The effect of temporal frequency variation on threshold contrast sensitivity deficits in optic neuritis

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SUMMARY The effect of increasing temporal frequency on contrast sensitivity anomalies in unilateral optic neuritis has been investigated. For 4 c/deg gratings no change in the deficit was observed at any temporal frequency whereas there was a tendency for the deficit to decrease with increase in temporal frequency for 0.5 c/deg gratings. The latter effect was not observed in a case of optic neuritis with severe deficit and not in two cases of other optic nerve pathology. An explanation based on the assumption that "threshold scotomata" might be present in cases of demyelinating optic nerve disease is proposed.

Over the past two decades our understanding of the complexities of normal visual function has been greatly enhanced by the methods introduced by Schade1 and formalised by Campbell and Robson.2 This approach has succeeded in directing our attention, previously fixed on acuity (spatial and temporal), towards the study of the sensitivity for intermediate sized (spatial or temporal) stimuli. The justification for this psychological change of direction was the neurophysiological finding that single cells in the animal visual system respond only over narrow ranges of spatial and temporal frequency. There is now independent psychophysical evidence for discrete spatial and temporal processing mechanisms or channels in human vision. The spatial channels have a bandwidth ranging from less than an octave to one octave3,4 and there are thought to be a minimum of seven.5 Temporal processing is thought to involve just two broadband channels.5 Tolhurst6 and Kulikowski and Tolhurst7 labelled these pattern and movement mechanisms according to their speculative contributions to perception.

Recent investigations of the visual loss resulting from optic nerve demyelination and other visual disorders have built upon and benefited from this emerging framework of normal visual processing. We now know, for example, that not only can a group of low frequency spatial channels be affected independently of those at high spatial frequencies8–11 but individual spatial channels at intermediate spatial frequencies can also be selectively affected.12,13 Although our appreciation of the way in which optic neuritis can affect the spatial channels of vision is well developed we know almost nothing of how the temporal channels are affected because all of these previous studies have used stationary stimuli or spatial stimuli temporally modulated at low rates. The present investigation has been directed towards this issue.

Apparatus and methods

Grating stimuli varying sinusoidally in space and time were generated on a large screen monitor (Joyce screen) digitally. The contrast of the stimuli was varied (3–10 settings) by the patient using an 80 position switched logarithmic attenuator. The field size was 15° x 10° and the screen's space averaged luminance remained constant at 200 cd/m². The frame rate was set to 100 Hz thus allowing three frames per temporal cycle at our highest temporal frequency (30 Hz). Each eye was carefully refracted. The other eye was occluded. A fixation mark was provided to stabilise eye movements and accommodation. The stimuli were always presented initially below threshold and adjusted by the patient until the spatial or temporal aspects of the stimulus could be detected, whichever predominated. Active pupils (2–4 mm) were used and the viewing distance was 114 mm.

Patients Patients were selected who had had an attack of unilateral optic neuritis recently. At the time of testing all demonstrated a uniocular loss in sensitivity over the whole or part of the spatial range, the fellow eye exhibiting no clinical
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The clinical details of all patients are summarised in table 1, and the results of visual evoked response studies (using the method described by Halliday et al\textsuperscript{14}) are shown in table 2.

