Useful resolution for picture perception as a function of eccentricity

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Abstract. Observers inspected for different lengths of time pictures which contained high-resolution information within an eye-contingent viewing window and low-resolution information outside the area of that window. A recognition test followed in which the pictures inspected were presented together with other, distractor, pictures. The time required to reach 75% picture recognition (the criterion study time) was determined as a function of window size and degree of completeness of video sampling of information outside the window. For each level of information sampling density, criterion study time decreased as window size increased up to a critical size, and then remained approximately constant beyond this size. From these critical-window sizes, a function which describes the resolution actually used by the visual system at each eccentricity (the useful-resolution function) was obtained and this decreased monotonically with eccentricity. The useful resolution at each eccentricity was coarser than the resolution available at that eccentricity as determined by visual acuity, suggesting that useful resolution is not limited by visual acuity. The relationship between useful resolution and saccade length was also analyzed.

1 Introduction

Normally we look at a picture using a series of brief fixations, and thus information from more than one view contributes to the processing of pictures. These serial eye movements seem to be used to supply new information for foveal vision, and one might therefore that only foveal vision is used in picture recognition. However, it has been shown that in processing a picture the visual system extracts information not only from a small area around the fovea but also over a wider area in the periphery (Nelson and Loftus 1980; Parker 1978). Indeed, peripheral vision has been shown to be indispensable for picture perception (Saida and Ikeda 1979; Shioiri et al 1983; Watanabe 1971), letter recognition (F. Ikeda et al 1985), the comparison of line length (M. Ikeda et al 1977), and in reading tasks (Ikeda and Saida 1978; McConkie and Rayner 1975). In these studies it was shown that when the observer’s visual field was artificially restricted to a foveal window that moved in synchrony with eye movements, performance in these recognition and reading tasks was poor.

Using this eye-contingent window technique, Saida and Ikeda (1979) examined the size of the visual field at each fixation that was necessary to process a picture. They measured the time required to reach a criterion level of 70% recognition of pictures as a function of the size of this window, and found that there was a critical size of the eye-contingent window beyond which an increase in the size of the visual field did not improve recognition performance. From this they concluded that the information from the area inside this critical window size was sufficient at each fixation for performance of the perceptual task. They named this area the useful visual field. The concept of a useful visual field suggests that not all the information from the periphery is needed in each fixation to perceive pictures under free eye-movements, but their finding that the

critical-window size was 50% of the size of the stimulus picture indicates that quite a wide area of the visual field contributes to picture perception.

On the other hand, it is well known that many visual abilities deteriorate as eccentricity increases, e.g., visual acuity (see review by Jacobs 1979), colour vision (M. Ikeda et al. 1985; Uchikawa et al. 1982), and target detectability (Engel 1971; Engel 1977; Widdel 1983). For picture perception as well, Nelson and Loftus (1980) found that the previously fixated details of a picture were recognized better than details seen only in the periphery. Obviously there is functional inhomogeneity over the visual field, which results in variation of visual system properties with eccentricity.

The results of Saida and Ikeda (1979) do not imply that the visual system needs the same amount of information inside all of the useful visual field as is required for foveal vision. Perhaps detailed information is superfluous in the periphery. In this paper, we investigate the level of image resolution that is used at each eccentricity in order to achieve picture recognition. We call this the useful resolution for picture perception. The useful visual field can then be defined as the area inside which useful resolution is greater than zero, since no information is required outside the useful visual field. In other words, the useful-resolution function defines the spatial properties of the useful visual field.

One possibility is that useful resolution is limited by peripheral visual acuity at each eccentricity, and all the information available in the periphery may contribute to picture processing. However, local properties such as acuity may not predict perception performance for pictures which stimulate a large area of the visual field, perhaps because of interactions between information from different parts of visual field. For example, it has been shown that a visual information load in the fovea, such as occurs during the reading of letters, leads to a deterioration in both the ability to detect a light in the periphery (Leibowitz and Appelle 1969; Voss 1981) and target discrimination (Ikeda and Takeuchi 1975). This suggests that the periphery is less sensitive when central vision is processing information than when the peripheral visual field alone is stimulated.

