In: D.M. Willows, Kruk, R.S. & Corcos, E. (eds)
Visual Process in Reading and Reading Disbilities
Hillsdale, New Jersey: Lawrence Erlbaum Associates
pp. 345-356, 1993

20 Reading and Visual Discomfort

Arnold Wilkins
Medical Research Council Applied Psychology Unit
Cambridge, England

Reading can provoke perceptual distortion, eye strain, headaches, and seizures. In this chapter it is argued that these adverse effects occur because the successive lines of printed text resemble a pattern of stripes. The stripelike pattern can have spatial characteristics within a critical range for which adverse effects are possible. The striped properties vary considerably from one text to another and depend in part on the horizontal and vertical spacing of the words. There are large individual differences in susceptibility to the effects of stripes. It is shown that in persons who are susceptible, text can usually be made clearer and more comfortable by covering the lines that are not being read, thereby attenuating the striped pattern. Some people find that tinted glasses reduce the anomalous perceptual effects provoked by text. The appropriate tint varies from one individual to another and may be very specific. It can be selected using a colorimeter and associated tinted trial lenses. The physiological basis for efficacy of the tints is uncertain but may relate to a selective impairment of achromatic or color-opponent channels. It may be possible to change the spatial characteristics of conventional text slightly and improve clarity without increasing costs.

PATTERNS CAN BE HARMFUL

About 4% of patients with epilepsy are photosensitive and liable to seizures induced by flickering light. About half these patients are sensitive not only to flickering light but also to geometric patterns, particularly stripes with certain specific characteristics. It can be inferred that the seizures arise in the visual cortex when normal physiological excitation involves more than a critical

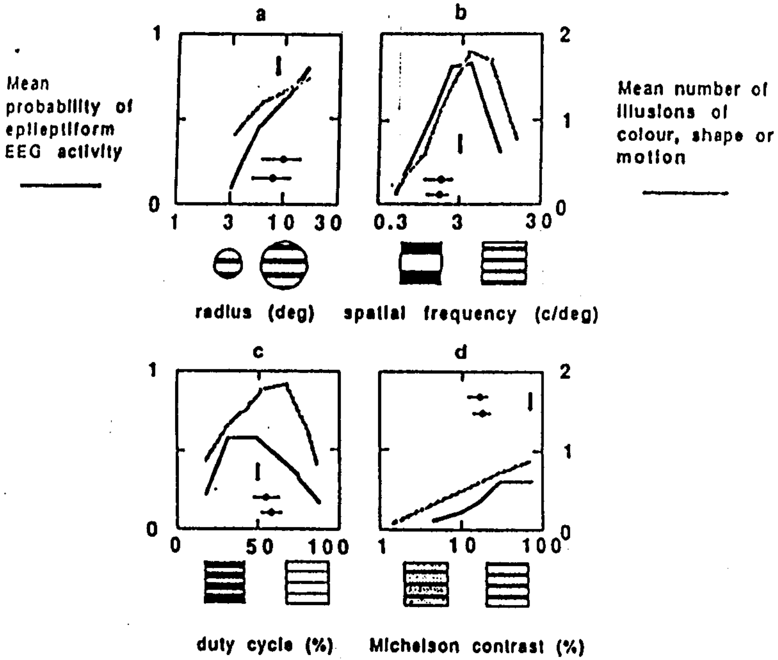


FIG. 20.1. Spatial characteristics of patterns responsible for illusions and seizures. The solid lines show the probability of epileptiform EEG activity in patients with photosensitive epilepsy. The probability was estimated from repeated randomized presentations of the pattern. The values for a group of patients were averaged. The gray lines show the average number of illusions of color, shape, or motion reported by normal observers. (a) Effects of the field size (angular subtense of the radius of the pattern at the eye). (b) Effects of the spatial frequency of a square-wave grating (number of spatial cycles of the pattern in one degree subtended at the eye). (c) Effects of the duty cycle (proportion of spatial cycle occupied by bright bars). (d) Effects of the Michelson contrast (difference in the luminance of the bright and dark sections of the pattern expressed as a proportion of their sum). Icons beneath each *x*-axis demonstrate variations in the parameter. The patterns in these icons are shown with horizontal stripes, although some of the data were collected using different orientations. In general, pattern orientation had little effect. The curves were obtained by manipulating each parameter independently, the values of the other parameters being chosen arbitrarily. As data were acquired it transpired that the values chosen were close to those for which illusions and epileptiform EEG activity were maximally likely (after Wilkins et al., 1984). The solid points and horizontal bars indicate the mean +/− 1 sd of the value of the parameter for text, when text is considered as stripes. The upper and lower bars refer to "less clear" and "clear" text, respectively. In (a), central fixation of the page is assumed and half the width of the page is taken as the radius of the pattern. In (b), the observer's choice of a comfortable reading distance is used. In (c), the estimate is based

number of cortical neurons (Wilkins, Binnie, Darby, & Kasteleijn-Nolst Trenité, 1990).

The patterns that provoke epileptiform activity in patients with photosensitive epilepsy are judged unpleasant by people who do not have epilepsy. The patterns induce a variety of anomalous visual effects that may be cortical in origin. People who suffer headaches and eye strain are particularly susceptible to the illusions (Khalil, 1991; Marcus & Soso, 1989; Wilkins et al., 1984). Susceptibility is increased up to 24 hours before a headache (Neary & Wilkins, unpublished data). In persons with migraine who have a consistently lateralized visual aura, the susceptibility (between headaches) is greater in the affected visual field (Khalil, 1991).

It is only when they have certain very specific spatial characteristics that patterns become aversive and induce anomalous visual effects and unpleasant neurological sequelae. The worst patterns are those of black-and-white stripes, particularly (a) when the pattern is large; (b) when each stripe subtends about 10 min of arc at the eye (i.e., the spatial frequency of the pattern is about 3 cycles/degree); (c) when the stripes have an even width and spacing (a duty cycle close to 50%); and (d) when the stripes are bright and strongly contrasting. The effects of these pattern characteristics are shown in Fig. 20.1. Figure 20.2 provides an example of an aversive pattern with spatial characteristics for which illusions and seizures are likely. The pattern is yet more aversive if it vibrates or changes phase (black-white, white-black) repeatedly at a frequency close to 20 Hz. Warning: Do not look at fig. 20.2 if you have epilepsy or migraine.

Text As a Striped Pattern

The successive lines of text form a pattern rather like that of stripes. If you look at the text in this paragraph and almost close your eyes so that you can no longer see detail, the stripes will become more apparent. You may find the text in this paragraph more difficult to read than on neighboring paragraphs, and that it becomes clearer when the lines above and below those you are reading are covered up. The text in this paragraph has been altered so that the spacing of lines and letters increases the effect of the stripes, as is described.

on the ratio of *x*-height to interline spacing. In (d) the estimates are based on the space-averaged reflectance of a rectangular section of the page, with width similar to that of the line and height less than the *x*-height of the letters (after Wilkins & Nimmo-Smith, 1987). Note that the parameter ranges for text are close to the peak of the functions for spatial frequency and duty cycle. The short vertical bars represent the values for the pattern shown in Fig. 20.2 when viewed from a distance of 0.4 m.

