Reading With Rods: The Superiority of Central Vision for Rapid Reading

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Purpose. To investigate why the central portion of the visual field is normally the optimal region for pattern recognition.

Method. The study uses a reading paradigm in which the text can only be seen with rod vision. Reading rates were measured as the text was positioned in different parts of the visual field.

Result. Observers obtained the highest reading rates when rod-generated images were viewed at or near the fovea.

Conclusion. The superiority of the central field for reading is neither linked to some exclusive property of the cone visual system, nor is it primarily related to visual sensitivity or spatiotemporal resolution. The superiority of reading in the central field is associated with some aspect of the visual cortical processes. Invest Ophthalmol Vis Sci 1993;34:2341–2347.

In humans, the ability to recognize complex spatial patterns rapidly is associated with vision in one portion of the visual field, the region immediately surrounding the fovea.[1,2] When asked to identify an object or read a word, observers typically move their eyes so as to bring the image on or near the central portion of their visual field. There seem to be few everyday circumstances in which normal observers will improve their ability to recognize an object by positioning its image in their peripheral visual field.

Why pattern recognition in humans is superior in the central portion rather than in the peripheral or across the entire visual field is not entirely understood. Neurophysiologic considerations suggest that pattern recognition may be linked to some aspect of the cone (photopic) visual system, to visual cortical processes, or to both. The cone visual system is implicated because of its high spatial resolution,[3] contrast sensitivity,[4] and color discrimination[5] in the central portions of the visual field. Cortical processes are implicated because there is a disproportionately greater volume of cortex devoted to the central rather than peripheral portions of the visual field.[6] The volume of cortex may correlate with the amount of processing performed on different portions of the visual image.

Little, if any, work has been done to study the role of cone vision in pattern recognition. In the course of our investigation into how people read with their rod vision,[7] we developed a method for testing whether cone vision is essential to the superiority of the central visual field. The method was to determine the optimal retinal location for pattern recognition when vision is mediated exclusively by the rod visual system. If the optimal location depends on the photoreceptor (rod or cone) system, we would expect the location to

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correspond to areas of the visual field where the photoreceptors would support the highest spatiotemporal acuity and contrast sensitivity. The location would lie near the fovea when vision is mediated by cones, but would lie eccentric to the fovea (though not necessarily localized to one specific area) when vision is mediated by rods.[8] If, however, the limiting physiologic factor depends little on whether the images are processed by rods or cones then the optimal field location would be the same regardless of whether vision is mediated exclusively by rods, cones, or by both rods and cones. The optimal field location would always lie near the observer's fovea.

This article reports our findings. The pattern recognition task chosen for our study was reading, a task that requires the observer to rapidly identify complex spatial patterns. Reading has been shown to be amenable to the study of either rod or cone vision.[7,9]

METHODS

The subjects and apparatus used in the investigation were the same as those used in our previous study on reading with the rod visual system.[7] Subjects had vision correctable to 20/20 or better and normal night vision. The four male subjects were between the ages of 26 and 41 yr, and the female subject was aged 24 yr. One male subject was deuteranomolous. In conducting the research, the tenets of the Declaration of Helsinki were followed and informed consent from participants was obtained after the nature of the procedures had been fully explained to them. Additionally, institutional human experimentation committee approval was obtained before the start of the investigation.

Subjects viewed the stimulus screen (Fig. 1) through a +8 diopter lens and a series of chromatic (either a red Kodak Wratten #26 [Eastman Kodak, Rochester, NY]; or a blue Edmund Scientific #866 [Barrington, NJ]) and neutral density (2.94) filters. To vary the eccentricity of the text, different fixation points were used. In the 0° condition, subjects were instructed to fixate between the diodes designated by +5° and −5°. For other viewing conditions, subjects fixated on only one diode designated by +5°, +10°, +15°, or +20°.

In an experimental trial, each observer was shown text consisting of a string of ten four-letter words randomly selected from a list of more than 300 words most commonly used by college students.[10] The sequence of words was rarely, if ever, repeated in a session. The height of the characters in each word subtended about 3.2° of visual angle. Words were flashed serially onto the screen rather than scrolled from right to left. Our rationale for this was similar to that of Turano and Rubin.[11] Flash presentation removes an observer's need to make saccadic eye movements during reading thereby eliminating eye movements as a possible explanation for performance differences. (However, it is also important to realize that in everyday reading, rod/cone or central/peripheral field inputs might differentially affect eye-movement control and, in turn, reading performance. If such effects occur, our flash presentation method would not detect them.) Sessions ran about 3 hr with each trial lasting less than 1 min.

