Achromatic and chromatic perceived contrast are reduced in the visual periphery

Zhuohan Jiang

Christopher Shooner

Kathy T. Mullen

The loss of contrast sensitivity with eccentricity is well documented, and is steeper for higher spatial frequencies, and for L/M cone-opponent stimuli compared to achromatic or S-cone-opponent. Here, we ask how perceived contrast depends on eccentricity when stimuli are presented at suprathreshold contrasts, and test two opposing predictions. Contrast constancy predicts no loss in perceived contrast across the visual field regardless of changes in detection threshold – appearance depends only on physical contrast. Conversely, perceived contrast may be scaled in the same way as detection threshold, reflecting the proportional increase in stimulus contrast above threshold. We measured perceived contrast for L/M cone-opponent, S-cone opponent, and Ach stimuli up to 18 degrees of eccentricity using a 2AFC contrast matching method between fovea and periphery. We tested a range of reference contrasts from low (close to detection threshold) to high suprathreshold contrasts and we relate suprathreshold perceived contrast to measured detection thresholds. We find evidence for a hybrid model in which apparent contrast is reduced with eccentricity for stimuli in the low and mid contrast range, with contrast constancy only attained at the highest contrasts. When equated for similar sensitivity losses, we find no difference between chromatic and Ach contrast responses.

Introduction

The loss of contrast sensitivity with increasing eccentricity has been well documented for both achromatic (Ach) and chromatic stimuli (Anderson, Mullen, & Hess, 1991; Georgeson & Sullivan, 1975; Koenderink, Bouman, de Mesquita, & Slappendel, 1978a; Koen-derink, Bouman, de Mesquita, & Slappendel, 1978b; Mullen, 1991; Mullen, Sakurai, & Chu, 2005; Mullen & Kingdom, 2002; Pointer & Hess, 1989; Robson & Graham, 1981). For periodic (grating) stimuli, the loss is steeper for higher spatial frequencies compared to lower ones (Mullen, 1991; Pointer & Hess, 1989; Robson & Graham, 1981) with a steep loss of visual acuity across the visual field for both chromatic and achromatic stimuli (Anderson et al., 1991). Although broadly similar effects occur in both color and achromatic visual pathways, color vision based on the responses of the L/M cone-opponent pathways (termed red-green [RG]), has a steeper loss in contrast sensitivity and visual acuity with eccentricity than either the achromatic or the S-cone opponent (blue-yellow [BY]) responses (Hansen, Pracejus, & Gegenfurtner, 2009; Mullen, 1991; Mullen et al., 2005; Mullen & Kingdom, 2002). This selectively greater loss of contrast sensitivity of the L/M cone opponent response across the visual field likely reflects the relative clustering of the supporting midget ganglions cells and parvocellular cells of the lateral geniculate nucleus (LGN) to the central regions (Dacey, 2000; Mullen & Kingdom, 1996; Shapley & Perry, 1986).

Given the documented contrast sensitivity loss across the visual field, one might expect to experience a perceived loss of contrast in the peripheral visual field, experienced as fading, or a perceptual blurring due to the selective loss of high spatial frequency sensitivity (Georgeson & Sullivan, 1975). Phenomenologically, this is not our perceptual experience. The apparent constancy of perceived contrast in the peripheral visual field has motivated researchers to seek a better understanding of the relationship between contrast

Citation: Jiang, Z., Shooner, C., & Mullen, K. T. (2022). Achromatic and chromatic perceived contrast are reduced in the visual periphery. Journal of Vision, 22(12):3, 1–12, https://doi.org/10.1167/jov.22.12.3.
threshold and suprathreshold contrast perception. A similar question arises for other conditions, besides the visual periphery, in which variation in contrast detection thresholds might be expected to influence contrast perception at suprathreshold levels. For example, the well-documented variation in contrast sensitivity across spatial frequency (the contrast sensitivity function) is thought to have little influence on perceived contrast when stimuli are above detection threshold, an effect termed “contrast constancy” (Brady & Field, 1995; Georgeson & Sullivan, 1975; Kulikowski, 1976; Stephens & Banks, 1985; Tippapa, Rovamo, Näätänen, Whitaker, & Mäkelä, 2000). Contrast constancy implies that contrast perception above threshold is constant, and not predicted by threshold-level sensitivity. Hence, contrast constancy tends to better reflect the physical contrast of the grating stimulus, which does not vary as viewing distance (spatial frequency) or viewing location (eccentricity) changes. Likewise, in clinical conditions in which there are threshold differences between the two eyes, such as amblyopia, the perceived contrast may remain constant between the eyes for suprathreshold stimuli, despite a threshold difference (Hess & Bradley, 1980; Loshin & Levi, 1983; Reynaud & Hess, 2016), an effect also related to contrast constancy.