On the other hand, in free-viewing conditions, eye movements can be used to bring some part of the peripheral image onto the fovea so that the higher acuity of foveal vision can be used to process details of the image. Thus, peripheral vision may require only sufficient information to guide the eyes to the next fixation. The requirements of this guidance operation may determine the useful resolution in the periphery. In fact, peripheral vision has been shown to be critical for programming saccades. Saccades are shortened when the visual field is decreased by a small eye-contingent window, both for reading (Ikeda and Saida 1978; McConekie and Rayner 1975; Rayner and Bertera 1979) and for picture scanning (Saida and Ikeda 1979). Although there are other roles of peripheral vision than the programming of saccades, it is possible that for picture perception peripheral vision needs to supply only enough information to guide eye movements. We investigated both of these factors—available resolution limited by peripheral acuity and eye-movement guidance—to examine whether they determined the useful-resolution function.

As we shall describe, we used a recognition test to establish a criterion of picture processing. We chose a recognition test because it has advantages over other tasks such as naming or discrimination paradigms. With a naming task, perceptual performance can be measured, for example, as the time needed to name a picture correctly. However, we think that picture perception involves not only naming but also the building of an internal representation of the picture. Such an internal representation cannot be expressed in terms of names, and therefore a naming task might fail to access the mechanism which builds internal representations. Loftus and Bell (1975) have in fact shown that two processes are used in picture recognition: first, naming, which is used to describe specific information about details, and second, a process that depends on the
description of the general visual information present in pictures without the assignment of names. A recognition test should therefore ideally access both named information and an internal representation that does not depend on naming. On the other hand, a discrimination task between two pictures presented simultaneously or sequentially might be a good method for measuring useful resolution. However, here the observer’s task becomes the detection of small differences between two pictures, and, therefore, the observer’s behaviour might differ in many ways from normal viewing behaviour. For these reasons, we considered the recognition test the most appropriate for the present experiment.

In order to obtain the useful-resolution function under free eye-movements, we developed an apparatus which produced high-resolution information in an eye-contingent window and low-resolution information in the surround. With it we could vary both window size and the level of resolution of information outside the window.

2 Principle

The solid curve shown in figure 1a represents the hypothetical useful-resolution function of the visual system, a function that is at its maximum at the centre of the visual field, and decreases with increase in eccentricity. A point on the function can be derived experimentally with the aid of an eye-contingent window with degraded information in the surround. A resolution profile for such a stimulus picture is shown by the heavy broken line in figure 1a. High-resolution information is available inside a window surrounded by low-resolution information in the periphery. In this example, R1 is the resolution level of information presented in the surround and E1 is the eccentricity at which useful resolution is equal to R1. If the size of the high-resolution window is increased without any change in the resolution level of information in the surround there is an improvement in the observer’s performance up until the window reaches eccentricity E1. If the window is increased beyond E1, however, no further improvement in performance is produced, because beyond the eccentricity (E1) at which useful resolution is equal to the level of resolution of surround information (R1) the surround information (R1) is sufficient for the visual system. In other words, there is no difference in performance for a picture which has high-resolution information everywhere and the same picture with a low-resolution (R1) surround and an eye-contingent high-resolution window that extends to eccentricity E1.

![Image](image.png)

**Figure 1.** (a) Hypothetical useful-resolution function of the visual field (solid curve) with the resolution profile of a stimulus picture (heavy broken line). R1 is the resolution level of the stimulus outside the eye-contingent window. E1 is the eccentricity at which useful resolution matches R1. Performance will improve as the size of the high-resolution window increases up to eccentricity E1. No further improvement in performance occurs beyond that point. (b) Experimental determination of the useful-resolution function. E1, E2, ..., En are the eccentricities obtained from critical-window sizes under conditions where the levels of resolution outside the eye-contingent window are R1, R2, ..., Rn respectively. These eccentricities represent half of the lengths of the critical-window.
The eccentricity (E1) at which surround picture resolution (R1) just matches useful resolution can be derived by measuring perceptual performance as a function of window size and finding the critical-window size beyond which a further increase in size produces no improvement in performance. Since E1 and R1 define a point on the useful-resolution function, this function can be established by finding critical-window sizes E1, E2, ..., En for different levels of resolution of surround information R1, R2, ..., Rn.