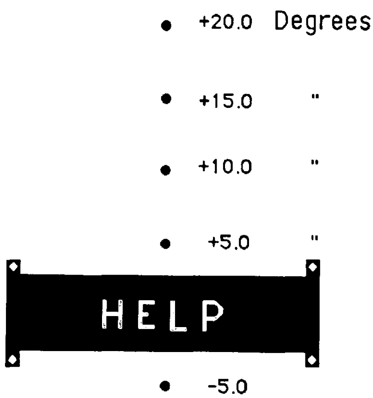

FIGURE 1. Relative locations of the fixation points in the stimulus display. The numbers indicate the retinal location of the text relative to the fixation point. For most conditions, only one fixation point was displayed. The exception was for the 0° eccentricity condition when the subject was instructed to fixate between the +5 and −5° fixation points.

Our method for isolating rod- and cone-reading performance made use of two well-known differences in the properties of rod and cone vision: First, that the recovery of sensitivity in the dark after exposure to a strong bleaching light is faster for cones than for rods; second, that the absolute sensitivity to short wavelength lights is greater for rods than cones. The absolute sensitivity to very long wavelength lights is greater for cones than for rods.[12]

The thresholds for detecting the text were measured as a function of time in the dark after the termination of a bleaching light (Fig. 2). The resulting dark-adaptation curve shows the familiar cone and rod branches. The dashed curve shows our extrapolation of the rod threshold branch above the cone plateau. We infer that reading is mediated exclusively by cones during the cone plateau period of the dark-adaptation curve (ie, between 6 and 16 min in the dark) when the luminance of text seen through a red (Wratten #26) filter is no higher than 1.0 log unit above the cone detection threshold. Reading is mediated exclusively by rods after the eye is completely dark adapted and when the luminance of the text seen through a blue filter (Edmund Scientific #866) is no greater than 1.5 log units above rod threshold.

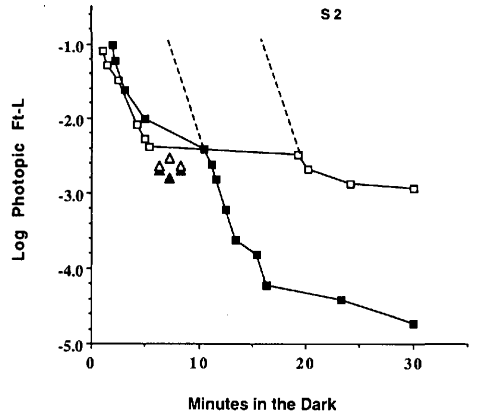

FIGURE 2. The dark adaptation curve for a representative subject. The open symbols show the curve obtained when the text was covered with the red filter; the closed symbols show the curve obtained with the blue filter. Thresholds were determined either by estimating the time in the dark at which text of constant luminance became just visible (*squares*) or the minimum luminance for detection at a constant time interval (*triangles*). The time scale is min in the dark after a 3-min exposure to a bleaching field.

Two psychophysical methods were used to measure reading performance. First, subjects read the words aloud into a tape recorder and the experimenter recorded the number of errors. The procedure was repeated at different word presentation rates for each stimulus condition. The method yielded information about both reading accuracy and reading speed.

Because the first method was so time-consuming, a faster method was used to compare the reading performance of rods and cones within the limited time period during which cone reading could be isolated. In our second method, subjects used a handheld controller to adjust the word presentation rate until they found the maximum rate at which they could identify words without making two consecutive word-identification errors. The reliability of this method was reported in an ancillary experiment.[13]

RESULTS

Reading as a Function of the Retinal Location of the Text

Reading was tested with the text centered at 0°, 5°, 10°, 15°, and 20° below the fixation dot. The luminance of the text was fixed at −1.56 log scotopic foot-Lamberts (0.42 log scotopic Trolands or −1.025 log scotopic candela/m²), which was about 0.75 log units below the cone threshold. Figure 3 shows that reading rate, computed as the product of the text presentation rate and the percentage of words read correctly,[2,9] varies as a function of the word presentation rate regardless of eccentricity. The reading rate achieved, however, generally was greater for the 0° and 5° eccentricity conditions than for any other condition.