Here, we investigate the relationship between contrast sensitivity, as defined by threshold measurements, and suprathreshold contrast perception, measured by contrast matching, in the peripheral visual field for both chromatic and achromatic stimuli. The particularly strong loss of L/M cone opponency across the visual field, shown by the steeper decline in contrast sensitivity compared to that for achromatic stimuli, raises the question of whether the RG contrast deficit is also revealed at suprathreshold contrasts by a loss in perceived contrast. Because the RG contrast sensitivity loss is thought to arise from a selective decline in midget ganglion and LGN parvocellular cells across the visual field, it is possible that different processes may underlie the RG and achromatic contrast deficits in the periphery. Vanston and Crognałe (2018) recently reported that suprathreshold RG stimuli were perceived to have a reduced contrast in the periphery. While this may suggest a lack of contrast constancy, the study was not designed to test this directly. In this study, we investigate and compare suprathreshold contrast perception for RG, BY, and Ach stimuli across the visual field.

We made systematic measurement of perceived contrast for RG, BY, and Ach stimuli up to 18 degrees of eccentricity, by matching a peripheral grating to a foveal reference stimulus with the same spatial parameters. We tested a range of reference contrasts from low (close to detection threshold) to high suprathreshold contrasts and we related suprathreshold perceived contrast to the measured detection thresholds for the stimuli. We tested our results against two predictions. One is contrast constancy, which predicts no loss in perceived contrast across the visual field regardless of any change in detection threshold. The other is a scaling of perceived contrast proportional to detection threshold, predicting that perceived contrast is determined by the proportional increase of stimulus contrast above threshold. Because contrast sensitivity declines with eccentricity, this predicts a loss in perceived contrast with eccentricity. We find evidence for a hybrid model in which there is a deficit in perceived contrast across eccentricity in the low to mid contrast range, with constancy only attained at high contrasts.

### Methods

#### Participants

Five participants (2 women) served as observers: the three authors and two individuals who were unaware of the purpose of the experiment. Participants provided written informed consent. All had normal or corrected-to-normal visual acuity. All procedures were approved by the Research Ethics Board of the McGill University Health Centre and conformed to the Declaration of Helsinki.

#### Apparatus

Stimuli were generated in MATLAB (The MathWorks, Natick, MA, USA) using the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) and displayed using a Display++ LCD monitor (Cambridge Research Systems, Kent, UK) with a resolution of $1920 \times 1080$ pixels, a mean luminance of $59 \text{ cd/m}^2$ and chromaticity $x,y = \{0.30, 0.33\}$. Observers viewed the screen from a distance of $1 \text{ m}$, at which it subtended $40 \times 22$ degrees of visual angle with a resolution of $48$ pixels per degree. The display supports 10-bit color resolution, with 1024 intensity levels per color channel. Linearity of the output of each color channel was confirmed using a SpectroCAL spectroradiometer (Cambridge Research Systems). The measured emission spectra of the monitor primaries were integrated with psychophysically derived cone fundamentals (Smith & Pokorny, 1975) to create a linear transformation specifying the red, green, blue (RGB) values required to elicit any target triplet of cone excitation levels.

#### Visual stimuli

Horizontal sinusoidal gratings were presented in 2-degree circular apertures, the outer 0.5 degrees smoothed with a raised-cosine profile. One condition
included a 4-degree aperture, as described in Results. Gratings were presented at the point of fixation or displaced into the right visual field along the horizontal meridian. The eccentricity and spatial frequency of the stimuli varied across conditions, as detailed below. Gratings were presented with a static spatial phase chosen randomly on each trial. Stimulus duration was 1.4 seconds, with contrast smoothly ramped up and down over the first and last 200 ms following a raised cosine temporal profile. Before each stimulus presentation, a thin circular cue (white ring) outlining the stimulus position was shown for 300 ms and removed 300 ms before stimulus onset. This cue aided the observers in attending to the stimulus location.

Stimulus chromaticity was defined within a cone contrast space as a modulation through the origin in a direction defined by a triplet \(\{l, m, s\} \), representing the fractional change in excitation of the long-, medium-, and short-wavelength-sensitive cones. Stimulus contrast was defined as the depth of this modulation, expressed as a vector length \(c = \sqrt{l^2 + m^2 + s^2} \). This definition differs from Michelson contrast; a full-contrast Ach grating modulates each cone by \(100\% \) (\(\sqrt{l^2 + m^2 + s^2} = \sqrt{3} \)), so has a total cone contrast of \(\sqrt{3} \approx 173\%\). Isoluminant chromatic stimuli were designed to isolate post-receptoral L/M and S/(L + M) cone opponent responses, referred to as “red-green” and “blue-yellow,” respectively. The BY stimulus is S-cone isolating, and is cardinal for the S/(L + M) cone opponent response as S cones are not thought to contribute significantly to either the luminance or L/M cone opponent mechanisms (Cole, Hine, & McIlhagga, 1993; Mullen & Losada, 1994). We verified that this direction was the optimal for isolation of the S-cones for each participant by using a method or adjustment varying vector angle within the isoluminant plane to determine the direction of minimum visibility (Michna, Yoshizawa, & Mullen, 2007). In all subjects, this corresponded closely to the S-cone isolating axis. The RG stimuli were defined as \(lms = [1, -a, (1 - a)/2] \), with the value of \(a\) measured separately for each observer to make the stimulus isoluminant, based on a minimum-motion experiment (Anstis & Cavanagh, 1983). The S-cone component in the RG stimulus ensured that \(S - (L + M)/2 = 0\), eliminating any BY signal from this stimulus and rendering it cardinal for the L/M cone-opponent mechanism.