3 Determination of picture recognition as a function of exposure time, window size, and surround sample density

3.1 Method

3.1.1 Subjects. Three male observers participated in the experiment. One had normal visual acuity, that of the others was corrected to normal.

3.1.2 Apparatus. With the aid of apparatus controlled by a microcomputer (as shown in schematic form in figure 2), stimulus pictures taken by a video camera could be reproduced on a cathode ray tube (CRT) at full resolution within a certain size window, and in degraded form outside of that window. In a circuit made specially for this

![Diagram of apparatus](image)

Figure 2. The apparatus used to provide high-resolution information inside the eye-contingent window and degraded information, achieved by a sampling technique, outside that window. In the montage circuit, the video switch replaced part of the stimuli video signal (from the video camera) with a uniform white video signal. This switching was controlled by a logical sum (composed signal) between window and sample-dot signals (which were both generated by the microcomputer). As a result of this operation, at the 'on' parts of the composed signal the luminance information of the stimulus picture was reproduced on the CRT, whereas white patches covered the stimulus picture at the 'off' parts. The position of the observer's eye was monitored with a photodiode and this information was used to position the window on the CRT at the centre of the observer's point of fixation. The size of the window and sample-dot density were controlled by microcomputer.
purpose (montage circuit), parts of the picture outside the window were sampled at random spatial positions (which were temporally static) and any position not included in the sample was replaced by a white video signal whose luminance was equal to that of the white parts of the stimulus pictures. The resolution of the picture information outside the windows, or surround sample density (SSD), was controlled by varying the density of sampling. An SSD of 0% means that all the information outside the eye-contingent window was replaced by a uniform white field, and as SSD increased, more of the picture was sampled and presented. The CRT was mounted at a distance of 120 cm from the observer. The stimulus field was the central part of the CRT which subtended 15 deg × 15 deg of visual angle and was covered by 167 × 214 sample dots. On the CRT the luminance level of the black parts of the stimulus pictures was 2 cd m⁻² and that of the white parts was 18 cd m⁻².

The position of the axis of the observer's eye was detected by the corneal reflection method with a photodiode. The horizontal (x-coordinate) and vertical (y-coordinate) components of the position of a light spot (the image of a light source reflected on the cornea) on the surface of the photodiode were amplified and fed separately into the microcomputer via an A/D converter. These signals were used to control the position of the window so that the centre of the window always coincided with the visual axis (within ±0.5 deg error and with a maximum delay of 25 ms), anywhere within the 15 deg × 15 deg stimulus field. The stimulus was observed monocularly with the right eye, but eye movement was monitored in the left eye. The eye-movement signals were recorded on a data recorder for later analysis. A bite bar was used to minimize head movement.

3.1.3 Stimulus pictures and sample dots. More than ten thousand black and white drawings of common scenes and objects were gathered from illustrated books for elementary school children and forty stimulus sets were made from them as follows. First, a pilot experiment was used to select one hundred and sixty groups of twenty pictures as targets such that the average difficulty for recognition of each group of twenty pictures was similar. Second, from the remaining original pictures forty groups of eighty pictures were chosen as distractors by random selection. Four twenty-picture groups of targets and one eighty-picture group of distractors constituted a stimulus set, making forty stimulus sets each with one hundred and sixty pictures.

The levels of SSD used were based on a pilot experiment in which observers were asked to name simple objects from line drawings (such as a goldfish, a dog, etc) that were sampled over the whole of the picture. When the sampling density was less than 20% observers had difficulty in naming the objects, which suggested that 20% was the lowest level of sampling which still conveyed useful information about the content of the pictures. On the other hand, with 50% sampling the observers judged that there was little effect on the information in the pictures. Based on these results, we used SSDs of 0, 25, 33, and 40%. Figure 3 shows the effect of sampling on an example of the pictures used.