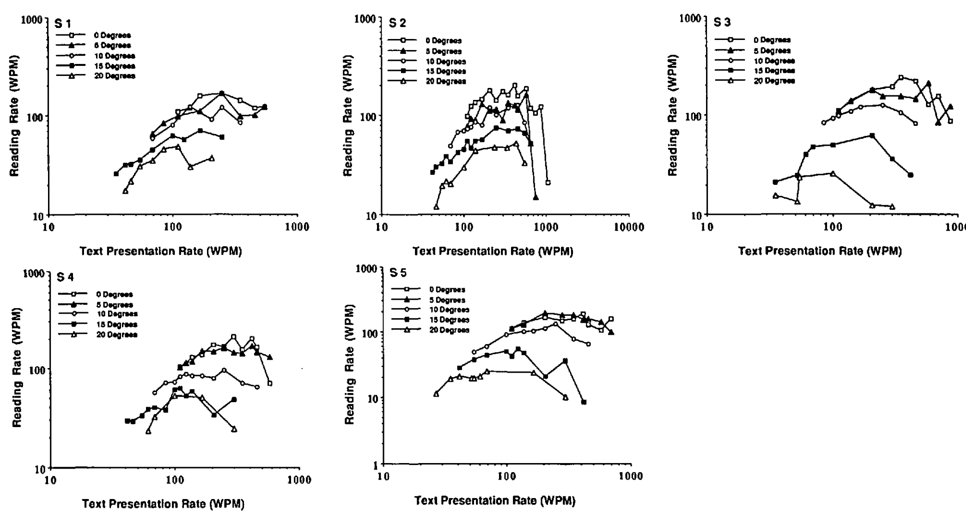

FIGURE 3. Reading rate as a function of the text presentation rate at five eccentric viewing conditions. The locations of the text in the visual field are shown at the top left of each plot.

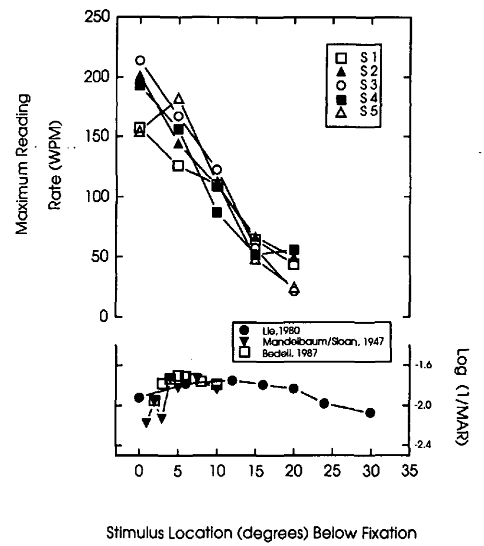

FIGURE 4. (*Top panel*) shows the maximum reading rates as a function of the text location in the visual field. The maximum rates were estimated from the data shown in Figure 3. (*Bottom panel*) illustrates how scotopic visual acuity[16-18] varies across similar regions of the visual field. The data from Mandelbaum and Sloan[16] and from Bedell[18] were shifted vertically by +0.53 and +0.64, respectively.

A method to estimate the maximum reading rate that minimized the influence of experimenter bias was chosen. The maxima were determined by first fitting a second-order polynomial function of the form $Y = A + BX + CX^2$ to each set of data. The maximum reading rate was the solution to the first derivative of the best fitting function. The results (Fig. 4) show that four of the observers read fastest when the words were near the 0° location. The fifth observer read best at 5°. The reading rate for all observers, however, fell off as the words were presented at more eccentric locations. A repeated measures analysis of variance indicated a significant main effect of eccentricity: $F(4,16) = 53.65$, $P < 0.05$. (Note: The fit of the second-order function to the data was generally good. The two exceptions were the fit for S3 at 5° and for S5 at 0°. The R^2 values were 0.36 and 0.29, respectively. The R^2 values for all other conditions were typically in the range of 0.70–0.99.)

Figure 5 shows the relationship between reading accuracy, that is, the percentage of words read correctly, and the location of the text in the visual field. For the 0°–10° locations, observers were able to read the text with 90%–100% accuracy provided that the text was presented slowly. The same appears true for four of the five observers for the 15° location. Only when text was presented at the farthest distance from fixation do the results show a qualitative change. At 20° the highest reading accuracy achievable was only between 40 and 60%. In addition, accuracy gener-