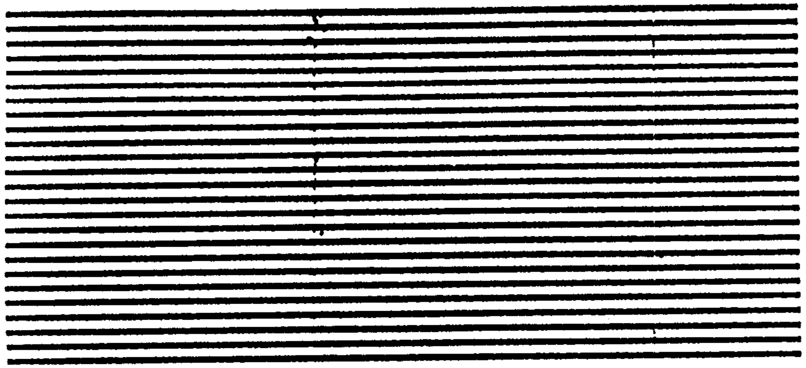


FIG. 20.2. An example of a pattern with characteristics likely to induce anomalous visual effects, discomfort, eye strain, headaches, and seizures. *Cover this pattern if you have epilepsy or migraine.*

Measuring the Stripes

The angular size of the grating-like pattern that text provides is determined by the size of the page (less the margins) and the distance from which the text is read. The reading distance and the interline spacing combine to determine the spatial frequency of the grating (the number of spatial cycles of the pattern in one degree of angle subtended at the eye). The ascenders and descenders of letters contribute little to the mean line density profile of a line of text (Wilkins & Nimmo-Smith, 1987). If, for the sake of simplicity they are ignored, the width of the stripes depends on the height of the central body of the letters, or x-*height*, and the *x*-height and interline spacing combine to provide an estimate of the ratio of bar width to bar separation (duty cycle) of the grating. (Note that in accordance with convention the duty cycle refers to the ratio of the width of the bright bar to the period of the grating, so that in the present context the duty cycle would be estimated from the difference between the interline spacing and the *x*-height expressed as a ratio of the interline spacing). The contrast of the grating is determined by the contrast of the ink on the paper and the width and spacing of the letter strokes and can be estimated from the space-averaged reflectance of a line of text, measured using simple photometric methods described by Wilkins and Nimmo-Smith (1987).

The horizontal bars in Fig. 20.1 show, for text printed on paper, the range of values of each pattern characteristic. These values were obtained in the study by Wilkins and Nimmo-Smith (1987), who asked volunteers to select books from their personal libraries, choosing those with "clear" and "less clear" text. The upper bars show the values for "less clear" text.

Extending the Measurements to Two Dimensions

Text is a two-dimensional pattern and the stripelike quality depends on the variation in character density within a line, and the extent to which such variations change from one line to another, as shown in Fig. 20.3.

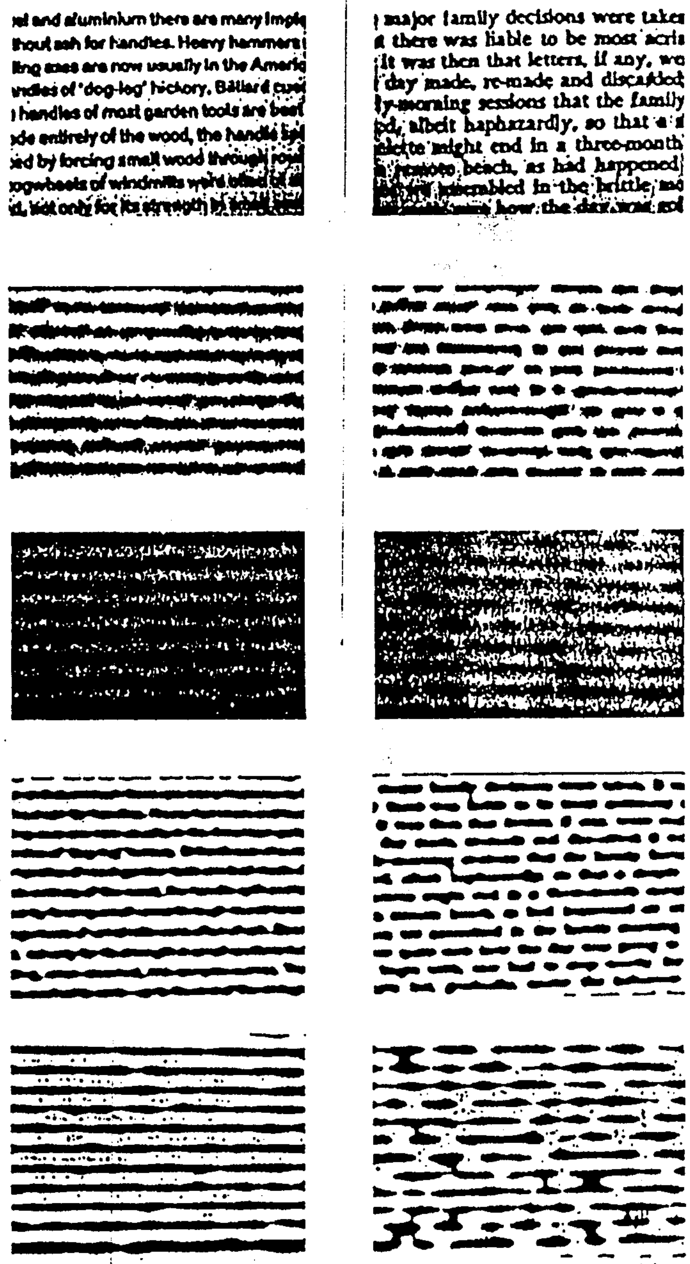
Consider the two samples of text shown in Fig. 20.3a. Both have similar line spacing and character spacing, but in the sample on the left the spaces between neighboring words are rather small.

Figure 20.1b shows that spatial frequencies in the range 1 to 8 cycles/degree are most likely to be harmful, at least for gratings with sharp edges, or more correctly, those with a square wave luminance profile. (The narrow spatial tuning of the function suggests that the higher frequency harmonics of the square wave gratings have only a small effect). Watt and Wilkins (unpublished observations) *filtered* samples of text so that only these midrange spatial frequencies were visible, see Fig. 20.3.

Figures 20.3b and 20.3c show the filtered images. In Fig. 20.3c the standard deviation of the filter is twice as large as in Fig. 20.3b, in other words more of the details (high spatial frequencies) have been removed. Note that the sample on the left is striped and remains so for a wide range of filter settings. In the sample of text on the left the words in a line easily blur together to form a stripe, whereas in the sample on the right the words tend to remain separate. As the standard deviation of the filter is increased, increasing the blur, the words in the sample on the right tend to coalesce with those on lines above and below as much as with those on the same line. In Figs. 20.3d and 20.3e the contrast of the filtered image has been exaggerated by setting all luminance values below the mean to black and those above to white. This serves to make the stripes more visible. Those readers who are susceptible to the effects of stripes may see illusions in the patterns on the left, but are less likely to do so in the patterns on the right, which have shorter line segments (see Fig. 20.1e). The text on the right may appear easier to read. For further examples of the effects of filtering see Watt, Bock, Thimbleby, and Wilkins (1990).