For each of the 25, 33, or 40 SSD conditions, one sample-dot pattern was generated and the same pattern was used for all pictures in that SSD condition. We did not generate new sample-dot patterns for each picture, since the effect of replacement of one sample-dot pattern of a picture by another sample-dot pattern with the same density was not noticeable.

(1) A similar method was used by Williams (1973), except the points that were not sampled were replaced by a black signal and the sampling points changed over time.
3.1.4 Procedure. Each session consisted of a study phase and a test phase, which together made up the recognition test. In the study phase, the observer inspected eighty target pictures of a stimulus set as they were presented on the CRT one after another, at one of the combinations of five window sizes (in deg: 2.7×2.7, 4.2×4.2, 6.7×6.7, 10.6×10.6, or nonrestricted viewing) and four levels of SSD (0, 25, 33, or 40%). Window size and SSD were kept constant during the study phase. Only exposure duration varied from trial to trial. This was chosen randomly from four different durations, which were defined in the range from 0.25 to 16 s so that they covered 3 log₂ units, eg 2, 4, 8, and 16 s, and were centred approximately on the duration that would produce the criterion performance in the test phase. Longer durations were used in the smallest-window condition with no surround (0% SSD), and shorter durations were chosen for larger SSDs and window sizes. For each of the four durations, pictures from one of four twenty-picture groups of the stimulus set were used. Eye movements were measured and recorded in each trial. Before each trial, the observer centred the window objectively to the point of his fixation.

In the test phase, which followed 5 min after the study phase, the observer was given a total of one hundred and sixty pictures, the eighty target pictures seen in the study phase and another eighty, previously unseen, distractor pictures. The pictures were presented one after another for a duration of 1 s each. Unlike the study phase, there was no restriction on the size of the visual field, so that the observer could see the entire picture at full resolution. The task was to identify the pictures that had been seen in the study phase. The observer was instructed to respond with one of four ratings: 4 for a 'confident yes', 3 for a 'probable yes', 2 for a 'probable no', and 1 for a 'confident no'. The percentages of correct confident 'yes' responses were tabulated. Uncertain responses were excluded from the analysis.
Because two sessions were run for each condition, the recognition rate for an exposure duration was obtained most often based on forty observations. Occasionally, however, the duration used in the first session for a condition was replaced by either a shorter or a longer duration in the second session, so that the resultant percent-correct curve would cover a sufficiently wide range of percentages (in these cases, the curves in figure 4 have five or sometimes six data points instead of four). In these cases some recognition rates were based on twenty observations.

The five window sizes with a particular level of SSD constituted a block that contained ten sessions, two sessions for each window size. A different block was run for each of the four SSD conditions. An observer therefore participated in the experiment for four blocks or forty sessions. The order of sampling density across blocks was 0, 25, 40, and 33% for two observers and the reverse order was used for the other observer. In each block, the five window sizes were tested in pseudorandom order, in which each window size appeared once in both the first and the second five sessions.

Each set of one hundred and sixty stimulus pictures was used only once for each observer so that six thousand and four hundred pictures in total were displayed for each observer. Because no stimulus set was used more than once in the same experimental condition, different observers inspected different pictures for the same condition.

Prior to the first session of each block, the observers had a practice session (which included both the study and the test phases) which included the four different window sizes (the nonrestricted condition was not included) at the SSD to be used. The stimuli used in these practice sessions were in addition to those used in the experimental sessions.

Figure 4. Percentage of correct ‘confident yes’ responses in the test phase as a function of exposure duration in the study phase for different levels of surround sample density (SSD) and window size (given as the length of one side). The curves are cumulative normal-distribution functions fitted to the data. Data are presented individually for the three observers (CI, KU, YN) in the first three columns, with mean data given in the fourth.
3.2 Results and discussion

3.2.1 Recognition rate. In figure 4, the percentages of correct confident yes responses obtained for the target pictures in the test phase are plotted against exposure duration in the study phase. The first three columns show the results for the three observers separately and the last column shows the average of all three. Results for different SSD levels are given separately in each of the four rows. The symbols on the graph represent the results for different sizes of the eye-contingent window. Observers occasionally gave a confident yes response for pictures not shown in the study phase. The number of these false positives was low, less than 2\% (the highest value for the averaged data was 1.67\% for the 4.2 deg window with 40\% SSD), and did not depend on window size or SSD.