Table 1 Clinical details of patients studied

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (yr)</th>
<th>Diagnosis</th>
<th>Length of history (Months)</th>
<th>Visual acuity</th>
<th>Ishihara test (Number of errors)</th>
<th>RAPD</th>
<th>Optic disc</th>
<th>Visual field</th>
<th>Contrast sensitivity function</th>
</tr>
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<tbody>
<tr>
<td>ER</td>
<td>26</td>
<td>Unilateral optic neuritis</td>
<td>18</td>
<td>6/6</td>
<td>0</td>
<td>-</td>
<td>Normal</td>
<td>Normal</td>
<td>Mid-frequency loss</td>
</tr>
<tr>
<td>KR</td>
<td>45</td>
<td>ditto</td>
<td>12</td>
<td>6/5</td>
<td>0</td>
<td>-</td>
<td>Normal</td>
<td>Normal</td>
<td>Mid-frequency loss</td>
</tr>
<tr>
<td>SS</td>
<td>28</td>
<td>ditto</td>
<td>24</td>
<td>6/12</td>
<td>6</td>
<td>+</td>
<td>Pallor</td>
<td>Normal</td>
<td>Generalised loss</td>
</tr>
<tr>
<td>PC</td>
<td>24</td>
<td>ditto</td>
<td>2</td>
<td>6/18</td>
<td>4</td>
<td>+</td>
<td>Temporal pallor</td>
<td>Paracentral scotoma to red only</td>
<td>Generalised loss</td>
</tr>
<tr>
<td>MS</td>
<td>35</td>
<td>ditto</td>
<td>3</td>
<td>6/6</td>
<td>1</td>
<td>-</td>
<td>Normal</td>
<td>Normal</td>
<td>Generalised loss</td>
</tr>
<tr>
<td>KW</td>
<td>19</td>
<td>ditto</td>
<td>2</td>
<td>6/24</td>
<td>1</td>
<td>+</td>
<td>Normal</td>
<td>Normal</td>
<td>Generalised loss</td>
</tr>
<tr>
<td>BB</td>
<td>35</td>
<td>ditto</td>
<td>2</td>
<td>6/18</td>
<td>4</td>
<td>+</td>
<td>Normal</td>
<td>Paracentral scotoma to red only</td>
<td>Generalised loss</td>
</tr>
<tr>
<td>KT</td>
<td>35</td>
<td>Bilateral optic neuritis</td>
<td>Right eye 1</td>
<td>6/36</td>
<td>12</td>
<td>+</td>
<td>Normal</td>
<td>Dense central scotoma</td>
<td>Generalised loss</td>
</tr>
<tr>
<td>SS</td>
<td>33</td>
<td>Left eye</td>
<td>18</td>
<td>6/6</td>
<td>0</td>
<td>-</td>
<td>Normal</td>
<td>Normal</td>
<td>Near normal</td>
</tr>
<tr>
<td>HD</td>
<td>62</td>
<td>Ischaemic optic neuropathy</td>
<td>9</td>
<td>6/60</td>
<td>12</td>
<td>+</td>
<td>Pallor</td>
<td>Normal</td>
<td>Generalised loss</td>
</tr>
</tbody>
</table>

Table 2 Visual evoked response latency and amplitude measurement

<table>
<thead>
<tr>
<th>Patient</th>
<th>P100 Latency (ms)*</th>
<th>P100 Peak to trough amplitude†</th>
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</thead>
<tbody>
<tr>
<td>ER</td>
<td>93</td>
<td>109</td>
</tr>
<tr>
<td>KR</td>
<td>96</td>
<td>116</td>
</tr>
<tr>
<td>SS</td>
<td>102</td>
<td>122</td>
</tr>
<tr>
<td>PC</td>
<td>100</td>
<td>187</td>
</tr>
<tr>
<td>MS</td>
<td>95</td>
<td>109</td>
</tr>
<tr>
<td>KW</td>
<td>98</td>
<td>123</td>
</tr>
<tr>
<td>BB</td>
<td>105</td>
<td>No measurable response</td>
</tr>
<tr>
<td>KT(R)</td>
<td>122</td>
<td>103</td>
</tr>
<tr>
<td>KT(L)</td>
<td>93</td>
<td>113</td>
</tr>
<tr>
<td>HD</td>
<td>95</td>
<td>110</td>
</tr>
</tbody>
</table>

*Abnormal = > 106 msec (99% confidence limits)
Abnormal = < 77% (99% confidence limits)
†Succeeding trough

Results

The contrast sensitivity results for the normal eyes of our patient group at two spatial (0.5 c/deg and 4 c/deg) and a wide range of temporal frequencies (1-30 Hz) is seen in fig 1. These results are compared to an age matched group of normal eyes (10) using the same methods. The dashed line which represents the 95% confidence limits (±2 SD) of normal sensitivity is seen to describe well the results of the fellow eyes of our patients. This result combined with the clinical evidence gave us greater confidence...
Fig 1  Contrast sensitivity for a wide range of temporal frequency (contrast reversal) is plotted for the normal eyes of all our cases of unilateral optic nerve pathology. These are compared with the 95% confidence limits (dashed curves) of a group of age matched normals. Results are displayed for low (0.5 c/deg) and medium spatial frequency (4 c/deg) stimuli whose functional dependence on temporal frequency differs. The fellow eye of each of our subjects appears to have normal threshold sensitivity at these two spatial frequencies.