VISUAL AND CLINICAL EFFECTS OF THE "STRIPES" IN TEXT

In the previous section it has been shown that text is theoretically appropriate for the induction of illusions, eye strain, headaches, and seizures. In the following sections it is shown that text does indeed provoke these unfortunate effects in people who are visually sensitive: those who suffer photophobia or photosensitive epilepsy. The anomalous visual effects and eye strain are considered first. The evidence concerning seizures is discussed later.



Anomalous Visual Effects

Wilkins and Nimmo-Smith (1987) asked normal observers to look at a letter in the center of a page of text for 30s. Various anomalous visual effects were reported, covering the range of illusions commonly seen in striped patterns, and including a lattice of faint rhomboid shapes: an illusion sometimes reported after prolonged observation of a striped pattern. When text with a larger typeface was used, so that the spatial frequency of the grating was reduced, the size of the rhomboid lattice increased in just the same way as when the spatial frequency of a grating is reduced.

The 3rd paragraph on page 437 has been typeset in such a way as to render illusions likely. The height of the central body of the letters (*x*-height) has been reduced so that at a typical reading distance of 0.4 m it subtends 10 min of arc at the eye; the lines of text have been separated by spaces of similar height so that the duty cycle of the "grating" is close to 50%; the contrast of the lines has been increased by reducing the spaces between adjacent letters and words. The spatial characteristics formed by the text are close to those for which illusions are maximally likely. When you look at the paragraph in a strong light the lines may seem to shimmer. If you gaze at a letter in the center of the paragraph for a while, a faint rhomboid lattice may appear. Compare the illusions you see in this paragraph with those seen in the grating in Fig. 20.2. They will be less intense but are probably similar in nature.

Eye Strain

The samples of text shown in Fig. 20.3 were selected by a 41-year-old woman who was unable to read for more than about 20 min before she suffered disorientation (which she described as feeling "disconcerted"). She selected the sample on the left of Fig. 20.3a as being particularly difficult to read: The other sample gave her no problems.

The degree to which the lines of text form stripes when blurred in this way

FIG. 20.3. Two samples of printed text (a) before and (b-e) after spatial filtering. Both samples have similar line spacing and character spacing but the sample on the left has greater interword spacing. These samples were selected by a 41-year-old woman who suffered an inability to read for periods of more than about 20 min without feeling "disconcerted." She selected the sample on the left as being particularly difficult to read: The sample on the right have her no problems. In (b) the samples of text above have been filtered by convolution with a Mexican hat filter, which has the effect of removing the high spatial frequency components. In (c) the filter has a standard deviation twice that in (b). In (d) and (e) the filtered images in (b) and (c) respectively have been altered to make the "stripes" more apparent by setting all luminance values above the mean to white and all those below to black.

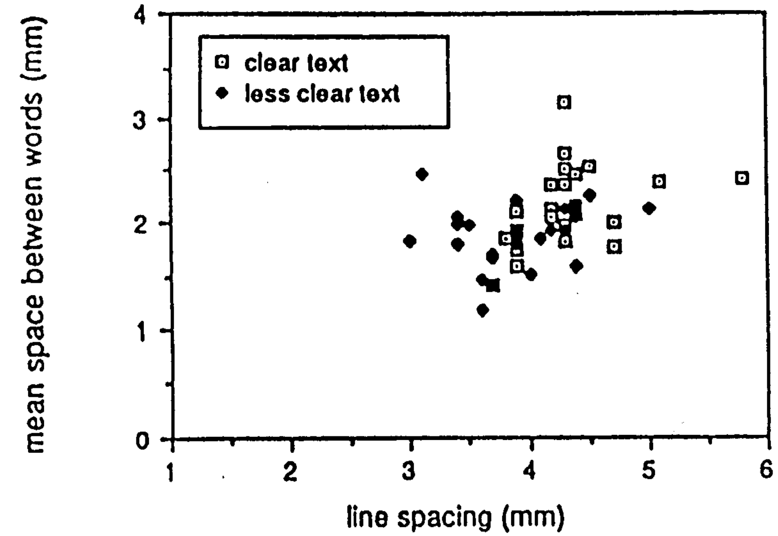


FIG. 20.4. The mean horizontal spacing between words plotted as a function of the vertical spacing between lines for samples of "clear" and "less clear" text selected by undergraduates. The samples of clear text tend to have a relatively large spacing between words and between lines (Wilkins, unpublished data).

depends in part on the relationship between the horizontal spacing between words and the vertical spacing between lines. Figure 20.4 shows these variables for samples of text selected as "clear" or "less clear" by undergraduates. As can be seen, "clear" text tends to have larger spaces between the words and between the lines.

PREVENTING EYE STRAIN, HEADACHES, AND SEIZURES

Reading Masks

In 1897 Prentice described a device that he christened the "Typoscope." It consisted simply of a card in which was cut a rectangular slot sufficient to reveal one line of text when the card was placed on the page of a book (see Mehr, 1969). The front surface of the card was matt black and was thought to reduce the effects of scattered light in patients with cataract and those with amblyopia (lazy eye) who wore lenses with strong magnification. The devise has been reinvented (and different versions patented) several times since then. Figure 20.5 provides a demonstration of the effects of a reading mask.

A demonstration of the effects of a reading mask. The text in this figure has been set in 12pt Times on a Macintosh computer using Aldus PageMaker (R) with default values for letter spacing, word spacing and line spacing. There are two passages of text, both identical, the lower one "covered" by a reading mask so as to reveal just three central lines. Compare the clarity of these lines in the top passage with their clarity in the the bottom passage. These are the central lines. Some people perceive these lines to have a greater clarity when the surrounding lines are masked. They report that the letters appear more contrasted, or that the lines appear further apart. You may perceive these improvements in clarity if you also see illusions of colour, shape or movement in the pattern of stripes shown in Figure 2. It is argued that the perceptual distortions you see in Figure 2 measure your susceptibility to stripes, that the successive lines of text resemble stripes, and that covering the unnecessary lines with a mask removes their deleterious effects, improving the clarity of the text that remains.

