Amblyopia masks the scale invariance of normal central vision

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In normal vision, detecting a kink (a change in orientation) in a line is scale invariant: it depends solely on the length/width ratio of the line (D. Whitaker, D. M. Levi, & G. J. Kennedy, 2008). Here we measure detection of a change in the orientation of lines of different length and blur and show that strabismic amblyopia is qualitatively different from normal foveal vision, in that: 1) stimulus blur has little effect on performance in the amblyopic eye, and 2) integration of orientation information follows a different rule. In normal foveal vision, performance improves in proportion to the square root of the ratio of line length to blur (L:B). In strabismic amblyopia improvement is proportional to line length. Our results are consistent with a substantial degree of internal neural blur in first-order cortical filters. This internal blur results in a loss of scale invariance in the amblyopic visual system. Peripheral vision also shows much less effect of stimulus blur and a failure of scale invariance, similar to the central vision of strabismic amblyopes. Our results suggest that both peripheral vision and strabismic amblyopia share a common bottleneck in having a truncated range of spatial mechanisms—a range that becomes more restricted with increasing eccentricity and depth of amblyopia.

Keywords: amblyopia, angle discrimination, deviation detection, scale invariance, peripheral vision


Introduction

Humans show a remarkable capacity to discern changes in the orientation of a static line, i.e., to judge an angle, and the process underlying this capacity is scale invariant, in that any two stimuli that possess the same two-dimensional geometry (length/width) result in the same level of performance (Whitaker, Levi, & Kennedy, 2008).

Amblyopia is a developmental disorder of spatial vision usually associated with the presence of strabismus, anisometropia, or form deprivation early in life (Ciuffreda, Levi & Selenow, 1991). Amblyopia results in a host of spatial deficits, including the ability to discern changes in the orientation of a thin static line (Levi & Tripathy, 2006). Specifically, while amblyopes show no deficit in detecting deviations in a single moving trajectory, 4 of the 5 amblyopes in Levi and Tripathy’s study showed deficits in detecting a deviation in a single static thin line. Their static task was essentially detection of a change in orientation, and while it has been documented that amblyopes show deficits in orientation discrimination with short lines or high contrast, high spatial frequency gratings (Skottun, Bradley, & Freeman, 1986; Venverlokh, 1983), the question of whether amblyopes show deficits in orientation discrimination has been controversial (see Summary and discussion section). Importantly, Levi and Tripathy found that the deficit for detecting a change in orientation increased with increasing viewing distance, and that at the largest distance, the deficit was related to the observer’s visual acuity.

In normal vision, detection of a change in orientation of a short line (but not a long one) is markedly degraded by stimulus blur. Thus, the amblyopic deficit may be simply a consequence of increased internal neural blur (Levi & Klein, 1990), which limits both visual acuity and the detection of changes in orientation. There are two main explanations for the visual losses in amblyopia: undersampling, i.e., a reduced complement of small (high spatial frequency) filters in the cortex of strabismic amblyopes (Levi & Klein, 1985, 1986; Sharma, Levi, & Coletta, 1999), and uncalibrated neural disarray or scrambling (Hess, 1982). The notion of increased neural blur is consistent with undersampling but not with scrambling (since small filters remain present). Recent work (Aaen-Stockdale & Hess, 2008) suggests that for a global motion task, the amblyopic deficit is scale invariant. Here we measure detection of a change in the orientation of (static) lines of different length and blur and show that strabismic amblyopes are qualitatively different from...
normal observers in that stimulus blur has little effect on performance, consistent with a substantial degree of internal neural blur. This internal blur results in a loss of scale invariance in the amblyopic visual system.

General methods

Our methods were largely identical to those of Whitaker et al. (2008) and will be described only in brief.

Stimuli

The stimuli were briefly presented (250 ms) high contrast (0.99 Weber contrast) Gaussian lines with a kink at the midpoint (defined by two vertical lines \( \theta \) arc wide and \( 128\) arc long leaving a vertical gap of \( 256\) arc between them—see Figure 1).

Stimuli were displayed on a Sony Multiscan G400 monitor with a Macintosh G4 as host computer and were generated using the macro capabilities of NIH Image (v1.61) and were presented against a gray background with a luminance of 41 cd/m\(^2\). Viewing distance was 93 cm.