**Procedure**

For each condition, defined as a combination of stimulus chromaticity (Ach, RG, or BY), spatial frequency, and eccentricity, we measured detection thresholds at the test eccentricity as well as the point of fixation. In a separate experiment, we measured contrast matching functions that related foveal to peripheral apparent contrast. Threshold measurements followed a temporal two-interval-forced-choice procedure; contrast was controlled with a two-down-one-up staircase, which terminated after five contrast reversals (approximately 40–50 trials). This was repeated over at least six staircases and all trials were combined in a maximum-likelihood fit of a logistic psychometric function from which we determined the threshold contrast yielding 75\% correct responses. Trials were blocked by stimulus condition, with foveal and peripheral tests in separate blocks. In the matching experiment, a foveal and a peripheral grating were presented simultaneously. The foveal stimulus had a fixed “reference” contrast (constant within a block of trials), While the contrast of the peripheral “match” stimulus was controlled with a one-up-one-down staircase designed to converge at the point of subjective equality (PSE). Specifically, observers reported which grating appeared higher in contrast. When the match stimulus was deemed higher, its contrast was reduced on the next trial (and increased when it was seen as lower). Two interleaved staircases started with different match contrasts, one well above and one below the physical contrast of the reference. All trials from at least three repeats (approximately 200 trials) were combined and fit with a logistic function from which we derived a PSE. For each stimulus condition, we tested a range of reference contrasts. This was bounded on the low end by the lowest contrast sufficiently visible for the observer to make confident judgments of apparent contrast (typically 6 to 10 times the detection threshold) and on the high end by the limits of our display. Specifically, achromatic reference contrasts ranged from 5.7\% to 150\% total cone contrast (see the previous section for our definition of contrast). RG reference contrasts varied from 1.3\% to 8\%, and BY from 18\% to 70\%. Note that RG contrast was limited by the gamut of our display, which can display a maximum of 12\% to 15\% RG contrast, depending on the observers’ individual isoluminant chromaticity. Reference contrasts above 8\% required match contrasts beyond this limit.

**Conditions tested**

For our first experiment, we measured contrast sensitivities and suprathreshold contrast matching for all three chromaticity conditions (Ach, RG, and BY) using a 1 cycle/degree grating at 12 degrees eccentricity. As shown below, for the Ach stimulus, this led to very small differences in contrast sensitivity between the fovea and periphery, making a comparison of suprathreshold Ach contrast matching results between the fovea and periphery less relevant. We therefore also tested higher spatial frequencies in the Ach case, with
the goal of increasing the foveal-peripheral contrast sensitivity difference. These spatial frequencies ranged from 4 to 8 c/degree, according to observers’ differing peripheral contrast sensitivities. In a second experiment, we performed separate tests of Ach and RG at 18 degrees eccentricity; in this case, the spatial frequency of the RG stimulus was reduced to 0.5 c/degree, and its size accordingly increased to 4 degrees, yielding the same number of cycles. Finally, we addressed eccentricity-dependence directly by testing peripheral locations from 4 to 16 degrees, but using a single foveal reference contrast, chosen to be six to eight times higher than foveal detection thresholds.

Bootstrap measures of reliability

For all experiments, we assessed reliability of the results using bootstrap procedures, in which randomly sampled subsets (90%) of the data were analyzed separately and 100 random samples were used to construct a bootstrap distribution of the measure of interest. We computed the mean of this distribution as well as a 95% confidence interval. For psychometric fits, 90% of trials were fit and a threshold or PSE was extracted from the fit. We found that these fits gave highly consistent results across subsamples; the very small confidence intervals that resulted are not plotted, as they were smaller than the symbol used to show the mean. For our method-of-adjustment experiments, the bootstrap computed the mean of 90% of observers’ reports. Confidence intervals in this case are shown in the corresponding figure.