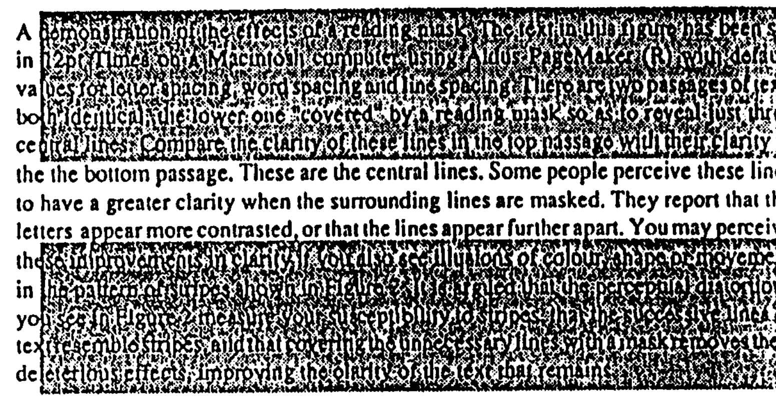


FIG. 20.5. Demonstration of the effects of a reading mask. For many readers, the text in the window appears clearer than the identical text in the unmasked paragraph above.

A reading mask such as that in Fig. 20.5 reduces the effects of the striped pattern by covering the stripes above and below those being read. In a study by Wilkins and Nimmo-Smith (1984) about 70% of normal observers noticed that the text in the "window" of such a mask appeared clearer. The observers who noticed the improvement in clarity tended to be those who reported many illusions in a pattern of striped lines (see Fig. 20.2). In the same study about one-third of a sample of people who suffered eye strain or headaches from reading reported that a reading mask was of sufficient benefit to be worth the nuisance of using it. No benefits were reported from "placebo" aids that did not cover the lines both above and below those being read. These studies helped with the design of an inexpensive reading aid now marketed as the "Cambridge Easy

TABLE 20.1
Incidence of epileptiform EEG activity (discharges/min) in three patients with photosensitive epilepsy and pattern sensitivity. The EEG was recorded whilst the patients were at rest and when they read a book with and without a mask that darkened and blurred the lines of text above and below those being read. (After Wilkins & Lindsay, 1985.)

	Patient MN	*Patient IJ*	*Patient RB*
At rest	0.70	0.00	Not tested
Reading without mask	1.48	2.67	8.52
Reading with mask	0.73	0.58	2.50

Reader" by Engineering and Design Plastics, 84 High Street, Cherry Hinton, Cambridge, UK. The device consists simply of two rectangular pieces of grey matt translucent plastic joined along one shorter edge by a magnetic slide.

Wilkins and Lindsay (1985) reported that the reading aid reduced liability to seizures in patients with epileptic pattern sensitivity. The electroencephalogram (EEG) was recorded during periods of rest, and also during randomly interleaved periods when the patient read a book in the usual way, and when the book was read using the reading mask. The mask darkened and blurred the lines of text above and below those being read, and was adjusted so that it left three lines unobscured. Table 20.1 shows the rate of epileptiform EEG discharges during the three conditions, for the two patients reported by Wilkins and Lindsay and for a third patient subsequently recorded by Darby (personal communication). The incidence of epileptiform discharges was significantly increased by reading, and significantly reduced by the use of the reading mask.

OVERLOAD OF THE VISUAL SYSTEM

The findings described so far have been interpreted from a theory of visual discomfort originally outlined by Wilkins et al. (1984). According to the theory, visual discomfort is a reflection of an "overload" of the visual system. The overload can be understood from several different but mutually consistent points of view. (a) The visual system is particularly sensitive to the stimuli that give rise to discomfort; (b) the stimuli that cause discomfort give a greater aggregate neurological response than others; (c) uncomfortable stimuli are difficult to process computationally.

Sensory Thresholds

Generally speaking, the patterns that evoke aversive effects are those for which sensory thresholds are low. In their classical work, Campbell and Robson (1968) demonstrated that, at low contrast, gratings can most readily be seen when their spatial frequency is close to 3 cycles/degree and when the bars of the grating have an even width and spacing (50% duty cycle). The low sensory thresholds suggest that, in some way, the physiological response to patterns with aversive characteristics is greater than that to other patterns.

Further evidence for a large physiological response is obtained at high contrasts. At high contrasts, aversive patterns interfere with perception, masking lower contrast stimuli. Ruddock and co-workers (Barbur & Ruddock, 1980; Holliday & Ruddock, 1983; Grounds, Holliday, & Ruddock, 1983) measured thresholds for the detection of a small dim circular target moving across a background modulated in space, in time, or in both. The background could be made to resemble the patterns that have aversive properties, and when it was, the moving target became more difficult to see. The background could also be made to flicker, and when the brightness and frequency were such as would provoke seizures in patients with photosensitive epilepsy, the target again became more difficult to see. The threshold functions showed subtle spatiotemporal interactions and had properties more complex than those implied by the limitations of Fig. 20.1, nevertheless they were generally consistent with the notion that the greater the physiological excitation induced by a visual stimulus, the greater its interference with the perception of other stimuli.

Aggregate Response

Aversive patterns tend to be those that give rise to high amplitude electrical responses from the brain (measured on the scalp as a visual evoked potential). For example, Plant, Zimmern, and Durden (1983) measured the amplitude of the evoked potential in response to (sinusoidal) gratings as a function of their spatial frequency and contrast. The functions were in broad agreement with those in Fig. 20.1.

As already mentioned, stimuli that are aversive are those that evoke seizure activity in patients with primary generalized epilepsy, suggesting that they can compromise cortical inhibitory processes. Recordings from single units and staining techniques have revealed that the visual cortex is organized into columns of cells responsive to bars and edges with similar orientation. A visual stimulus such as a grating is likely to result in patches of localized excitation of pyramidal neurons, those that respond to the grating orientation. Certain interneurons inhibit the firing of pyramidal neurons making them selectively sensitive to particular orientations (Sillito, 1979). The operation of these interneurons may be compromised if the local availability of inhibitory neurotransmitters is depleted by a strong localized excitation. This depletion may result in a spread of activation that gives rise to illusions. In patients whose cortex is hyperexcitable, the activation may spread further, inducing seizures (Meldrum & Wilkins, 1984; Wilkins et al., 1984). As already mentioned, aversive patterns are those that give rise to seizures in patients with photosensitive epilepsy.

Computational Vision

The brain's computational algorithms may analyze the visual scene at different spatial scales, the smaller scales responsible for analysis of the fine detail, and larger scales for the analysis of spatial position (Watt, 1988, 1991). Any repetitive image content may make it difficult to analyze spatial position. Consider the image of a piano keyboard. The white keys form a repetitive pattern. If only the white keys are visible, it is difficult to identify the position of any one particular key, such as middle C: The spatial scales that resolve the individual keys give an ambiguous output because one key is very much like another. The black keys differ from the white keys in that they are grouped, and although they have a repetitive structure, the structure differs at a variety of spatial scales. The structure of the finer scales that resolve the individual keys differs from the structure of the coarser scales that fail to resolve the keys but resolve instead only the gaps between the groups of two or three keys. In other words, the coarser scales can provide unambiguous information as to the position of each black key, perhaps in a hierarchy as suggested by Watt (1991, p. 181).

Aversive patterns have repetitive spatial content at all spatial scales: There is no grouping of the image that can facilitate the computation of position; this may make for greater computational complexity, and hence computational "overload."