Fig 2  Contrast sensitivity is plotted for different rates of contrast reversal for low spatial frequency stimuli. In each case the normal eye (○) is compared with its fellow (●) suffering from optic neuritis. Thresholds are seen to be raised for stationary stimuli and those reversing in contrast at slow rates but not at high temporal rates. The standard deviation did not vary as a function of temporal frequency and was less than the symbol size.
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to use the fellow eye as a control for each patient. Note that there is a different shape of temporal function for 0.5 c/deg and 4 c/deg. At 0.5 c/deg it exhibits bandpass characteristics while at 4 c/deg it is low pass.

In figs 2 and 3 sensitivity is compared for a wide range of temporal frequencies for two spatial frequencies. The results for the normal eyes are shown as unfilled symbols while those of the affected eye as filled symbols. For the low spatial stimulus (0.5 c/deg) the loss of sensitivity in optic neuritis depends upon the temporal rate of stimulation. In all cases losses occurring at low temporal frequencies diminished as temporal frequency increased. Contrast settings were no less accurate in the affected than the unaffected eye at any temporal frequency.

The temporal results (fig 3) for a higher spatial frequency (4 c/deg) are quite different. Here the loss of sensitivity was independent of the temporal rate of stimulation, since the dashed curve which best fits the results for the affected eye (filled symbols) is a parallel displaced version of the best fitting curve for the fellow normal eye (filled line and unfilled symbols). On these coordinates such a parallel displacement indicates that the sensitivity of the affected eye is maintained at a constant ratio to that of the normal eye independently of temporal frequency.

In fig 4 the transition between the temporal dependence of visual loss in optic neuritis at low spatial frequencies and the temporal invariance at intermediate spatial frequencies was investigated by incorporating an intermediate spatial frequency (1 c/deg) for another patient. This patient exhibits results similar to those already described in figs 2 and 3 for 0.5 and 4 c/deg. At 1 c/deg the loss (normal eye is unfilled and the affected eye filled symbols) is seen to be independent of temporal frequency as it was for 4 c/deg. The transition between these two types of temporal loss may then occur between 0.5 and 1 c/deg.

We supposed that the relative preservation of

Fig 3 Contrast thresholds are plotted for different rates of contrast reversal for a medium spatial stimulus (4 c/deg). These results differ in two ways from those displayed in fig 2 for low spatial frequency stimuli. First, the shape of the normal curve (○) is low pass and second the thresholds in optic neuritis (●) are elevated to the same extent at low and high temporal rates. In each case the dashed curve is a parallel shifted version of the curve that best fits the normal eye's results. The standard deviation was less than the symbol size in all cases.
Contrast thresholds are compared for three different spatial frequencies at different rates of contrast reversal. As the spatial frequency is increased the shape of the normal eye's function changes from band pass to low pass and the loss of sensitivity becomes more evenly distributed across temporal frequency. The transition from the uneven loss at low spatial frequency to the even loss at medium spatial frequencies depicted in fig 2 and 3 is seen to occur between 0.5 and 1 c/deg in this patient.

Fig 5  Contrast sensitivity is plotted for different rates of contrast reversal for three cases; a bilateral optic neuritis, a compressive optic neuropathy and an ischaemic neuropathy. In the case of bilateral optic neuritis one eye (●) was only minimally affected compared with the 95% confidence limits for normals (dashed curves) whereas the fellow eye (▲) was severely affected. This loss, the most severe encountered for low spatial frequencies was evenly distributed across temporal frequency. For the compressive and ischaemic neuropathy thresholds are compared with the fellow unaffected eye. In each case though the threshold loss was not any more severe than those displayed in fig 2, the loss was evenly distributed across temporal frequency for low and medium spatial frequency stimuli. In each case the dashed curve that fits the results for the affected eye (●) is a parallel shifted version of the curve best fitting the results for the normal fellow eye (○).
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contrast sensitivity to a low spatial frequency grating at high temporal frequency would break down if the deficit were severe and this is certainly suggested by the results obtained in the more severely affected eye of KT (fig 5). It should be noted, however, that her "recovered" eye shows a similar temporal frequency dependence to the cases in fig 3 when compared with our control data (dashed lines). The losses in the two cases of other optic nerve pathology were comparable to some of the optic neuritis patients and yet they did not demonstrate this spatio-temporal dependence. The comparative rarity of these other disorders, and the difficulty in finding such patients with the relatively mild losses of contrast sensitivity that are common in recovered optic neuritis confounds further exploration of the specificity of this finding to optic neuritis, but it is our intention to investigate its potential for differential diagnosis.