The experimental points relating performance to exposure duration for each window size were fitted by a cumulative normal-frequency function by the least-squares method. The results are shown in figure 4 (five lines in each panel). For 0\% SSD, all observers show shifts of their percent-correct curve with decrease in window size, i.e. as window size decreased, longer exposure durations were needed in the study phase to maintain the same performance. The exception was the 10.6 deg window, for which performance did not differ systematically from that in the nonrestricted condition. The level of SSD also influenced the recognition rate. As SSD increased from 0\%, the effect of window size was reduced, i.e. the percent-correct curves vary less as a function of window size for larger SSDs (33 and 40\%) than for smaller SSDs (0 and 25\%).

3.2.2 Criterion study time versus window size, and critical-window sizes. The exposure duration at the 75\% correct level was extracted from each curve of figure 4 and defined as the criterion study time. This value is shown plotted against window size in figure 5, both separately for the three observers and for their average results. Data for the nonrestricted condition were plotted as being for a window size of 15 deg. For each level of SSD, criterion study time varies quite smoothly with window size for the average results. For 0\% SSD, criterion study time decreases substantially as window size increases, up to the 10.6 deg window, which requires the same study time to reach criterion performance as the nonrestricted condition. This suggests that increasing the size of the window beyond about 10 deg produces no improvement in picture processing and thus the critical-window size (described in section 2) is around 10 deg for 0\% SSD. For 33 and 40\% SSD, the critical study time is approximately constant for window sizes larger than 4.2 deg. Thus, for both of 33 and 40\% SSD, the critical-window size appears to be around 4 deg. For 25\% SSD, the decrease in study time

![Figure 5. Criterion study time as a function of window size (on a logarithmic scale) for four surround sample densities (SSDs). The window size is shown as the length of one side of the window. Equation (1) was used to fit the curves. Data presented both individually for the three observers (CI, KU, YN) and as mean result.](image-url)
with window size is more gradual, making it more difficult to define the critical-window size. The results for the individual observers are more variable but follow the same pattern as the averaged results.

To establish quantitatively the inflection point from which we could determine critical-window size, we first fitted the data in figure 5 using the following form of the power function, which we chose because it is constrained to flatten to a minimum at a window size of 15 deg:

$$T(w) = a \left( \frac{w}{15} \right)^b + \left( \frac{15}{w} \right)^b + c,$$

where \(w\) is window size in deg, and \(a\), \(b\), and \(c\) are free parameters adjusted to obtain the best-fitting function. The fit of simple exponential function,

$$T(w) = a \exp(bw) + c,$$

was also examined. However, this function continues to decrease monotonically with increasing window size, whereas the experimental data show approximately constant values of criterion study time at large window sizes. For the average data, the sum of squares of residuals for the best-fitting function shown in equation (1) was 0.038, 0.146, 0.030, and 0.057 for 0, 25, 33, and 40% SSD respectively, while that for the best-fitting function shown in equation (2) was larger in each case (0.230, 0.225, 0.030, and 0.062 respectively). However, the determination of the inflection points did not depend critically on the choice of fitting function; the best-fitting curves obtained with equation (1) are therefore shown in figure 5 and these are the functions we used for further analysis.

We then defined the critical-window size as that window size beyond which there was no further statistical decrease in criterion study time. This point corresponds to the study time that was elevated by 0.4 s compared to the study time for the 15 deg window on each curve. This value of 0.4 s is the standard deviation of the criterion study time in the nonrestricted condition (the data from the 15 deg window in figure 5) for the averaged results. In this procedure it is assumed that criterion study time is constant when the function is within the standard deviation of the data for the nonrestricted condition.