Method of adjustment (control)

Our findings differed from those of Georgeson & Sullivan (1975) (see Results). To explore this difference, we tested several stimulus manipulations that brought our methods into closer agreement with theirs. We increased our stimulus size from 2 degrees to 4, eliminated our smoothed spatial envelope, viewed the stimuli monocularly (left eye, temporal retina), and used a method of adjustment instead of our 2AFC. With these changes, we replicated the methods of Georgeson and Sullivan as closely as possible. We also tested conditions in which only one of these changes was made (e.g. increasing the size while keeping all other factors the same as our main experiment). For both threshold measurements and contrast matching, observers were given unlimited time to adjust the contrast of the variable grating using a button box: button presses increased or decreased the variable contrast in steps of 1%. Threshold measurements were repeated 20 times per condition; each matching condition was tested with a minimum of six repetitions.

Results

Figure 1 shows example data from one observer (#3) for an achromatic test stimulus (6 c/deg), presented at 12 degrees eccentricity in the right visual field. The contrast matching data is shown with filled circles. The observer’s match of the peripheral stimulus to the foveal reference stimulus is plotted as a function of increasing contrast of the reference. The filled square plots the detection thresholds for the same stimulus in periphery and fovea. The solid lines illustrate two different predictions for the relationship between detection threshold and suprathreshold contrast perception. For the blue line, a constant scale factor accounts for both threshold and matching data: the proportional loss of sensitivity in the periphery predicts the reduction of perceived contrast at suprathreshold levels. For the red line, the prediction is of contrast constancy – once the peripheral stimulus can be detected, its contrast is perceived to be the same as in the fovea (the unity line). In fact, the data for the example observer lie between these two predictions. Over a wide range of low to mid-level contrasts, the observer perceived the peripheral stimulus as lower in contrast than the foveal one, but this difference got smaller as the base contrast was increased. At the highest base contrast tested, foveal and peripheral contrasts were seen as the same, reflecting contrast constancy.

Results are shown over a wider range of chromatic and achromatic stimuli in Figure 2. Results are for five observers with stimuli presented at 12 degrees eccentricity. Columns A, B, and C show data for RG, BY, and Ach stimuli, respectively, presented at the same spatial frequency (1 c/degree). For these conditions,
the RG stimuli tend to have the greatest threshold difference between fovea and periphery and Ach the smallest, in keeping with past reports (Mullen 1991). Contrast matching data show a similar effect to the Ach condition in Figure 1. At low base contrasts, perceived contrast is lower in the periphery compared to the fovea but this difference is reduced as base contrast increases, trending toward veridical matching of contrast between
fovea and periphery. A similar pattern is seen for the RG and BY stimuli. The effect is less pronounced for Ach stimuli as the threshold difference between fovea and periphery is small or non-existent. To increase this threshold difference for Ach stimuli, we switched to a higher spatial frequency (6-8 c/degree), shown in column D. This spatial frequency was selected as it produced similar threshold differences to those obtained for RG stimuli (at 1 c/degree). Under these conditions, the RG and the Ach stimuli produced comparable contrast matching effects, with a gradual transition toward contrast constancy as the base contrast increases.

This transition appears to show a power-law relationship: Matched contrasts tended to fall on straight lines on double logarithmic axes, implying that match contrasts were proportional to reference contrast raised to some exponent. We fit a line to the data in each panel (Table 1). The slope of this line (the power-law exponent) varied from near one, when matches were veridical, to 0.4 in cases of large differences in perceived contrast.

To facilitate comparisons between the Ach and RG data, we plot data sets that have similar threshold differences between the fovea and periphery normalized to foveal detection thresholds in Figure 3. We have also added a new data set collected at 18 degrees of eccentricity. For this eccentricity, the spatial frequency of the RG stimulus was lowered to 0.5 c/degree as the 1 c/degree stimulus used at 12 degrees could no longer be detected sufficiently to make a reliable contrast match. The spatial frequency of the Ach stimulus was selected for each subject to produce a threshold difference between fovea and periphery similar to the one obtained for the RG stimulus (4-6 c/deg, see Figure 3 legend). For equivalent foveal-peripheral threshold differences, our results show very similar contrast matching functions between RG and Ach stimuli at both eccentricities. The functions substantially overlap in four of the five observers, although not in observer four whose chromatic and achromatic threshold differences were less well matched. These results suggest that, once threshold differences are

|        | RG      | BY      | Ach     | Ach – high SF |
|--------|---------|---------|---------|---------------|
| Observer 1 | 0.76    | 0.83    | 0.86    | 0.81          |
| Observer 2 | 0.47    | 0.53    | 0.80    | 0.72          |
| Observer 3 | 0.39    | 0.59    | 0.69    | 0.55          |
| Observer 4 | 0.84    | 0.97    | 0.88    | 0.44          |
| Observer 5 | 0.70    | 0.75    | 0.98    | 0.79          |

Table 1. Table of fitted slopes for data in Figure 2. Each value represents the exponent of a power-law relationship: Peripheral (matched) contrast was proportional to foveal (reference) contrast raised to these exponents.
taken into account, there is no difference in the form of suprathreshold matching between the chromatic and achromatic stimuli. Likewise, once threshold differences are equivalent, we find similar contrast matching results at 12 and 18 degrees of eccentricity suggesting no eccentricity dependent effects, at least within this range.

