at all. With this model there would be no need to suggest a change in gain. In fact, the partial-contrast constancy might indicate some deficit in gain.

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Given that observers with advanced maculopathy use a PRL for fixation, some discussion of the performance of eccentric retina is in order. At eccentric retinal locations, visually normal observers show overconstancy,7 a trend to overestimate the test gratings’ contrast at higher spatial frequencies (>3 cpd), especially at low contrasts. Observers with maculopathy, matching with a PRL (shown in Fig. 3), did not show this trend but, rather, underestimated test grating contrast at higher spatial frequencies (>0.58 cpd). In other words, they have partial-contrast constancy. There are two possible ways to explain this. First, the PRL functions as a new “fovea,” losing the normal overconstancy of eccentric vision but utilizing adjustment of the gain to compensate for the loss of CS caused by the disease process. Second, the PRL still functions as eccentric retina with contrast overconstancy, which in itself partially tends to compensate for loss of CS resulting from the disease process. The present data are not able to distinguish between these two situations.

Studies of suprathreshold contrast perception may give information that is more relevant to daily function than contrast sensitivity. This study has shown a suprathreshold contrast perception defect in maculopathy compared with normal, though this deficit is not as great as that for CS. Thus, we would conclude that the actual performance of people with ARMD may not be as poor as CS predicts. Whether this is found to be true is a matter for future research.

Conclusions

We have shown that a degree of contrast constancy is apparent in subjects with maculopathy, though deficits persist compared with control subjects. No significant difference was observed among three groups of subjects with maculopathy in suprathreshold contrast matching. Evidence indicates that either the gain of the visual system adjusts to compensate for CS losses (though incompletely) or that contrast overconstancy, as in normal peripheral vision, helps to compensate for the CS loss. A third possibility is that maculopathy results in an increase of noise in the visual system that affects threshold, but not suprathreshold, performance.

References