Discussion

Our results suggest that visual loss in some cases of optic neuritis depends upon both the spatial and temporal frequency of the stimulus. For low spatial frequency stimuli sensitivity is more severely impaired at low temporal frequencies. As the temporal frequency is increased so the threshold anomaly diminishes. This is not so at higher spatial frequencies.

In concluding this, efforts were undertaken to ensure that the steeper high frequencies limbs of the low spatial frequency curves are not masking any parallel displacement of the thresholds for the affected eye. Also on a number of occasions low spatial frequency curves were repeated using higher frame rates (200 Hz) and found to be consistently less affected in optic neuritis for higher temporal rates of stimulation. This effect was always much greater than the standard deviation of the threshold setting (less than symbol size). For medium spatial frequency stimuli the loss of sensitivity in optic neuritis is independent of temporal frequency. This complex spatio-temporal dependence of the visual loss in optic neuritis was not observed in a more severe case nor in the two cases of compressive and ischaemic optic nerve pathology.

At first glance these findings seem to indicate that there may be two different temporal channels for low and high spatial frequencies. At low spatial frequencies the high temporal channel is less affected whereas at medium spatial frequencies there is either only one temporal channel or, if there are two, both are equally affected. Furthermore, the results seem to be at odds with previous studies of critical flicker frequency (CFF) in multiple sclerosis in which reduced CFFs were found for low spatial frequency stimuli (that is spots greater than 1 deg in diameter) in a high percentage of eyes. Our findings, on the other hand, suggest a diminished threshold abnormality as temporal frequency is increased for low spatial frequencies in cases of optic neuritis with mild deficits.

An important difference between the CFF studies and our own which may help to reconcile these discrepancies and simplify our analysis of the way in which temporal channels are affected in optic neuritis concerns the area of stimulation and hence its localisation in the visual field. The CFF experiments utilised small, highly localised (though spatially broad-band) stimuli (for example spots) whereas the contrast threshold technique involves large areas of stimulation with periodic (spatially narrow-band) stimuli. Correspondence between these two approaches would be expected only when the deficit being investigated does not vary across the visual field.

We were aware that two of our unilateral cases exhibited small (measuring a few degrees in extent) relative scotomata to red targets which were para-central and just within the stimulus field. It is also possible that subtle, relative scotomata, not detectable clinically were present in all the patients and that such patchy deficits would, at threshold, become absolute, particularly as demyelination is likely to affect the optic nerve in a patchy manner.

In an attempt to find out if the presence of such "threshold scotomata" might explain our findings and hence resolve the disagreement with previous CFF studies we examined the effects that different simulated scotomata have on contrast thresholds for our spatio-temporal stimulus. The results for a normal observer of three different types of scotoma (a central scotoma of 8° diameter, an annular scotoma extending from 1.5° to 8° and a peripheral scotoma sparing 1.5° diameter) are shown in fig 6. These scotomata were simulated by masks placed on our stimulus screen. The masks and the surround were kept at the same space average luminance as that of the stimulus. As can be seen the threshold changes across temporal frequency for the two spatial frequencies used (0.5 c/deg and 4 c/deg) are similar to those seen in the unilateral optic neuritis cases (figs 2-4) whether or not a scotoma was clinically detected. For each scotoma the contrast sensitivity was less affected for low spatial and high temporal rates of stimulation.

The simplest explanation for the effect of simulated scotomata is that for low spatial frequency stimuli there is a difference in spatial (areal) summation for stimuli varying at low and high temporal rates such that as the area of stimulation is
would then result in a parallel displacement of the overall temporal function. Finally, this difference in area summation for different temporal frequencies occurs with medium spatial frequency stimuli then a given loss of area would result in a parallel displacement of the overall temporal function. Finally, this difference in area summation for low spatial frequency stimuli temporally modulated at high rates should not vary greatly with eccentricity if it is to form the basis of an explanation for the similar results with different types of scotomata (fig 6).