Figure 4 shows contrast matches as a function of eccentricity (0-16 degrees) for RG and Ach stimuli of fixed foveal contrast for three observers. The fixed contrast was 0.02 for RG stimuli, representing a relatively low end of the contrast range tested in previous experiments. The contrast of the Ach stimulus was selected for each subject to have a similar sensitivity loss to the RG at the fovea (see legend). Observers two and three show an increase in matching contrast, corresponding to a decrease in perceived contrast, across eccentricity that is similar in both RG and Ach stimuli. This is illustrated in the lower normalized plot. Observer 1, however, shows a flatter response, particularly for the Ach stimuli. While the lack of change across eccentricity suggests contrast constancy for this stimulus, the match is not veridical to the foveal contrast and indicates a constant, small contrast loss across eccentricity. This observer in previous plots has also tended to show less change in the contrast match (proportional to the foveal contrast) than the others. Detection thresholds are plotted as dashed lines. If perceived contrast is determined by a threshold scaling, we would expect a parallel shift upward in the contrast matching function, in proportion to the threshold change. Clearly, these contrast matching functions are flatter than a threshold scaling prediction, but neither do they reflect contrast constancy as they are not flat nor matching the foveal contrast. Given the shape of our contrast matching function in Figures 2 and 3, we expected a bias toward threshold scaling at lower stimulus contrasts. A greater bias toward contrast
constancy might be found for stimuli presented at higher contrasts. The lack of contrast constancy in our data for the low and mid contrast ranges is surprising, because contrast constancy has been reported previously over a wide range of contrasts for foveal-peripheral contrast matching measurements (Georgeson & Sullivan, 1975). This was reported as an additional experiment on two observers (their figure 6) within a larger study that focused primarily on contrast constancy across spatial frequency. Data was collected for Ach stimuli presented at 4 and 13 degrees of eccentricity, using spatial frequencies and eccentricities similar to ones we have used here (e.g. Ach, 4-5 c/deg, presented at 13 deg). Georgeson and Sullivan (1975) reported that, once the foveal grating exceeded the peripheral threshold, observers made settings that were much closer to the physical match, whereas in this same range of contrasts we find perceived contrasts are lower than predicted by contrast constancy. To ascertain whether differences in stimulus presentation, or methods of data collection, explain the differences in results, we collected new data sets while replicating the stimuli and methods of Georgeson and Sullivan (1975) as closely as possible. As described in the Methods, we changed our protocols to use a method of adjustment similar to the one they used. We also removed the spatial envelope from our stimuli so that they were hard-edged, increased size from 2 to 4 degrees diameter, and adopted monocular viewing with the left eye (temporal retina). In addition, we systematically tested conditions in which only one change was made at a time while keeping other factors the same as our main experiment. 

Figure 5 (left panel) shows a comparison of contrast matching functions measured in our laboratory in three participants using a close replication of the methods and stimuli of Georgeson and Sullivan (1975), together with their data plotted in the same coordinates. Both data sets use stimuli with a diameter of 4 degrees presented at 12 to 13 degrees eccentricity. To facilitate comparisons, all contrast values have been converted to units of total cone contrast (see Methods) rather than the Michelson contrasts reported by Georgeson and Sullivan (1975). Although one participant (observer 2) shows quite a close replication of the Georgeson and Sullivan data, the other two show higher peripheral contrast matches, converging to physically match the foveal contrast at high reference contrasts, following the pattern that we have seen in Figures 1 to 3. Collectively, results spread from contrast constancy to a deficit in peripheral contrast perception. Moreover, we see that Georgeson and Sullivan (1975) made contrast matches to very low contrasts near threshold, which our subjects were unable to do. At this point, the contrast matches form a horizontal plateau aligning with the peripheral stimulus threshold, suggesting that the matching method is limited by detection threshold at these low contrast levels. In the right panel, conditions are the same as in the left, except that we used a stimulus diameter of 2 degrees, as in our previous experiments.
The dashed lines are the Georgeson and Sullivan (1975) data replotted from the left panel. Our data now diverge more from that of Georgeson and Sullivan (1975), showing a greater loss of perceived contrast in the periphery and less constancy. Possible reasons for this are raised in the Discussion. We found no effect of the remaining factors when tested individually (hard-edged versus soft-edged stimuli, binocular versus monocular viewing, and method of adjustment versus 2AFC).