The critical-window sizes obtained by this procedure were plotted against the SSD levels in figure 6. The critical-window sizes for the averaged results are 9.5, 6.5, 4.0 and 3.8 deg for 0, 25, 33, and 40% SSD respectively. These values agree with the critical-window sizes estimated by visual inspection of figure 5. Similar values were obtained for the data from individual observers.

![Figure 6](image)

**Figure 6.** Critical-window size as a function of surround sample density (SSD). The critical-window sizes are expressed as the length of one side of the window. Individual and averaged results are shown.
4 Determination of the useful-resolution function

Although SSD has been used to express the degradation of stimulus information outside the eye-contingent window, the size of the smallest resolvable feature in images sampled at each level of density is probably a more general way to define the level of the degradation. In order to determine this resolution for each SSD, we measured the visibility of the gap in Landolt’s rings at the four levels of sampling used in the main experiment.

4.1 Available resolution of sampled images

4.1.1 Procedure. Resolution was measured as the minimum size of gap which could be seen in sampled images of Landolt’s rings displayed at the centre of the screen. The rings were sampled at densities of 25, 33, 40, or 100% (no degradation). For each sampling density, seven different sizes of Landolt’s rings were chosen so that they would cover the range of sizes between clearly above and clearly below threshold. The gap in the rings of these varying sizes was displayed at one of eight positions; top, upper right, right, lower right, bottom, lower left, left, or upper left. Prior to presentation of the stimulus, a fixation spot was displayed at the centre of the screen. The stimulus was presented for 1 s and then removed. Observers were asked to detect the position of the gap and respond verbally with one of the eight gap positions. The order of presentation was random across both gap position and ring size. For each of the four levels of sampling there were fifty-six presentations for each observer; each of seven sizes of the rings was displayed once at each gap position. Five observers participated in this experiment; two of them were from the main experiment.

4.1.2 Results. For each sample density, responses were pooled over all positions and observers, and the percentage correct detection of gap position was calculated for the seven different sizes of Landolt’s rings. These data were distributed between 15 and 100%, depending on the size of Landolt’s ring. The cumulative normal-frequency curve whose values varied from 12.5% (chance level) to 100% was used to describe the experimental data. The size of the gap in a Landolt’s ring that gave 56.25% correct responses from the curve was defined as the threshold (56.25% is the average of 100% and 12.5%). As shown in figure 7, we expressed the resolution for each level of sampling as the visual angle of the gap size at threshold. Since the Landolt’s rings were sampled by the same system as used in the main experiment, the resolution obtained includes all effects of our sampling technique such as reduction of contrast on images, the effect of switching noise or other possible artifacts of the system, in addition to the reduction in resolution due to a coarse spatial grain.

![Figure 7. Available resolution as a function of sampling density (on a logarithmic scale) in Landolt’s rings. Resolution was measured as the minimum size of gap which could be seen in sampled images of the rings displayed at the centre of the screen.](image)
The minimum value of resolution in figure 7 is 0.05 deg, which was obtained for the 100% sampling condition. The observers' minimum resolution, limited by their visual acuity, was found to be better than 0.02 deg in a pilot measurement, where the Landolt's rings were presented as continuous black and white stimuli on paper (not on a CRT). Therefore, maximum resolution is limited by display characteristics and not by the visual acuity of the observers.

4.2 Useful-resolution function

We now have the necessary information to derive the useful-resolution function as described in figure 1b. This function relates useful resolution to eccentricity whereas our data in figure 6 show critical-window size as a function of surround sampling density. To obtain the desired function, the axes of figure 6 were first exchanged so that the function represents SSD on the vertical axis as a function of critical-window size. Then, to obtain eccentricity from the size of the critical window, the length of one side of the critical window was halved, yielding the eccentricity of the edge of the critical window. Finally, using the relationship between SSD and resolution obtained in the previous experiment, we translated SSD values into units of resolution.

Figure 8 shows the resulting useful-resolution function for individual observers and for their average data. Useful resolution decreases as eccentricity increases until it reaches zero at an eccentricity of about 4.5 deg. The decreasing property of the function indicates that picture detail information is not required for picture perception in the periphery, and that it is only central vision that processes the high-resolution details of pictures.