We tested these area summation predictions on two normal observers, the results for one of whom are displayed in fig 7 (for 0.5 c/deg) and 8 (for 4 c/deg). In each figure the effect on threshold sensitivity of varying the area of stimulation at two different rates of temporal modulation (1 Hz and 32 Hz) are shown. On the left half of each figure results are shown for central stimulation, on the right of each figure are results for eccentric (5°) stimulation. Close inspection of these results confirms all three predictions. Firstly, the sensitivity fall off as the stimulus area is reduced is much less rapid for the 32 Hz low spatial frequency stimulus (fig 7) than for the 1 Hz condition. Secondly, for the 4 c/deg stimulus a decrease in the area of stimulation affected thresholds equally for low and high rates of temporal modulation (fig 8). Thirdly, this difference was not dependent upon the region of the visual field tested within the central 10°.

Fig 6 Different types of scotoma are simulated for normal vision and assessed in terms of their effect on contrast thresholds at different temporal frequencies. Three different types of scotoma and two different spatial frequencies (0.5 c/deg and 4 c/deg) are used. The thresholds for each scotoma are compared with those for full field stimulation comparable to that used in the initial part of this study. The central scotoma was produced with an 8° diameter mask, the annular scotoma by a mask whose inner diameter was 2° and outer diameter 8°. The peripheral scotoma was produced by a mask sparing the central 1-5° diameter. In each case the threshold loss is unevenly distributed across temporal frequency for the 0.5 c/deg stimulus yet evenly distributed across temporal frequency for the 4 c/deg stimulus. These results on normals with different simulated scotomata mimic those found in some cases of optic neuritis.
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Fig 7 Contrast sensitivity is plotted against the area of stimulation for a low spatial frequency (0.5 c/deg) stimulus at two different rates of contrast reversal (1 Hz ○, □ and 32 Hz ▲, ●). Two different loci in the visual field are investigated 0° (left frame) and 5° (right frame). For both positions in the visual field, area summation is much more critical for the low temporal condition. The threshold fall off as stimulus area is decreased is more gradual for the 32 Hz stimulus. These results suggest a possible explanation for the optic neuritis results for figures 2–4 and the simulated scotoma results of fig 6.

Fig 8 Contrast sensitivity is plotted against the area of stimulation for a medium spatial frequency (4 c/deg) stimulus at two different rates of contrast reversal (1 Hz ○, □ and 32 Hz ▲, ●). Two different loci in the visual field are investigated 0° (left frame) and 5° (right frame). For both positions in the visual field, similar area summation is seen at each of these two temporal frequencies. These curves which show asymptotes around 4° × 4° fields are parallel shifted versions of one another. A comparison of these results at 4 c/deg with those at 0.5 c/deg (fig 7) suggests a possible explanation for the optic neuritis results of fig 2–4 as well as the simulated scotoma in normals (fig 6) in terms of losses in areal summation due to clinically undetectable threshold scotoma (see text).

For normals this finding that thresholds for low spatial frequency stimuli temporally modulated at high rates are not as much affected by stimulus area (as compared with those at low rates of modulation) implies that the detecting mechanism is localised in space. Any slight increase in sensitivity with increasing area being due to probability summation. Such a result suggests a plausible explanation for the present findings in patients with optic neuritis. If there are subtle relative scotomat, be they central, paramacular, or patchily distributed across the visual field, differential threshold changes due to differences in area summation would result which would be consistent with our results. In more severe cases of optic neuritis where the visual field studied is affected or in cases of optic nerve pathology of a less patchy nature (for example ischaemia or compression) thresholds would be affected equally at all temporal frequencies.

This suggestion of the presence of subtle threshold scotomat in different parts of the visual field in recovered optic neuritis has special relevance for the present contrast sensitivity approach. The technique involves the measurement of contrast thresholds for relatively large fields of stationary or slowly modulated periodic stimuli (gratings) scotomat which do not reduce the area of stimulation below the asymptote of the curve shown in figs 7 and 8 will not be detected. Small, more localised grating patches should be used to probe different regions of the visual field. This would represent a compromise between localisation in space (area) and spatial frequency.

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References

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