CONTROL OF EYE MOVEMENTS

The notion of visual overload is undoubtedly simplistic, but it may have heuristic value. It is attractive when one considers not only pattern glare such as already discussed, but the ocular motor control that reading demands. When the eyes move from one point of regard to another they do so in a series of high velocity jerks known as *saccades*. Findlay (1982) and Ottes, van Gisbergen, and Eggermont (1984) asked observers to make an eye movement to one of two spots, both of which could easily be seen in the periphery of vision. When the spots were close together, the eyes landed at a point in space between the two spots, and then made a subsequent small corrective movement toward the appropriate target. It was difficult, if not impossible, for subjects to learn to move their eyes directly to one of the targets, even though they could distinguish them in peripheral vision before they began the eye movement. It was as if the part of the visual system controlling the first fast movement was unable to distinguish the two spots, but used instead some more global representation. Text in which the words coalesce to form stripes in the midrange spatial frequencies (e.g., the text on the left in Fig. 20.3) should place greater computational demands on the saccadic system, increasing the likelihood of overload, but see O'Regan (in press) for review.

TINTED GLASSES

Irlen Institute

Helen Irlen founded the Irlen Institute, which supplies tinted glasses for people with a sensitivity to light that she called "scotopic sensitivity." The term implies an undue sensitivity of the rod receptors and there is, as yet, little scientific evidence to justify its use. On the other hand, the clinical condition Irlen described overlaps with photophobia and involves many symptoms of visual discomfort. Opticians have long prescribed tinted glasses for those with photophobia, although with little to support the practice.

Wilkins and Neary (1991) examined 20 volunteers with a history of reading difficulty selected by the Irlen Institute as having benefited from the use of their tinted glasses. Fourteen were from different families. All had a history of reading problems and only one wore refractive correction. Many had migraine in the family. Nearly all had good acuity, contrast sensitivity, and stereopsis (in other words they were well able to see small detail and faint contours, and they were able use differences between the images in the two eyes to form a perception of depth). Ten had poor muscle balance (when the two eyes were not constrained to look at the same object, the axes of the eyes did not remain directed at the same point in space).

Vision with the tinted glasses was compared with vision using (a) dark (neutral density) glasses having the same (photopic) transmission and (b) untinted lenses that corrected any residual refractive error. In a few subjects acuity and muscle balance were significantly improved when the tints were worn. For the group as a whole there was a modest increase in the speed of visual search. The subjects were asked to report the illusions they saw in a pattern of stripes. Fewer illusions were reported when the tinted glasses were worn, irrespective of whether illusions of color were included.

Some of the beneficial effects could have been due to changes in motivation, although it is difficult to see how muscle balance could be affected in this way, given that subjects were unaware as to what the test was measuring and how the measurements were made.

This study, and other similar studies reviewed by Evans and Drasdo (1991), have the disadvantage that subjects are aware of the color of the lens placed in front of their eyes before they look through it and adapt to its color. It is difficult to obtain a genuine placebo. An "intuitive colorimeter" was designed to overcome some of these problems, and to provide a continuously variable source of colored light.

Intuitive Colorimeter

The colorimeter is a variant of the Burnham (1952) colorimeter. It enables hue and saturation to be varied independently and continuously, keeping luminance constant. It thus allows a wide range of color space to be explored thoroughly and quickly (Wilkins, Nimmo-Smith, & Jansons, 1992). For example, hue can be varied, keeping saturation and brightness more or less constant. The colorimeter has a wheel divided into three sectors, each sector transmitting light of a different color. A collimated cylindrical beam of white light passes through the wheel, and is colored as a result. The colored light is then mixed by multiple reflection and illuminates a page of print. When the wheel is concentric with the beam, the three sectors have equal proportion and, given the appropriate filters, the mixed light is white. The wheel is free to translate so that the beam can pass eccentrically through it. The filters then no longer have similar area. The mixture becomes progressively more saturated as eccentricity increases. The wheel is also free to rotate. This changes the hue. In terms of the CIE 1976 Uniform Chromaticity Scale Diagram, rotating the wheel moves the coordinates of the mixed light in a near-circular locus centered on white. Changing its eccentricity moves the coordinates along radii from white.

A series of children has been examined using the apparatus. For most children—but not all—there is a region of color space within which the perceptual distortions of text reportedly abate. When asked to vary the color until the distortions disappear, some children produce a very consistent setting. There appears to be a patch of color space within which the distortions disappear, but the location of that patch varies from one observer to another. For children with reading difficulties there is a tendency for the symptom-free area of color space to be within the left-hand half of the CIE 1976 Uniform Chromaticity Scale Diagram ($u' < 0.25$). Some children find no consistent area. They report a reduction in distortions but for colors that vary over time.

Those observers who consistently report a benefit from certain colors usually also find a region of color space in which the distortions become worse and text may become painful. The signs of discomfort are obvious: Observers wince or avert their gaze. The colors with which this discomfort occurs are usually complementary to those with which distortions abate. When adults with migraine are asked to mix colors that make text *un*comfortable they tend to choose shades of red (Chronicle & Wilkins, 1991). When using the colorimeter, these colors are rarely chosen by children who have reading disorders and report perceptual distortions. As already mentioned, many of these children have parents with migraine.

Subjective Precision Tinting

A set of tinted trial lenses has been developed using plastic (CR39 resin) lenses dyed with progressively increasing deposition of each of seven chemically stable dyes, avoiding composite dyes where possible. The dyes chosen have the following appearance: rose, orange, yellow, green, turquoise, blue, and purple. They have CIE 1976 hue angles about 50 degrees apart. There are five levels of deposition of each dye. The levels range from a very light tint to a very strong tint, the dye deposition doubling from one level to the next. The set of trial lenses has two trial lenses at each level (one for each eye). Thirty-one ($2^5 - 1$) levels of dye deposition can be obtained for each dye by superimposing the five trial lenses. To obtain a given color of tint, trial lenses from two dyes with similar hue angle are combined. To obtain orangey red, for example, orange and rose trial lenses would be combined. A total of 961 (31 × 31) combinations of orange and rose are possible. There are 7 combinations of neighboring colors: rose with orange, orange with yellow, yellow with green, and so forth making 7 × 961 = 6,727 combinations of dyes with similar hue. Any desired color within a large gamut can therefore be very closely approximated using only two dyes at a time.

Individuals usually report a reduction in discomfort and distortion when viewing a natural scene through the combination of lenses that matches the visible appearance of the colorimeter setting. When the setting has a strong saturation, however, lenses with the same hue angle but lower saturation are sometimes preferred, perhaps because these interfere less with color constancy and leave white surfaces remaining white in appearance.

In open trials, patients with reading disorders, eye strain, headaches, or photosensitive epilepsy have reported a reduction of symptoms when wearing glasses tinted using the aforementioned techniques (Maclachlan, Yale, & Wilkins, in press). Double-blind placebo-controlled clinical trials are now under way.

Possible Mechanisms

There are many alternative explanations for any beneficial effects of tinted glasses and more than one mechanism may be involved.