The eccentricity at which useful resolution reaches zero (4.5 deg) corresponds to a window size which represents 36% of the area of the stimulus. This value is quantitatively similar to the 50% area found to be useful visual field by Saida and Ikeda (1979).

![Figure 8. The useful-resolution function for the three observers and for the averaged results.](image)

- The level of resolution outside the eye-contingent window, which is expressed by the resolution in visual angle instead of the level of surround sample density, is plotted against the eccentricity of the critical-window's edge (half of the length of one side of the window). The scale on the right side of the panel shows the corresponding sample density.

5 Comparison of available and useful resolution

5.1 Available resolution in the periphery

As shown in figure 8, useful resolution decreases monotonically with eccentricity, as does visual acuity. Useful resolution, therefore, may be limited by visual acuity and could simply be a measure of the available resolution at each eccentricity. To examine whether this is the case, we measured the threshold size of the gap in Landolt's rings as a function of eccentricity for the three observers used in the main experiment.
5.1.1 Procedure. The procedure used in this experiment was approximately the same as that described in the previous experiment, but the level of sampling was always 100% (no degradation) and Landolt's rings were displayed at $\pm 2.1$, $\pm 5.3$, and $\pm 7.5$ deg in the periphery on the horizontal or the vertical meridian in addition to in the central visual field (0 deg eccentricity). For each position in the visual field, six different sizes of Landolt's rings were chosen so that they would cover the sizes between clearly above and clearly below threshold at each position. Each of six rings was presented once at each one of eight positions of the gap, and thus an observer had forty-eight trials for each position in the visual field.

5.1.2 Results. The threshold gap distance in Landolt's ring was defined as a function of eccentricity for each meridian separately for each observer, with the same procedure described in the previous experiment. In figure 9, available resolution as a function of eccentricity is shown by crosses. These points indicate the average over the two meridians and three observers.

Available resolution decreased with eccentricity, although the decrease seen is not as steep as has been reported previously (see review by Jacobs 1979). This difference is probably the result of limits placed on resolution by our experimental apparatus, particularly at the fovea.

![Figure 9. Comparison of available resolution and useful resolution as a function of eccentricity. The data for available resolution are averaged over both meridians (horizontal and vertical) and three observers. The average useful-resolution function is replotted from figure 8.](image)

5.2 Available resolution and useful resolution
Useful resolution was replotted in figure 9 from figure 8 to compare it to the resolution available at each eccentricity. Observers could see a gap of less than 0.1 deg even at an eccentricity of 7.5 deg, but at this eccentricity no information contributed to picture perception. For smaller eccentricities as well, useful resolution was substantially less than available resolution. This shows that useful resolution is not limited by peripheral acuity.

6 Saccade length and useful resolution
It has been shown that saccades shorten when the visual field is reduced by the introduction of a small eye-contingent window for picture scanning (Saida and Ikeda 1979). Shorter saccades mean that more fixations are required to search over a picture, and thus the time required to encode a picture may be influenced by saccade length; useful resolution may, in fact, be determined by a process which controls saccade programming. In this case, useful resolution would be the resolution required to guide the eyes to the next fixation point. This implies that when there is less information than the useful resolution at a given eccentricity, the saccade-control process cannot obtain enough information to program a saccade to this eccentricity. If this is true, then
when the eye-contingent window is smaller than the critical-window size (thus, providing insufficient information outside the window), the number of saccades to points outside the window should be reduced. This should shorten the average length of saccades in picture scanning with an eye-contingent window smaller than the critical-window size. To examine this issue we studied the effect of window size on saccade length from the records of eye movements in the main experiment.

Figure 10 shows the median saccade length (with the 25 and 75% percentiles) for the data pooled over three observers as a function of window size for all four levels of SSD. The data for the nonrestricted condition were plotted as being for a window size of 15 deg. At 0% SSD, saccade length increased substantially as window size increased, except that the median saccade length for the 10.6 deg window was longer than that for the nonrestricted condition. Similar results were found for the other SSDs, but the differences in saccade length between window sizes decreased as SSD increased.