We varied the standard deviation (\( \sigma \)) of the lines in order to produce stimuli of different blur levels (\( 2\), \( 5.65\), and \( 16\) \( \theta \)) and their lengths (from \( 12\) to \( 384\) \( \theta \)). The orientation of the lines to the left of the vertical midline was random from trial to trial with the constraint that this was within \( 35^\circ \) either side of the horizontal. The vertical position of the line at the horizontal midline was always midway between the two vertical reference lines. At this point the path direction of the line could change, either deviating upward or downward.

On any trial, one of seven equally spaced deviations could be presented: \(-3, -2, -1, 0, 1, 2, \) or \(3\) multiples of step size, where negative values indicate upward deviations, positive values represent downward. These seven levels were randomly interleaved within a method of constant stimuli. After each trial, observers responded as to whether they thought the direction of orientation change was upward or downward. Angular step size was chosen such that responses ranged from approximately 100% upward to 100% downward. Observers performed four runs (70 trials per run) at each length and blur level, resulting in 280 trials for each threshold estimation. We computed thresholds by fitting a cumulative normal function to the data, with the upper and lower asymptotes of the fit being fixed at 100% and 0%, respectively. The \( SD \) of the normal fit was taken to be the empirical deviation threshold, corresponding to the change in orientation that yields a \( d' = 1 \).

Table 1. Observer characteristics. Note: \(^{a}\)The acuities listed in this table were determined using a LogMAR letter chart, and we specify both the full line letter acuity and the single letter acuity.
Observers

We tested 5 strabismic amblyopes (including one of the authors, 2 with both anisometropia and strabismus—see Table 1) and 3 normal control observers (including two of the authors from the study of Whitaker et al. (2008)). Note that the thresholds of the normal observers reported here are higher than those reported by Whitaker et al., since we specified threshold at a higher $d'$. Two of the amblyopic observers had participated in the study of Levi and Tripathy (2006), and all were highly experienced psychophysical observers.

Results

Threshold vs. line length

In the normal fovea, both line length and blur have a strong influence on the ability to discern the change in orientation of a static line. Thresholds for the discrimination of an angular deviation improve with line length until reaching a plateau at just above 1° (Figure 2, top—gray symbols; stimulus blur coded by symbol size). Lines with the same ratio of length-to-blur result in the same angular deviation threshold (Figure 2, bottom—gray symbols). This scale invariance is a pervasive property of human vision and holds for positional acuities (Levi, Jiang, & Klein, 1990; Toet, van Eekhout, Simons, & Koenderink, 1987; Whitaker, Bradley, Barrett, & McGraw, 2002), visual illusions (Kooi, 1993; Skillen, Whitaker, Popple, & McGraw, 2002), and texture discrimination (Kingdom & Keeble, 1999), in addition to the angular judgments examined here (Whitaker et al., 2008).

Like the normal observers, the preferred eyes of amblyopic observers show a marked effect of line length (Figure 2, top, black symbols) and similar scale invariance when replotted as a function of the ratio of length to blur (Figure 2, bottom). However, the non-amblyopic eye thresholds are, on average, slightly higher at all line lengths.

In contrast to the normal observers, the amblyopic eyes show much less effect of stimulus blur (Figure 3, left column). Indeed, the most severe amblyope (SC—top panel of Figure 3) has nearly identical thresholds at any given line length, over the 8-fold range of stimulus blur. Repplotting the data as a function of the length-to-blur ratio (Figure 3, right column) results in markedly different thresholds at a given length-to-blur ratio, indicating a failure of scale invariance.

The amblyopic eye data differ from normal in another respect. The scaled data of normal and non-amblyopic eyes are well fit by a bilinear function of the form

$$\text{Th} = \text{Th}_p \left( \frac{L_s}{L_o} \right)^n \quad \text{for } L_s < L_o$$

$$\text{Th} = \text{Th}_p \quad \text{for } L_s > L_o,$$

where $\text{Th}$ is the threshold at a given line length; $\text{Th}_p$ is the plateau threshold; $L_s$ is the scaled line length, $L_o$ is the optimum line length, and $n$ is the slope of the best fitting power function.
For both the normal and non-amblyopic eyes, the slope of the best fitting power function is \( \approx 0.5 \) (see Table 2) showing an approximately square root relationship between performance and line length, consistent with the performance of an ideal observer (Levi & Klein, 1986). As noted above, the amblyopic eyes cannot be well fit by a single line. Importantly, except at the largest blur, the amblyopic eyes show a much steeper slope, consistent with a slope of 1 at the two smallest blur levels, indicating complete integration over line length. Note that in a few cases a single power function provided a better fit to the data of the amblyopic eye than the bilinear function, and in those cases we report the slope of the single power function in Table 2.