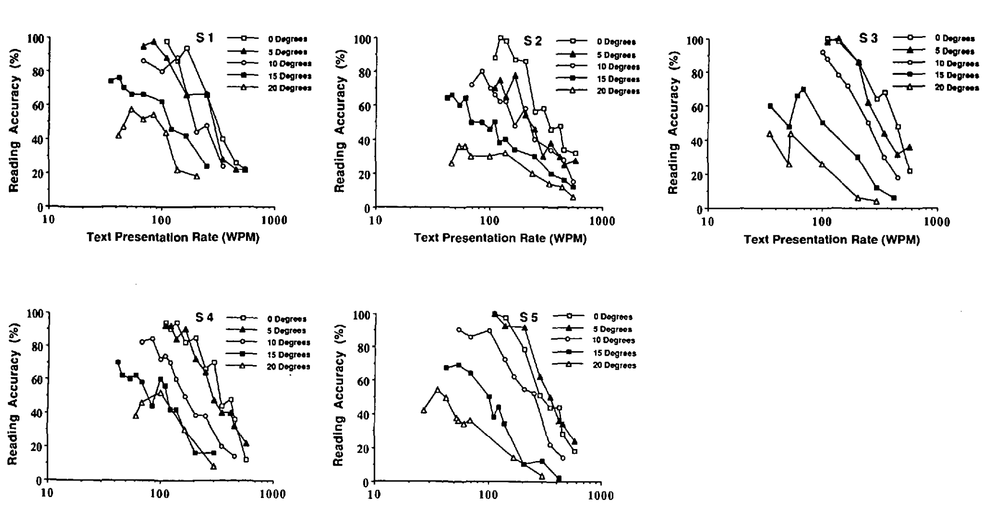

FIGURE 5. The reading accuracy (percentage of words read correctly) when the text was presented at different eccentricities from the fixation.

ally worsened when the text was presented slower than approximately 100 wpm.

In ancillary experiments, we also examined whether the observers could maintain their fixation on the red light-emitting diodes while reading eccentrically presented text. The results confirm that during the reading task observers did not require saccadic eye movements either toward or away from the text.

Reading with Rods Versus Reading with Cones

A comparison of reading performance for rod and for cone vision is complicated by two potential problems: the presence of a central scotoma in rod but not cone vision and differences in the effects of luminance on rod and on cone reading rates. To eliminate the problem of the central scotoma, reading was tested at 5° below the fixation point for both rod and cone conditions. To equate the different photoreceptor systems for luminance levels, the testing was conducted at 0.5 and 1.0 log units above the absolute threshold for the rods and for the cones. Higher luminance levels were not tested, because the cones could not be isolated from the rods.

Table 1 summarizes the mean reading rates for the four subjects studied. The results for three subjects were very similar, whereas the results for the fourth showed a smaller difference between rod and cone reading. Overall, the results show that the reading rate with cone vision was about 50 wpm greater than with rod vision. A repeated measures analysis of variance indicated that the difference was significant ($F(1,2) = 10.46$, $P < 0.05$).

Ancillary experiments indicate that the superior performance for cone reading is not attributable to the wavelength of the text. For example, it was ascertained that the reading rate at 0.5 log units above threshold was nearly identical for text viewed through the red and the blue filters. This finding is consistent with that of a previous investigation.[9] The reading performance was also tested when the text was fixated rather than eccentrically viewed, and the results were similar; that is, reading with cone vision was faster than with rod vision.

TABLE 1. Rod and Cone Reading Rates

	Log Text Luminance (Above Threshold)	
Photoreceptor	*0.5*	*1.0*
Rod	73.41 ± 3.05	165.55 ± 31.66
Cone	124.27 ± 14.31	217.21 ± 14.99

Values are mean ± SEM (words/min).

DISCUSSION

Physiologic Basis for the Superior Pattern Recognition in the Central Visual Field

Whether one views patterns under everyday lighting conditions in which cones (and perhaps rods as well) operate, or under the laboratory conditions described here where only rods operate, the observer's pattern recognition is optimal when the image lies near the fovea. Therefore, we conclude that the optimal field location for at least one type of pattern recognition, reading, is somewhat independent of the photoreceptor system and, more specifically, is not dependent on some exclusive property of the cone visual system.

The results of the current study are informative also because the rod visual system itself does not offer any compelling basis for superior vision in the central visual field. The density of rods does not correlate with the reading performance; density decreases,[14] but reading performance increases, toward the fovea. The density of rods is maximal around 20° eccentric to the fovea. Neither the contrast sensitivity[8,15] nor the spatial resolution[16-18] capability of the night visual system correlates with our results. Whereas reading rate increases toward the fovea, the contrast sensitivity and spatial acuity (Fig. 4, *bottom panel*) for rod vision remain relatively constant with eccentricity over the central 20°.