Explanations can be divided into those that are peripheral and those that are central. The peripheral explanations might involve (a) chromatic aberration contributing constructively or destructively to the control of accommodation; (b) the role of rods in controlling pupil size at photopic luminance levels (Berman, Fein, Jewett, Saika, & Ashford, 1992), with secondary effects on accommodation and vergence; or even (c) a contribution from fluorescence of intraocular structures. Possible central mechanisms include (a) the reduction of pattern glare (Wilkins & Neary, 1991) or (b) the restoration of optimal signal transmission over selectively impaired pathways. In the present context, the last two explanations merit further consideration.

The signals from the cones are thought to be combined early in visual processing so as to give a luminance signal (a combination of signals from the three cone types) and two color difference signals, one red-green, and the other yellow-blue, the latter obtained by an opposition of a signal from the short wavelength cones with signals from the other two types. Buchsbaum and Gottschalk (1983) showed that these three signals are precisely what might be anticipated if the information transmission were optimized. The signals from the cones are redundant (their spectral sensitivities overlap), and by summing the cone outputs to give a luminance signal, and by subtracting their outputs to derive two color difference signals, information can be transmitted more efficiently.

Suppose that the visual pathways are impaired by disease in such a way as to change the relative information capacity of the channels carrying the luminance and color difference signals. It follows from the mathematics outlined by Buchsbaum and Gottschalk that the information transmission could be optimized for the damaged system by changing the spectral composition of light captured by the cones. In other words, there may be some colored lens that will affect the signaling from the three cone types in such a way as to optimize the signal transmission over the damaged pathways. The color would need to be sufficiently saturated to overcome the adaptation that would undoubtedly occur.

There is evidence that the visual pathways may indeed be affected. In children with specific reading disability there exists a selective deficit on psychophysical tasks that measure transient system function, but not on those that measure the sustained system (see Lovegrove & Williams, chap. 14). The transient system is thought to signal luminance rather than information about color differences. The selective deficits, therefore, suggest an imbalance of function between achromatic and chromatic channels, although it would be inappropriate to equate the achromatic channel of Buchsbaum and Gottschalk with magnocellular pathways and transient system function (see Breitmeyer, chap. 5).

People with migraine show deficits in contrast sensitivity that are greater the longer the duration of the disease (Khalil, 1991). These deficits suggest that repeated attacks of migraine may damage the visual system. Since migraine affects the circulation of blood in the brain, the visual deficits may result from a transient insufficiency of blood supply. This might be expected to have a greater effect on cells with a high metabolic turnover. There are blob-like regions of layers 2 and 3 of the primary visual cortex of monkeys that are labeled preferentially with radioactive 2-deoxyglucose because of their heightened metabolic activity (Horton & Hubel, 1981; Humphrey & Hendrickson, 1983). These blobs are also revealed by cytochrome oxidase staining. They receive inputs from both magnocellular and parvocellular pathways. Within the blobs the cells show poor orientation tuning but a color opponency (Livingstone & Hubel, 1988). The surrounding inter-blob cells show no color opponency. The blob cells project to striped areas of V2 that are also concerned with the processing of color. Interference with the activity of cells in the blobs and stripes might be expected to affect the processing of color, given that cells in the blobs are color-opponent, whereas those in the surrounding tissue are not. Perhaps this is one mechanism for the selective color preferences shown by people with migraine (Chronicle & Wilkins, 1991).

An impairment of channel function may place a greater computational burden on the signal processing capabilities of the visual cortex, contributing in some quite nonspecific way to a processing overload similar to that described in the

previous section. This may give rise to symptoms of visual discomfort by a breakdown of intracortical inhibitory mechanisms similar to those already hypothesized for the visual induction of migraine headache by Wilkins et al (1984). Interpretations of this kind are admittedly highly speculative and far from complete, but they may in time provide an explanation for the reduction of perceptual distortions and associated visual discomfort that is sometimes reportedly brought about by the wearing of tinted glasses.

If children find text aversive, and their visual orientation is compromised by anomalous visual effects, then the process of learning to read may be made yet more difficult. Any relationship between visual discomfort and visual dyslexia may not, however, be causal but due to shared brain mechanisms. The argument for a causal link is weakened by the fact that the text used in early readers differs from adult text in having large letters and few words, often on a single line. It is therefore less likely to give rise to anomalous visual effects and to discomfort. Anecdotally, however, the visual problems experienced by dyslexic children often arise as they progress to adult text. And sometimes even children's text is far from ideal. The text may be printed in a bold typeface, and the letters and words closely spaced. The appropriate grouping of the image then becomes difficult, particularly for an observer unfamiliar with letter shapes. Children with dyslexia can be more susceptible than others to the effects of crowding (Atkinson, 1991). Willows (1974) showed that poor readers read single-spaced text more slowly and less accurately than double-spaced, regardless of content. No such differences emerged for good readers.

TEMPORAL FACTORS

So far, we have considered only the spatial characteristics of text, although the visual stimulus it provides can vary in both space and time. The page is often illuminated by fluorescent light, or presented on the surface of a visual display terminal and under these conditions the luminance is varying continuously. Fluorescent light is generated by a gas discharge that occurs twice with each cycle of the AC electricity supply. On a visual display terminal the text is lit once each time the cathode ray refreshes the screen. The resulting pulsations of light are usually too rapid to be seen as flicker but they affect the visual system nevertheless. As reviewed by Kennedy (chap. 10), Eysel and Burandt (1984) recorded from the lateral geniculate nucleus of the cat and showed that under fluorescent lighting the cells fired more strongly than under daylight or incandescent light, and they fired at a certain interval after each light pulsation. Berman, Greenhouse, Bailey, Clear, and Rausch (1991) recorded electrical signals from the human retina (electroretinogram) in response to the pulsation from fluorescent lighting and Wilkins (1986) and Neary and Wilkins (1989) demonstrated small effects of the pulsation on the control of saccades across text and other patterns.

Wilkins, Nimmo-Smith, Slater, and Bedocs (1989) monitored the incidence of eye strain and headaches in office workers when the rooms were lit with conventional fluorescent lighting or with a new type, outwardly identical, from which the pulsations were electronically removed (i.e., lighting with electronic high frequency ballast). The incidence of eye strain and headache was halved under the new lighting.

The pulsation from fluorescent lighting depends on a coating of phosphor on the inner surface of the lamp. The phosphor fluoresces, converting the ultraviolet energy from the gas discharge into visible light. The most common (and cheapest) lamps use a halophosphate coating. This fluoresces at the long wavelength (red) end of the visible spectrum and exhibits phosphorescence, holding much of the long wavelength light from one discharge to the next (Wilkins & Clark, 1990). This means that most of the light pulsation is at the short wavelength end of the spectrum. Spectacles that reduce short wavelength light (e.g., amber, yellow, or rose tints) can therefore reduce the overall pulsation from fluorescent lighting. Wilkins and Wilkinson (1991) designed an ophthalmic tint (now commercially available) that reduces the pulsation of light from halophosphate lamps. In a double-blind study it has been shown to reduce migraine in children (Good, Taylor, & Mortimer, 1991). People with migraine often complain of fluorescent lighting: They can show a high amplitude steady-state evoked potential in response to intermittent light (Golla & Winter, 1959; Lehtonen, 1974; Jonkman & Lelieveld, 1981; Marsters, Good, & Mortimer, 1988), particularly at high frequencies (Brundrett, 1974).