Our task is essentially detection of a change in orientation (see Figure 1), and it has been documented that amblyopes show deficits in orientation discrimination with short lines or high contrast, high spatial frequency gratings (Skottun et al., 1986; Venverloh, 1983, but see Hess & Malin, 2003; Mansouri, Hess, & Allen, 2007), so it is not altogether surprising that they also show deficits in angle judgments (change in orientation) of this sort and that the deficits are most marked with short lines.

What is surprising is that the results of the amblyopic eyes are qualitatively different from those of the normal observers. This can be seen most clearly in the most severe amblyope (SC—top row of Figure 3). For his amblyopic eye, the unscaled data (left column, solid symbols) appear to be superimposed, while the scaled data (right column) segregate depending on stimulus blur, as if the amblyopic visual system had a substantial internal neural blur that rendered stimuli of the same length, but different external blur effectively identical in blur. This is true but to a lesser extent, for each of the amblyopes, particularly at the shorter line lengths.

This can be seen more clearly in Figure 4, where thresholds are plotted as a function of blur (specified as the Gaussian standard deviation of the line). This figure represents essentially two vertical cuts through the left most panel of Figure 3: one with a short line length (24'—top panel), and the other with a long one (384'—bottom panel). First consider the top panel (‘short’ 24' lines). Compared to the non-amblyopic eyes (open squares), the amblyopic eyes show elevated thresholds at the smallest stimulus blur (\( \sigma = 2' \)). The threshold elevation at the smallest blur ranges from \( \approx 50\% \) to more than a log unit when compared with the normal observers (gray circles). As discussed below, the threshold with short lines and small stimulus blur are closely tied to the observers’ line letter acuity (Figure 5). The curves fit to the normal

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**Figure 3.** Left column: Threshold versus stimulus length for each eye of 5 amblyopes. The amblyopic eye data are replotted as a function of line length/blur (right column). For comparison, the gray and black dashed lines show the best fitting bilinear functions for the normal and non-amblyopic eyes, respectively (from Figure 2).
In Figure 4 (top) are an equivalent blur fit of the form:

\[ T_h = T_h^0 \cdot 1 + \left( \frac{\sigma_e}{\sigma_t} \right)^2 \]

where \( T_h^0 \) is threshold with no stimulus blur; \( \sigma_e \) is the amount of stimulus blur on the screen, and \( \sigma_t \) is the observer’s blur tolerance. This function is actually a form of the more familiar function that has been frequently used to quantify equivalent intrinsic noise (Barlow, 1957; Pellé, 1990), i.e., the amount of noise that must be added to a stimulus in order to elevate thresholds by \( \sqrt{2} \). Levi and Klein (1990) used the parameterization shown above, to quantify the amount of intrinsic blur in amblyopia, i.e., the amount of blur that had to be added to the stimulus in order to elevate thresholds by \( \sqrt{2} \). Indeed, Chung and Levi (1997) used it to quantify amblyopes’ tolerance to image motion. For the normal (gray circles) and non-amblyopic (open squares) eyes in Figure 4 (top) are an equivalent blur fit of the form:

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Table 2. The best fitting slope (\( n \)) from the fits to Figures 2 and 3.

<table>
<thead>
<tr>
<th>Observer</th>
<th>Blur level (min)</th>
<th>Slope (( n ))</th>
<th>95% CI</th>
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<tbody>
<tr>
<td>Normal mean</td>
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<td>0.08</td>
</tr>
<tr>
<td>NAE mean</td>
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<td>0.06</td>
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<tr>
<td>Amblyopic eyes</td>
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<tr>
<td>AP</td>
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<tr>
<td>SM</td>
<td></td>
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</tr>
<tr>
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<td>Mean</td>
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<tr>
<td>Mean</td>
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The lower panel of Figure 4 shows similar data for long (384’) lines. For long lines the normal (gray circles) and non-amblyopic (open squares) eyes show somewhat greater blur tolerance (\( \sigma_t \approx 13' \)) similar to that of four of the 5 amblyopic eyes (mean \( \sigma_t \approx 12.5' \)). We were unable to fit the data of SC because his thresholds actually improved at the largest blur level tested. Interestingly, for

![Figure 4](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/932855/)

**Figure 4.** Threshold versus blur. **Top:** Short (24’) line. **Bottom:** Long (384’ line). The curves are "Equivalent blur" functions (see text). Note, for clarity we plot the amblyopic eye data in color (red for strabismic and blue for both strabismic and anisometropic).
long lines, the amblyopic eyes are within a factor of two of the fellow (non-amblyopic) eyes and in some cases are even better than the non-amblyopic and normal eyes.