The arrows in Figure 10 indicate the estimates of critical-window size derived from the analysis of criterion study time; study time remained constant for window sizes larger than the critical values. If study time is primarily dependent on saccade length, saccade length should also be constant (or at least not shorter than that for the nonrestricted condition) for windows which are larger than the size indicated by the arrow. Figure 10 shows that saccade length was fairly constant for windows larger than that indicated by the arrow for all SSD levels, although the median saccade for the

![Graph](image)

**Figure 10.** Median saccade length (with 25% and 75% percentiles) as a function of size of eye-contingent window (expressed as the length of one side of the window, on a logarithmic scale) for each level of surround sample density (SSD). Squares, median; upper lines, 75% percentiles; bottom lines, 25% percentiles. Arrows indicate the critical-window sizes determined from the criterion study time data for the averaged results.

**Table 1.** Wilcoxon test of difference in saccade length between the nonrestricted condition and each window size for each level of surround sample density (SSD). Window size given as the length of one side of the window.

<table>
<thead>
<tr>
<th>SSD/%</th>
<th>Window size/deg</th>
<th>10.6</th>
<th>6.7</th>
<th>4.2</th>
<th>2.7</th>
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<tbody>
<tr>
<td>0</td>
<td>25</td>
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<td>0.25</td>
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<td>0.33</td>
<td>40</td>
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Significant at a probability of 5% (*) and 1% (**)
10.6 deg window was always longer than that for the others. Table 1 shows the results of a Wilcoxon test, which tested whether the saccade lengths for each of the window sizes were shorter than that with nonrestricted viewing for each level of SSD.

In general, changes in window size which lengthened the criterion study time shortened saccade length, and changes in window size which did not influence criterion study time did not influence saccade length. This agreement between the effect of window size on saccade length and study time suggests that useful resolution is determined by a process which controls saccade programming. However, as we will argue below, another explanation is possible.

7 General discussion
Useful resolution was found to decrease monotonically as eccentricity increased. Thus not all the information available at each fixation contributed to picture processing; low-resolution information was sufficient in the periphery, although high-resolution information was required in the central visual field.

The useful resolution we measured is coarser than the limits of peripheral acuity, and thus the lower useful resolution in the periphery cannot be attributed simply to deterioration of acuity. On the other hand, the saccade programming process may determine useful resolution at each eccentricity, because saccade lengths became shorter when the eye-contingent window was smaller than the critical-window size. However, although eye movements and useful resolution seem to have a strong relationship, the process of programming saccades may itself depend on understanding the content of the picture. According to Loftus and Mackworth (1978), fixations are drawn to areas in a scene that feature unexpected items. For example, these authors found more fixations to an octopus than to a tractor when both were located on a road in the same farm scene. Their results suggest that the saccadic programming process is not simply an automated scanning process that seeks detail independently of content but is an integrated part of the picture perception process. It is possible, therefore, that a process which encodes picture content both determines useful resolution and influences saccadic programming.

In several studies it has been suggested that the peripheral visual field is used not only for guiding foveal vision but also for processing pictures (Shioiri et al. 1983; Watanabe 1971; Yoshida 1982). When observing a picture with an eye-contingent window smaller than 3 deg in size (and less than 3% the area of a stimulus picture), observers sometimes failed to name a picture correctly that was easily named under normal viewing, even when they were able to scan the entire picture. If the efficient scanning of pictures were the only advantage of a large visual field, a small eye-contingent window should not hamper identification with unlimited viewing time. Therefore, the role of the information defined by useful resolution could be not only for guiding eye movements, but also for actively processing pictures.

We did not explore the effect of stimulus size on the useful-resolution function in this report. Saida and Ikeda (1979) found that the useful visual field size is different for different stimulus sizes but that the useful visual field size is a constant fraction of the stimulus picture size. Since their useful visual field is equivalent to the area where useful resolution is greater than zero in this report, the shape of the useful-resolution function (figure 8) should also change when stimulus picture size is varied.

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