On a visual display terminal with a cathode ray tube the screen is usually scanned by a spot of light that zig-zags down the screen varying in brightness so as to create the image. The phosphor on the screen usually loses most of its light from one scan to the next, so the picture is lit only very briefly, though at high frequency. When the eyes make a saccade, for example, from the left of the screen to the right, the eyes move extremely rapidly so that the image appears on the screen only once or maybe twice during the flight of the eye. The top part of the image is drawn earlier and therefore to the left of the image relative to the bottom of the screen. The visual image painted during the flight of the eye is therefore brief and distorted and can sometimes evade the saccadic suppression that normally makes it difficult to see the retinal image created whilst the eye is in flight. The intra-saccadic stimulation appears as a momentary image that can interfere with the perceptual stability of the visual world as the eyes come to rest. The small corrective saccades that normally follow the larger saccades are increased in number, perhaps as a result (Neary & Wilkins, 1989). As reviewed elsewhere in this volume, Kennedy and Murray (1991) showed that for typists (who read with attention to orthography and who complain of visual discomfort) there is a two-fold increase in the number of corrective saccades during reading when the display is lit intermittently, even when it is lit 100 times per second. The increase occurs with displays that scan in a raster and also with those that have no directional component to the flicker (Kennedy, personal communication).

IMPROVING TEXT WITHOUT INCREASING COSTS

In the first three sections it has been shown that the pattern from text can provoke illusions, headaches, eye strain, and even seizures in those who are susceptible. The pattern can be reduced by covering the lines with a reading mask, but according to the theory outlined by Wilkins et al. (1984), the mask should not be necessary: It should be possible to reduce the effects of the pattern in other ways. One obvious way is to increase the spacing between the lines. As can be seen from Fig. 20.1, this has two effects: It increases the duty cycle and decreases the spatial frequency of the "grating." Both changes are in a direction appropriate for a reduction in the adverse effects of the pattern. The clarity of text has long been known to depend on the spacing of the lines (see, for example, Tinker, 1963), and this might be one reason why.

Increasing the spacing of the lines is likely to increase the costs of printing, because these costs depend partly on the amount of paper used. Can line spacing be increased without increasing costs?

The amount of paper used depends in part on the average area of paper occupied by a character. The average area is the product of the separation of the lines and the mean horizontal distance from one character to the next. Wilkins and Nimmo-Smith (1987) asked volunteers to select books from their own libraries that had "clear" or "less clear" print. They showed that subjects' judgments of clarity were strongly associated with the spacing between the lines, but not so strongly associated with the area of paper used per character. Interline spacing accounted for 33.7% and 37.7% of the variance associated with judgments of clarity in the two studies. The average area occupied by a letter explained 6.6% and 30.3% respectively. In other words there were books with text judged as "clear" that cost no more to print than books with text judged as "less clear." Evidently printing convention does not specify the spatial characteristics of text appropriately for the maximization of clarity at a given cost.

It should therefore be possible to improve the clarity of text without making it more expensive. One way of doing so might be to increase the spacing between lines while reducing the average spacing between characters. Both these changes would only need to be extremely slight, and both the line spacing and character spacing could remain within the limits set by conventional typographic practice. It would be important to ensure that the decrease in the average horizontal spacing between characters occurred within words, and maintained an appropriate relationship between horizontal word spacing and vertical line spacing.

CONCLUSION

The theory of visual discomfort outlined here explains why small changes in the layout of the words on a page can have large effects on the clarity of text. The theory provides some guidance as to how the clarity of text might be improved without making it more expensive. The theory provides an explanation for the visual discomfort with which the use of cathode ray tube displays has been associated. It links the anomalous visual effects reported in text by some children with visual dyslexia to those reported in response to more stressful stimuli by normal observers (particularly those with migraine). The theory suggests possible physiological mechanisms in common. It also suggests ways in which the visual stimulation can be altered so as to make the anomalous effects less likely. Finally, the theory provides one explanation (among many) for the beneficial effects of tinted glasses.

According to the theory, we need to think of the visual problems involved in reading as arising from a combination of factors, including those relating to the spatial and temporal characteristics of the stimulus, and those relating to the reader's difficulties with visual processing. The former we can do something about, for the benefit not only of those with reading difficulties, but of a broad cross-section of the population as well. The latter may ultimately be traceable to brain mechanisms in posterior areas that sustain the links between visual and linguistic information. It may be these mechanisms that are jointly responsible for anomalous visual effects and language difficulties.

ACKNOWLEDGMENT

This chapter is a revision of a chapter published in J. F. Stein (Ed.), *Vision and Visual Dyslexia: Vision and Visual Dysfunction* (Vol. 13). London: MacMillan Press.

REFERENCES

Atkinson, J. (1991). Review of human visual development: crowding and dyslexia. In J. F. Stein (Ed.), *Vision and visual dyslexia: Vision and visual dysfunction* (Vol 13., pp. 44–57). London: MacMillan.

Barbur, J. L., Ruddock, K. H. (1980). Spatial characteristics of movement detection mechanisms in human vision: I. Achromatic vision. *Biological Cybernetics, 37*, 77–92.

Berman, S. M., Fein, G., Jewett, D. L., Saika, G., & Ashford, F. (1992). Spectral determinants of steady-state pupil size with full field of view. Manuscript in preparation.

Berman, S. M., Greenhouse, D. S., Bailey, I. L., Clear, R. D., & Raasch, T. W. (1991). Human electroretinogram responses to video displays, fluorescent lighting, and other high frequency sources. *Optometry and Vision Science, 68*(8), 645–662.

Burnham, R. W. (1952). A colorimeter for research in colour perception. *American Journal of Psychology, 65*, 603–608.

Buchsbaum, G., & Gottschalk, A. (1983). Trichromacy, opponent colours coding and optimum colour information transmission in the retina. *Proceedings of the Royal Society of London, B 220*, 89–113.

Brundrett, G. W. (1974). Human sensitivity to flicker. *Lighting Research and Technology, 6*(3), 127–143.

Campbell, F. W., & Robson, J. G. (1986). Application of Fourier analysis to the visibility of gratings. *Journal of Physiology (London), 197*, 551–566.

Chronicle, E. P., & Wilkins, A. J. (1991, October). Colour and visual discomfort in migraineurs. *The Lancet, 338*, 890.

Evans, B.J.W., & Drasdo, N. (1991). Tinted lenses and related therapies for learning disabilities—a review. *Ophthalmic and Physiological Optics, 11*, 206–217.

Eysel, U. T., Burandt, U. (1984). Fluorescent tube light evokes flicker responses in visual neurons. *Vision Research, 24*, 943–948.