**Summary and discussion**

**Detection of a change in orientation is scale-invariant in normal but not in amblyopic vision**

We measured the ability of strabismic amblyopes to detect a change in the orientation of a high contrast line as a function of line length and blur. Our main new result is that amblyopes are qualitatively different from normal observers, in that stimulus blur has less effect on their performance (particularly for short lines), consistent with a substantial degree of internal neural blur. This internal blur results in a loss of scale invariance in the amblyopic visual system.

What are the implications for this loss of scale invariance? In normal vision, lines of different length, but with the same ratio of length to blur, result in the same angular deviation threshold (Whitaker et al., 2008). This scale invariance can be easily explained on the basis of self-similar visual filters whose size is determined by stimulus blur (e.g., Levi & Klein, 1985; Whitaker et al., 2008; Wilson, 1991). In this scheme, filter size is determined by the stimulus blur. Spatially scaled versions of the filters result in the same level of performance for a given length to blur ratio; however, a loss of small filters would limit the range of blur that would engage self-similar filters in amblyopic visual system and may limit both visual acuity and the ability to detect changes in the orientation of a line at small levels of blur.

The idea that the amblyopic visual system suffers a loss of small filters is neither novel nor controversial. Indeed, it is a central assumption of almost all models of amblyopia (Barrett, Bradley & McGraw, 2004; Levi & Klein, 1985; Wilson, 1991). This loss provides a simple account for the loss of acuity, contrast sensitivity at high spatial frequencies, and orientation judgements at a small scale. However, our study of orientation judgements over a large range of spatial scales helps to clarify the amblyopic loss of orientation discrimination, which, as noted below, has been somewhat controversial.

For normal observers, the data are remarkably similar to performance in both single line orientation and curvature discrimination tasks (Heeley & Buchanan-Smith, 1998; Whitaker & McGraw, 1998). Both orientation and curvature thresholds (when defined in angular terms) demonstrate scale invariance in that performance across a range of blur levels and line lengths collapse together as function of stimulus length divided by blur. The same trend is shown, with performance improving with line length before reaching a plateau. The optimum thresholds (≥0.5°–1°) are also similar to the optimum angular deviation thresholds found in the present study. Thus, our findings would predict abnormalities in curvature discrimination at fine spatial scales in the amblyopic visual system (see Levi, Li, & Klein, 2005).

Scale invariance implies that in normal vision, a kink in a line will be detected with the same level of accuracy over a wide range of viewing distances. The loss of scale invariance in strabismic amblyopia implies that when the line’s blur is reduced below the observer’s elevated internal neural blur, the ability to detect a kink will be markedly reduced.

Do our findings have implications for other types of invariant visual processing? Kingdom, Field, and Olmos (2007) have shown that we are relatively insensitive to geometric transformation of scenes, including the expansion and contraction commonly experienced by self-motion. This might help us to assign particular precedence to external visual events of potential importance. The radically altered nature of scale invariance in the amblyopic visual system raises an interesting question regarding the sensitivity of amblyopes to geometric transformations of this kind. One other notable failure of scale invariance in strabismic amblyopia relates to the effect of flankers on acuity. In normal foveal vision, the effect of flankers is scale invariant (Levi, Klein, &...
Hariharan, 2002); interestingly, similar to the present results, the scale invariance breaks down in the normal periphery (Levi, Hariharan, & Klein, 2002b) and in the central field of strabismic amblyopes (Levi, Hariharan, & Klein, 2002a) where flanks affect acuity over a fixed distance.

We note that our results differ from those of Aaen-Stockdale and Hess (2008), who reported that the amblyopic deficit for global motion is scale invariant. They attribute the scale invariant loss to specific deficits in motion processing in extra-striate areas. For our static orientation task, the losses depend on scale and are attributable to low-level losses of small filters.