**Discussion**

In summary, our results support a hybrid model of suprathreshold contrast perception across the visual field with neither threshold scaling nor contrast constancy providing an accurate description. First, a scaling of perceived contrast proportional to detection threshold, predicting that perceived contrast is determined by the proportional increase of stimulus contrast above threshold, has some relevance for low contrasts near threshold, but over most of the contrast range using multiple of detection threshold to scale suprathreshold contrast will be inaccurate. Second, we find that contrast constancy, in which perceived contrast in the periphery and fovea match when their physical contrasts are equal despite threshold differences, also does not predict the contrast matching functions (see Figures 1–3). Instead, matches show a lower perceived contrast in the periphery than that predicted from constancy, particularly in the low to mid-range of suprathreshold contrasts. Perceived contrast in the periphery only matches foveal contrasts when the stimulus contrasts were very high, and, in a few observers, constancy did not occur at all. This result is consistent across all stimulus types (Ach, RG, and BY). We found no difference between Ach and RG contrast matching functions when these are compared for stimuli with equivalent foveal-peripheral threshold differences. Hence, despite the greater threshold loss across the visual field for RG stimuli, the response to suprathreshold contrast between the two systems is similar.

Using a magnitude estimation method, Cannon (1985) reported results similar to ours for achromatic stimuli. Foveal and peripheral perceived contrast were matched at spatial frequencies of 2 to 4 c/degree for all contrasts tested but at higher spatial frequencies (8-16 c/degree), peripheral perceived contrast was reduced for low but not high physical contrasts.

Vanston and Crognaele (2018) investigated the effect of eccentricity on perceived contrast on RG, BY, and Ach stimuli and found a reduction in perceived contrast for the Ach and RG stimuli, smaller than our result in Figure 4. Curiously, however, the BY perceived contrast increased with eccentricity. However, their study was not designed to directly measure contrast constancy and has important differences from ours. Firstly, all peripheral stimuli, including the RG and BY, were matched to Ach foveal stimuli (9% contrast). Second, the matching stimulus was a ring of Gabor surrounding the Ach foveal stimulus, increasing in size with eccentricity to reduce or remove any change in threshold. Last, no thresholds were measured. Given the variation in stimulus size and spatial frequency across the visual field with the concomitant change in threshold, it is hard to compare the two data sets and know whether the loss in perceived contrast for RG stimuli are of similar origins.

Using an exact replication of Georgeson and Sullivan’s (1975) study, including a stimulus diameter of 4 degrees and comparing data for our three observers with two of ours, our data still show that perceived contrasts are lower in the periphery than predicted by contrast constancy, although the differences were not great. However, when we make the same comparison using a smaller, 2-degree stimulus diameter, as used in this study, the differences are larger and contrast constancy is only found at high stimulus contrasts. As we found no effect of other methodological differences between the two studies (stimulus edges, binocular/monocular viewing, or method of adjustment/2AFC), it is likely that the larger stimulus diameter used by Georgeson and Sullivan caused their observers to make settings that were much closer to the physical match. This may be because larger stimuli are less well localized in eccentricity, and it is likely the more eccentric part of the foveal stimulus is visually matched to the more central part of the peripheral one. In addition, combined with the extending viewing required for method of adjustment, there is increased chance of eye movements between the stimuli that will produce matches nearer the physical contrast. Last, intersubject variations due to the low subject numbers also limits this comparison.

Even though we have shown a loss in perceived contrast with eccentricity from 0 to 18 degrees, we are not typically consciously aware of this under natural viewing conditions. This may be because there are wide ranges of conditions under which contrast constancy is maintained, including high stimulus contrasts and mid-low spatial frequencies, particularly for achromatic conditions which show less contrast sensitivity loss with eccentricity. Moreover, natural images are spatially broadband, combining the full range of spatial frequencies and contrasts, which will likely obscure the more specific losses in perceived contrast.

While our matching experiment does not provide a direct estimate of how physical contrast is mapped to perceived contrast (see Shooner & Mullen, 2022, for a discussion of experiments that can), it does provide insight into the relative form such a transducer takes.
in the periphery, compared to the fovea. The simple power-law relationship found in matching foveal to peripheral contrast suggests that transduction in the periphery is identical to the fovea, aside from a power-law scaling of input contrast: peripheral contrast being scaled and raised to an exponent before any subsequent processing. Interestingly, this input scaling leads to the same contrast-matching predictions regardless of what those subsequent processes are. We illustrate this in Figure 6.

If we assume a foveal transducer of arbitrary form, we can derive a corresponding peripheral transducer such that together they predict a given power-law matching result (see the Appendix for mathematical details). In Figure 6A, we show a hypothetical pair of this sort, in which the foveal transducer is simply linear, and the peripheral transducer is a power-law function. For this illustration, we used the power-law parameters fit to the data in Figure 1. Note that the supposed peripheral transducer is accelerating, with an exponent near two (the inverse of the slope of 0.5 fit to the matching data). In Figure 6B, we show another hypothetical pair, where the foveal transducer has a more realistic sigmoidal shape. The derived peripheral transducer is similar in shape but with a nonlinear scaling along the input axis. Using either of these pairs to model a matching experiment leads to an identical result, which is shown in Figure 6C as a solid line together with the data from Figure 1, from which the model transducers were derived.