Furthermore, even though the actual density of rods is equal to or greater than that of cones as close as 1.4° from the center of the fovea,[14] proximal retinal neurons apparently do not exploit the finer rod mosaic to provide high spatial resolution in nighttime illumination. Therefore, the relatively high density of the rods cannot explain our results. Finally, there is little reason to suppose that the processing of images in the central portion of the visual field is faster than that in the periphery. The temporal acuity of the rod vision is relatively constant across the central 20°.[8] We therefore infer that the superiority of the central field in pattern recognition has relatively little to do with the variations in the photoreceptor densities or visual sensitivity/resolution across the visual field.

A decline in reading accuracy was observed at 20° for presentation rates lower than 100 wpm (Fig. 5). This finding is interesting because it suggests a competition between two aspects of scotopic perception in the peripheral visual field, word identification and visibility. To identify each word, the temporal presentation rate must be decreased. But when the rate is decreased, observers report that the images of the words seem to fade. The physiologic processes underlying this finding are not known.

Although rod signals are processed separately from cone signals in the distal layers of the retina, rod signals converge with cone signals at the retinal ganglion cell layer so that all rod signals eventually travel through the ganglion cells that also carry cone signals.[19] That rod and cone signals share afferent pathways is interesting in view of our results that the optimal location for the recognition of rod- or cone-generated images is the same. Our results are explicable if one supposes that the superiority of the central visual field is caused by some process or property of the visual pathway lying beyond the site where rod and cone signals converge, i.e., the proximal layers of the retina.

The visual cortex is a likely site for several reasons. First, the visual cortex is the initial location in the visual pathway where the high density and overlap of ganglion cell receptive fields from the central visual field can be taken advantage of. Before reaching the cortex, relatively little processing of the retinal ganglion cell signals occurs.[20] Second, the anatomy of the visual cortex is conducive to the superiority of the central visual field. There is a disproportionately greater volume of cortex devoted to the central, as compared to the peripheral, visual field.[6] This greater volume is believed to be related to the high density of retinal ganglion cells[21] through which either rod- or cone-generated images project to the visual cortex. Our results, however, do not rule out higher level cortical processes, such as those involved in cognition, attention, or learning, although no relationship between the central visual field and such processes has been established at this time.

Comparison of Performance with Rod and Cone Vision

From everyday experience, most researchers would predict that reading is faster when visual images are generated by cones rather than by rods. However, the question has never been rigorously examined and, in fact, was difficult to investigate until the location of optimal reading for rod and cone vision was determined.

Results from our investigation confirm the expectation that reading with cone-isolated vision is faster than with rod-isolated vision; however, the results cannot be explained by luminance differences, because the luminance of the text was equated for rod and cone vision. Likewise, the results cannot be explained by the presence of a physiologic central scotoma in scotopic but not photopic viewing conditions as in our main experiment, the text was viewed at 5° from the fovea.

The difference in reading rates for rod and cone vision underscores an important point. Although the optimal location for pattern recognition may have little to do with the duplex nature of vision, the actual reading rate does. Among possible explanations for faster cone-mediated reading are the lower temporal resolution of the rod visual pathway, even when rod signals are conveyed by the fast rod pathway,[22,23] and the greater diversity of visual neurons mediating cone vision. With regard to the latter point, cone vision is transmitted to the brain by way of both retinal ganglion cells that exclusively carry cone signals and those that carry rod signals.[19,24] Additionally, whereas rod vision may be mediated mostly by on-center neurons,[25] cone vision is mediated by both on- and off-center neurons.[19]

Applied Significance of the Results

We do not anticipate that many people will wish to read with their rod vision or that in high photopic illumination rods can contribute much to the recognition of text images. However, our results suggest that patients with cone degeneration may be able to optimize their reading performance by recruiting the rods in the central portions of the visual field. Therefore, such factors as the degree of dark adaptation and the scotopic luminance of the text are important.

These results may also be relevant to investigations concerned with how patients with central scotoma select a preferred locus for reading.[26-28] It is generally believed that the retinal region for optimal reading probably represents a trade-off between a number of different factors. Our results suggest that for rod vision and perhaps cone vision as well, the distance of the text from the fovea may dominate photoreceptor density, visual sensitivity, contrast sensitivity, spatial acuity, or temporal acuity.

Key Words

Reading, pattern recognition, photoreceptors, night vision, central scotoma

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