**Strabismic amblyopia is similar to normal periphery**

Our results also have important implications for normal peripheral vision. Vision in strabismic amblyopia has often been likened to that of the normal periphery (Levi, 1991; Levi & Carkeet, 1993; Song, Pelli, & Levi, in preparation). Does scale invariance fail in the normal periphery? Figure 6 shows peripheral data of two normal observers.

As with the amblyopic data (Figure 2), peripheral performance eventually approaches that of the normal fovea given sufficient stimulus size (Whitaker, Mäkelä, Rovamo, & Latham, 1992). However, in contrast to the normal fovea (gray symbols), the periphery shows much less effect of stimulus blur (the top two panels of Figure 6 show threshold versus length.). Indeed, in the periphery thresholds at any given line length are nearly identical over the 8-fold range of stimulus blur. Replotting the data as a function of the length-to-blur ratio (Figure 6, bottom panel) results in markedly different thresholds at a given length-to-blur ratio, indicating a failure of scale invariance in peripheral vision, similar to the central vision of strabismic amblyopes. The results demonstrate what we already know about peripheral vision—performance varies as a function of eccentricity at a much faster rate for small, high spatial frequency stimuli than for coarse stimuli. It would seem to suggest that both peripheral vision and amblyopic vision share a common bottleneck in having a truncated range of spatial mechanisms—a range that becomes more restricted with increasing eccentricity and depth of amblyopia.

**Integration over line length**

The amblyopic visual system shows abnormal integration along the length of the lines. Normal observers (and the non-amblyopic eyes) show a square root relationship between line length and performance. For normal eyes, thresholds decrease in proportion to \( \sqrt{L:B} \) until L:B (the...
Abnormal integration over line length has been previously reported in amblyopic eyes. For example, Levi and Klein (1986) showed that the amblyopic eyes of strabismics require more samples than normal fovea, to reduce positional uncertainty in a bisection task. In this task, strabismic amblyopes showed a square root relationship (slope \( \approx 0.5 \)) between performance and the number of samples; whereas the normal fovea showed a considerably flatter slope (\( \approx 0.2–0.3 \)). They suggested that a sparse sampling grain and/or scrambling of the neural signals would introduce positional noise, which is uncorrelated between stimulus samples in strabismic amblyopia. Indeed, Wang, Levi, and Klein (1998) showed that the visual system of strabismic amblyopes is characterized by both positional uncertainty and markedly reduced sampling efficiency. Mussap and Levi (2000) measured the ability to detect a dotted line in noise dots (i.e., observers had to indicate whether the dotted line was horizontal or vertical). They found essentially normal performance for small numbers of target dots (<7) and deficits when the target consisted of more than 7 dots and suggested that the deficits may be the consequence of stunted second-stage integrative processes. This notion of stunted integrative processes may also explain why amblyopes show an increased Fraser illusion, a decreased “phase” illusion, and a reversed tilted chain illusion (Popple & Levi, 2000), and why amblyopes need more samples to determine the orientation of an E-like pattern (Levi, Klein, & Sharma, 1999).

Although the current results also show that amblyopes need more samples (or larger samples) to accurately detect a change in orientation, they suggest that the amblyopic visual system is more, not less, efficient than normal. Thresholds are reduced in proportion to length, rather than to the square root of length. We think the most likely explanation is that our results reflect an abnormality in scale selection. Whitaker et al. (2008) explain the scale invariance of normal performance on the basis of self-similar oriented cortical filters, whose size is determined by the stimulus blur. If the amblyopic cortex is missing or unable to use the smallest filters (Levi & Klein, 1985, 1986), it would engage inappropriately large filters (since our stimuli are spatially low pass and broad bandwidth, e.g., Levi & Klein, 2003; Levi, Waugh, & Beard, 1994). The consequence would be that performance would be independent of stimulus blur, until the stimulus blur exceeded the size of the smallest available filter. This increased internal neural blur would result in integration over longer fixed distances (for stimulus blur less than the internal blur), and since the integration would be taking place within a neural unit (physiological rather than probabilistic integration), the slope of the threshold vs. length function would be close to unity. This interpretation is consistent with the suggestion that the deficit in orientation discrimination in the amblyopic visual system is based on a selective deficit of first- as opposed to second-order processing (Demanins, Hess, Williams, & Keeble, 1999). We do not mean to imply that second-order deficits do not exist, just that they are not necessary to explain the current results.