Our results therefore suggest that compared to the fovea, peripheral contrast processing involves a different scaling of contrast, and a nonlinearity that is more strongly accelerating. An attenuation of effective contrast in the periphery is predictable from a combination of low-level physiological factors (e.g. density of ganglion cells). The basis for contrast being exponentiated is less clear. Neurons in visual cortex exhibit expansive nonlinear contrast response at low contrast (Albrecht & Hamilton, 1982) but to our knowledge the eccentricity dependence of this effect has not been reported. One possible explanation is that the visual system partially compensates for eccentricity-dependent losses through nonlinear amplification mechanisms, which lead to a more strongly nonlinear contrast response in the periphery.

If the form of nonlinear contrast processing does vary with eccentricity, this should be measurable by

Figure 6. Panels (A) and (B) show two hypothetical pairs of contrast transducers (foveal and peripheral). In each case, the peripheral transducer differs from the foveal by a power-law scaling of input contrast (contrast is scaled and raised to an exponent prior to any other computation). The power-law parameters used are those fit to the data in Figure 1. In A, the foveal transducer is linear and the peripheral is therefore a simple power-law function. For the more realistic sigmoidal transducer is B, the scaling results in a peripheral transducer
other psychophysical methods. Legge and Kersten (1987) measured contrast discrimination across the visual field. In this type of experiment, differences in nonlinearity would be expected to yield differences in the shape of threshold-versus-contrast (“dipper”) functions. They did not find this, instead revealing identical dipper functions (when differences in sensitivity were taken into account). Note, however, that they tested a relatively low spatial frequency of 2 c/degree, a condition in which we would expect to find something close to contrast constancy based on our results (see Figure 2). An alternative test would be a contrast-difference-scaling experiment (Knoblauch, Marsh-Armstrong, & Werner, 2020; Maloney & Yang, 2003; Shooner & Mullen, 2022) which gives a direct estimate of the mapping from physical to perceived contrast. A scaling experiment comparing fovea to periphery may be an avenue for future work.

Keywords: peripheral vision, contrast sensitivity, contrast matching, perceived contrast, contrast constancy, color vision, isoluminance

Acknowledgments

The authors thank Gazal Javed for her help in piloting an earlier version of this study and Fred Kingdom and Alex Reynaud for helpful discussion.

Funded by Canadian Institutes of Health Research (CIHR) grant 153277 and Natural Science and Engineering Research Council of Canada (NSERC) grant RGPIN 03824 to K.T.M. We thank all our participants for their assistance with data collection.

Commercial relationships: none.

Corresponding author: Kathy T. Mullen.
Email: kathy.mullen@mcgill.ca.
Address: McGill Vision Research, Department of Ophthalmology & Visual Sciences, McGill University, Montreal, Quebec, Canada.

References

Albrecht, D. G., & Hamilton, D. B. (1982). Striate cortex of monkey and cat: Contrast response function. Journal of Neurophysiology, 48(1), 217–237.

Anderson, S. J., Mullen, K. T., & Hess, R. F. (1991). Human peripheral spatial resolution for achromatic and chromatic stimuli: Limits imposed by optical and retinal factors. The Journal of Physiology, 442, 47–64.

Anstis, S., & Cavanagh, P. (1983). A minimum motion technique for judging equiluminance. York University; Academic Press, London, UK.

Brady, N., & Field, D. J. (1995). What’s constant in contrast constancy? The effects of scaling on the perceived contrast of bandpass patterns. Vision Research, 35(6), 739–756.

Brainard, D. H. (1997). The Psychophysics Toolbox. Spatial Vision, 10(4), 433–436.

Cannon, M. W., Jr. (1985). Perceived contrast in the fovea and periphery. Journal of the Optical Society of America A, 2(10), 1760–1768.

Cole, G. R., Hine, T., & McIlhagga, W. (1993). Detection mechanisms in L-, M-, and S-cone contrast space. Journal of the Optical Society of America A, 10(1), 38–51.

Dacey, D. M. (2000). Parallel Pathways for Spectral Coding in Primate Retina. Annual Review of Neuroscience, 23(1), 743–775.

Georgeson, M. A., & Sullivan, G. D. (1975). Contrast constancy: Deblurring in human vision by spatial frequency channels. The Journal of Physiology, 252(3), 627–656.

Hansen, T., Pracejus, L., & Gegenfurtner, K. R. (2009). Color perception in the intermediate periphery of the visual field. Journal of Vision, 9(4), 1–12.

Hess, R. F., & Bradley, A. (1980). Contrast perception above threshold is only minimally impaired in human amblyopia. Nature, 287(5781), 463–464.

Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? European Conference on Visual Perception.

Knoblauch, K., Marsh-Armstrong, B., & Werner, J. S. (2020). Suprathreshold contrast response in normal and anomalous trichromats. Journal of the Optical Society of America A, 37(4), A133–A144.