Findlay, J. M. (1982). Global processing for saccadic eye movements. *Vision Research, 22*, 1033–1045.

Golla, F. L., & Winter, A. L. (1959). Analysis of cerebral responses to flicker in patients complaining of episodic headache. *Electroencephalography and Clinical Neurophysiology, 11*, 539–549.

Good, P. A., Taylor, R. H., & Mortimer, M. J. (1991). The use of tinted glasses in childhood migraine. *Headache, 31*, 533–536.

Grounds, A. R., Holliday, I. E., & Ruddock, K. H. (1983). Two spatio-temporal filters in human vision: II. Selective modification in amblyopia, albinism and hemianopia. *Biological Cybernetics, 47*, 191–201.

Holliday, I. E., & Ruddock, K. H. (1983). Two spatio-temporal filters in human vision: I. Temporal and spatial frequency response characteristics. *Biological Cybernetics, 47*, 173–190.

Horton, J. C., & Hubel, D. H. (1981). A regular patchy distribution of cytochrome-oxidase staining in primary visual cortex of the macaque monkey. *Nature, 292*, 762–764.

Humphrey, A. L., & Hendrickson, A. E. (1983). Background and stimulus-induced patterns of high metabolic activity in the visual cortex (area 17) of the squirrel and macaque monkey. *Journal of Neuroscience, 3*, 345–358.

Jonkman, E. J., & Lelieveld, M. H. (1981). EEG computer analysis in patients with migraine. *Electroencephalography and Clinical Neurophysiology, 52*, 652–655.

Kennedy, A., & Murray, W. S. (1991). The effects of flicker on eye movement control. *Quarterly Journal of Experimental Psychology, 43A*(1), 79–99.

Khalil, N. (1991). *Investigations of visual function in migraine by visual evoked potentials and visual psychophysical tests.* Unpublished doctoral dissertation, University of London.

Lehtonen, J. (1974). Visual evoked cortical potentials for single flashes and flickering light in migraine. *Headache, 14*, 1–12.

Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology and perception. *Science, 240*, 740–749.

Maclachlan, A., Yale, S., & Wilkins, A. (in press). Open trial of subjective precision tinting: A follow-up of 55 patients. *Ophthalmic and Physiological Optics.*

Marcus, D. A., & Soso, M. J. (1989). Migraine and stripe-induced discomfort. *Archives of Neurology, 46*, 1129–1132.

Marsters, J. B., Good, P. A., & Mortimer, M. J. (1988). A diagnostic test for migraine using the visual evoked potential. *Headache, 28*, 526–530.

Mehr, E. B. (1969). The typoscope by Charles Prentice. *American Journal of Optometry, 46*, 885–887.

Meldrum, B. S., & Wilkins, A. J. (1984). Photosensitive epilepsy in man and the baboon: Integration of pharmacological and psychophysical evidence. In P. A. Schwartzkroin & H. V. Wheal (Eds.), *Electrophysiology of Epilepsy* (pp. 51–77). Academic Press: London.

Neary, C., & Wilkins, A. J. (1989). Effects of phosphor persistence on perception and the control of eye movements. *Perception, 18*, 257–264.

O'Regan, K. (in press). Eye movements and reading. In E. Knowles (Ed.), *Eye movements and their role in visual and cognitive processes* (Vol. 4). London: Elsevier.

Ottes, F. P., van Gisbergen, J.A.M., & Eggermont, J. J. (1984). Metrics of saccadic responses to double stimuli: Two different modes. *Vision Research, 24*, 1169–1179.

Plant, G. T., Zimmern, R. L., & Durden, K. (1983). Transient visually evoked potentials to the pattern reversal and onset of sinusoidal gratings. *Electroencephalography and Clinical Neurophysiology, 56*, 147–158.

Sillito, A. M. (1979). Inhibitory mechanisms influencing complex cell orientation selectivity and their modification at high resting discharge levels. *Journal of Physiology (London), 289*, 33–53.

Tinker, M. A. (1963). *Legibility of print*. Ames, IA: Iowa State University Press.

Watt, R. J. (1988). *Visual processing: Computational, psychophysical and cognitive research*. London: Lawrence Erlbaum Associates.

Watt, R. J. (1991). *Understanding vision*. Academic Press: London.

Watt, R. J., Bock, J., Thimbleby, H., & Wilkins, A. J. (1990). Visible aspects of text. British Telecom internal report: *Applying Visual Psychophysics to User Interface Design*. Proceedings of conference at Lavenham. Martlesham: British Telecom.

Wilkins, A. J. (1986). Intermittent illumination from fluorescent lighting and visual display units affects movements of the eyes across text. *Human Factors, 28*(1), 75–81.

Wilkins, A. J., Binnie, C. D., Darby, C. E., & Kasteleijn-Nolst Trenité, D. (1990). Inferences regarding the visual precipitation of seizures, eye-strain and headaches. In M. Avoli, P. Gloor, G. Kostopoulos, & R. Naquet (Ed.), *Generalised epilepsy* (pp. 314–326). Boston: Birkhauser.

Wilkins, A. J., & Clark, C. (1990). Modulation of light from fluorescent lamps. *Lighting Research and Technology, 22*(2), 103–109.

Wilkins, A. J., & Lindsay, J. (1985). Common forms of reflex epilepsy: Physiological mechanisms and techniques for treatment. In T. A. Pedley and B. S. Meldrum (Eds.), *Recent advances in epilepsy* (Vol. 2, pp. 239–271). Edinburgh: Churchill Livingstone.

Wilkins, A. J., & Neary, C. (1991). Some visual optometric and perceptual effects of coloured glasses. *Ophthalmic and Physiological Optics, 11*, 163–171.

Wilkins, A. J., & Nimmo-Smith, I. (1984). On the reduction of eye-strain when reading. *Ophthalmic and Physiological Optics, 4*(1), 53–59.

Wilkins, A. J., & Nimmo-Smith, I. (1987). The clarity and comfort of printed text. *Ergonomics, 30*(12), 1705–1720.

Wilkins, A. J., Nimmo-Smith, I., & Jansons, J. (1992). A colorimeter for the intuitive manipulation of hue and saturation, and its application in the study of perceptual distortion. *Ophthalmic and Physiological Optics.*

Wilkins, A. J., Nimmo-Smith, I., Slater, A. I., & Bedocs, L. (1989). Fluorescent lighting, headaches and eye-strain. *Lighting Research and Technology, 21*(1), 11–18.

Wilkins, A. J., Nimmo-Smith, I., Tait, A., McManus, C., Della Sala, S., Tilley, A., Arnold, K., Barrie, M., & Scott, S. (1984). A neurological basis for visual discomfort. *Brain, 107*, 989–1017.

Wilkins, A. J., & Wilkinson, P. (1991). A tint to reduce eye-strain from fluorescent lighting? Preliminary observations. *Ophthalmic and Physiological Optics, 11*, 172–175.

Willows, D. M. (1974). Reading between the lines: Selective attention in good and poor readers. *Child Development, 45*, 408–415.