We note that the normal periphery also shows near perfect integration (peripheral slope \( \approx 0.97 \pm 0.15 \) [95% confidence interval]) over long distances. For DW at 10 degrees, over a scaled length of more than 100 at the smallest blur, consistent with a truncated range of spatial mechanisms in peripheral and amblyopic vision.

Relation to other studies

Our task reveals an amblyopic deficit in the detection of a change in orientation at fine spatial scales. To date, however, studies of orientation discrimination in amblyopia have had rather mixed results. A number of studies have suggested that orientation discrimination is normal or nearly so with the amblyopic eye. For example, Hess and Malin (2003) reported normal orientation discrimination in amblyopic eyes at near threshold contrast levels, even at high spatial frequencies. However, in their study observers had to discriminate between gratings of 70 vs. 110 degrees, so only coarse orientation judgements were required. Similarly, Mansouri et al. (2007) showed that amblyopes are normal or very nearly so in judging the orientation variance of an array of 16 Gabor patches, even at relatively high spatial frequencies. On the other hand, several studies have reported that amblyopes show deficits in orientation discrimination with short lines (e.g., Vandenbussche, Vogels, & Orban, 1986; Venverloh, 1983), or with high contrast, high spatial frequency gratings (Demanins et al., 1999; Skottun et al., 1986), and there has been a report (Rentschler & Hilz, 1979) of a deficit in orientation selectivity in two out of their five amblyopic subjects. Our results may help explain these discrepant results. Firstly, our task is aimed at measuring very fine orientation discrimination, giving, under optimal conditions, normal thresholds of less than 1.5 degrees. In part, this is because our task of detecting a change in

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orientation, rather than judging the orientation of an isolated line or Gabor patch, provides a built-in reference, and thus minimizes effects of orientation biases, drifts in perceived orientation, or torsion of the eyes. Using a similar task Levi and Tripathy (2006) found that four of their 5 amblyopes showed deficits in detecting a single static deviation and that the deficits increased with viewing distance. They attributed this to a decrease in the line length, and the present study shows that line length is indeed important. Interestingly, they reported that threshold for a single trajectory at 3.3 m is closely related to the observers’ visual acuity (their Figure 8). Figure 5 replots their data (gray dots) along with the threshold for a short (24') line with \( \sigma = 2' \) (open circles) from the current study. Although the stimuli were quite different, both show a clear-cut relationship between the threshold for detecting a deviation in the orientation of a short line and the observers’ visual acuity. The best fitting power function for the current data has a log–log slope that is consistent with proportionality (0.92 ± 0.1). We hypothesize that the same neural internal blur limits performance on both tasks (acuity and detection of a local change in orientation).

Compared to their fellow non-amblyopic eyes, four of our five amblyopic observers show deficits for short lines (e.g., 12 or 24') with the smallest blur (the exception is SM), and all five are worse than the normal control observers. The loss depends on visual acuity (Figure 5) and varies from \( \approx 2 \) to over a factor of fourteen (relative to normal). Blurring the short lines worsens performance in normal and non-amblyopic eyes, eliminating the deficit in 4 of the 5 observers (relative to their preferred eye) and reducing it in the fifth. Lengthening the lines (at all levels of blur) reduces or eliminates the deficit relative to the non-amblyopic eyes.

Our explanation is consistent with the notion of undersampling, i.e., a reduced complement of small (high spatial frequency) filters in the cortex of strabismic amblyopes (Levi & Klein, 1985, 1986; Sharma, Levi, & Coletta, 1999). An alternative hypothesis is that strabismic amblyopia is characterized by uncalibrated neural disarray or scrambling (Hess, 1982). However, Demanins et al. (1999) found that the amblyopic deficit occurred not only with large patches of gratings but also with sparse arrays of randomly positioned Gabor micropatterns, which would factor out any effect of either neural disarray or abnormal local interactions.

**Conclusions**

Strabismic amblyopes show deficits in judging a kink (a change in the orientation) in a line. This deficit is most marked at short line lengths and is more or less proportional to their loss of visual acuity. In this task, strabismic amblyopes are qualitatively different from normal observers in that stimulus blur has less effect on their performance, consistent with a substantial degree of internal neural blur. This internal blur results in a loss of scale invariance in the amblyopic visual system.

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