Koenderink, J. J., Bouman, M. A., de Mesquita, A. E. B., & Slappendel, S. (1978a). Perimetry of contrast detection thresholds of moving spatial sine wave patterns. I. The near peripheral visual field (eccentricity 0–8). Journal of the Optical Society of America, 68(6), 845–849.

Koenderink, J. J., Bouman, M. A., de Mesquita, A. E. B., & Slappendel, S. (1978b). Perimetry of contrast detection thresholds of moving spatial sine wave patterns. II. The far peripheral visual field (eccentricity 0°–50°). Journal of the Optical Society of America, 68(6), 850–854.

Kulikowski, J. J. (1976). Effective contrast constancy and linearity of contrast sensation. Vision Research, 16(12), 1419–1431.
Legge, G. E., & Kersten, D. (1987). Contrast discrimination in peripheral vision. *Journal of the Optical Society of America A, 4*(8), 1594–1598.

Loshin, D. S., & Levi, D. M. (1983). Suprathreshold contrast perception in functional amblyopia. *Documenta Ophthalmologica, 55*(3), 213–236.

Maloney, L. T., & Yang, J. N. (2003). Maximum likelihood difference scaling. *Journal of Vision, 3*(8), 5.

Michna, M. L., Yoshizawa, T., & Mullen, K. T. (2007). S-cone contributions to linear and non-linear motion processing. *Vision Research, 47*(8), 1042–1054.

Mullen, K. T. (1991). Colour vision as a post-receptoral specialization of the central visual field. *Vision Research, 31*(1), 119–130.

Mullen, K. T., & Kingdom, F. A. A. (1996). Losses in peripheral colour sensitivity predicted from “hit and miss” post-receptoral cone connections. *Vision Research, 36*(13), 1995–2000.

Mullen, K. T., & Kingdom, F. A. A. (2002). Differential distributions of red–green and blue–yellow cone opponency across the visual field. *Visual Neuroscience, 19*(1), 109–118.

Mullen, K. T., & Losada, M. A. (1994). Evidence for separate pathways for color and luminance detection mechanisms. *Journal of the Optical Society of America A, 11*(12), 3136–3151.

Mullen, K. T., Sakurai, M., & Chu, W. (2005). Does L/M Cone Opponency Disappear in Human Periphery? *Perception, 34*(8), 951–959.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442.

Pointer, J. S., & Hess, R. F. (1989). The contrast sensitivity gradient across the human visual field: With emphasis on the low spatial frequency range. *Vision Research, 29*(9), 1133–1151.

Reynaud, A., & Hess, R. F. (2016). Is Suppression Just Normal Dichoptic Masking? Suprathreshold Considerations. *Investigative Ophthalmology & Visual Science, 57*(13), 5107–5115.

Robson, J. G., & Graham, N. (1981). Probability summation and regional variation in contrast sensitivity across the visual field. *Vision Research, 21*(3), 409–418.

Shapley, R. M., & Perry, V. H. (1986). Cat and monkey retinal ganglion cells and their visual functional roles. *Trends in Neurosciences, 9*, 229–235.

Shooner, C., & Mullen, K. T. (2022). Linking perceived to physical contrast: Comparing results from discrimination and difference-scaling experiments. *Journal of Vision, 22*(1), 13.

Smith, V. C., & Pokorny, J. (1975). Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm. *Vision Research, 15*(2), 161–171.

Stephens, B. R., & Banks, M. S. (1985). The development of contrast constancy. *Journal of Experimental Child Psychology, 40*(3), 528–547.

Tiippana, K., Rovamo, J., Näätänen, R., Whitaker, D., & Mäkelä, P. (2000). Contrast matching across spatial frequencies for isoluminant chromatic gratings. *Vision Research, 40*(16), 2159–2165.

Vanston, J. E., & Crognale, M. A. (2018). Effects of eccentricity on color contrast. *Journal of the Optical Society of America A, 35*(4), B122–B129.

---

**Appendix**

To perform the simulation shown in Figure 6, we assume a transducer $\psi(c)$ that maps physical contrast to perceived contrast, and may differ between fovea and periphery. A perceptual match implies that the foveal and peripheral transducers produce equal outputs in response to their (possibly different) inputs:

$$\psi_P(c_{\text{match}}) = \psi_F(c_{\text{reference}})$$

The observed power-law relationship between match and reference contrast can be expressed with either as the independent variable, so we write this as

$$c_{\text{reference}} = ac_{\text{match}}^b$$

Combining these gives a general relationship between the two transducers:

$$\psi_P(c) = \psi_F(ac^b)$$

Therefore, for any mapping $\psi(c)$ assumed to describe foveal processing, a corresponding peripheral mapping is obtained by introducing power-law scaling of the input contrast. Note that the exponent $b$ is the inverse of the slope measured from our matching plots (Table 1), and therefore tends to be greater than one, implying a more expansive nonlinearity in the periphery.