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Relative rod and cone contributions in iconic storage

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Using a two-alternative forced-choice procedure, subjects were required to detect a 4′ spatial gap between two briefly presented luminous rectangles when there was a temporal delay between the offset of the first rectangle and the onset of the second. Since the rectangles were never on simultaneously, detection of the spatial gap must have involved short-term visual storage (STVS). For each condition (fixed ISI, wavelength, eccentricity), luminance was varied, and the 75% threshold for detecting the gap with STVS was estimated. The difference in the gap detection thresholds for the white and colored conditions were calculated and compared to the difference predicted from both the relative rod and cone densities of each colored filter. (This latter difference was determined experimentally with absolute and differential standard threshold procedures and was also calculated theoretically.) The results were that, for eccentricities of about 3°-10°, gap detection was done by the cones for ISIs up to roughly 100 msec but by rods for longer ISIs.

In his now-classic experiments, Sperling (1960) showed that after a brief visual presentation has ended, the information is still available for hundreds of milliseconds, or even longer, in the form of a large-capacity, rapidly fading visual storage. He suggested that the image that was produced by the stimulus was the source of this storage, and the image was later called an "icon" by Neisser (1967) to distinguish it from other forms of visual images. We shall adopt the convention that iconic memory refers to the storage provided by the persisting image, or icon. However, the partial-report superiority that is found in a Sperling task may be due to output interference and other forms of memory in addition to iconic memory (Dick, 1974; Holding, 1975; Sakitt, 1976). Other paradigms that have been used to demonstrate iconic memory include the work of Averbach and Coriell (1961), Eriksen and Collins (1967), and Estes and Taylor (1964). There are numerous other studies in this area, and the reader is referred to recent reviews by Coltheart, Lea, and Thompson (1974), Dick (1974), and Sakitt (1976) for details.

Recently it was shown that the rod photoreceptors produce an icon which is robust enough to provide a typical partial report superiority (Sakitt, 1975, 1976). In normal dark-adapted observers, the subjective duration of the icon was determined mainly by the rod photoreceptors. This was true for both photopic- and scotopic-level stimuli. However, since the subjective duration of the icon is determined by the longer lasting icon, such experiments do not reveal the nature of a possible shorter cone icon.

The present study was conducted to investigate the relative contributions of rods and cones to iconic storage. In order to do so, we used a task in which subjects were required to detect a spatial gap between two luminous rectangles that were never on simultaneously. This task is related to the paradigm used by Eriksen and Collins (1968). Such detection had to be done by using short-term visual storage. By varying the ISI between the rectangles, we were able to investigate the spatial information stored by both the cone and the rod systems.

EXPERIMENT 1
SEPARATION OF ROD AND CONE FUNCTION IN ICONIC STORAGE

Method

Subjects. The subjects were three Stanford students, two males, D.V. and G.L., and a female, J.L., all of whom participated both as subjects and experimenters. Two subjects were involved in the experiments as part of an undergraduate course in independent research. The second author, G.L., was also one of the subjects. All subjects but G.L. had normal vision, and G.L., who is slightly myopic, wore his normal-correction spectacles while acting as a subject. Each subject was used extensively over a period of several months, and the total data collection took place over 9 months.

Stimulus and Apparatus. The stimulus consisted of two flashes, each 15 msec in duration and separated by a variable ISI. Each flash consisted of a single solid luminous rectangle 58′ high. If the rectangles had been presented simultaneously, they would have appeared as shown in Figure 1a, where the spatial gap between the rectangles was either 0′ or 4′ for this experiment. The retinal location of the gap was controlled by variable fiber-optics fixation points for either central viewing or 3°, 7°, or 10° eccentricity in the temporal retina of the left eye.

Figure 1b describes the temporal presentation of the rectangles.

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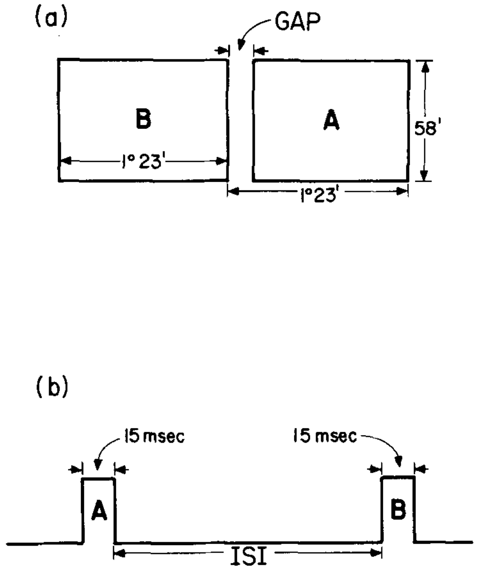

Figure 1. (a) Spatial relationship of rectangles if they had been presented simultaneously. (b) Temporal relationship of rectangles.

The second rectangle was always 1°23′ wide. The first rectangle was either 1°23′ wide or 1°19′ wide in order to provide either a 0′ or 4′ spatial gap, respectively, between the two rectangles. The difference in rectangle sizes was not a cue, as discussed later. The background against which these rectangles were presented was dark.

The viewing apparatus consisted of a rear-projector arrangement with two Kodak Ektragraphic slide projectors (Model AF-2) with high-intensity bulbs (GE ENG) and an opal glass screen (Edmund Scientific Co. No. 2149) upon which the stimulus targets were rear-projected. The two Carousel slide projectors were located 75 mm from the 90 × 120 mm opal glass screen. This screen was mounted in a black wooden frame, which in turn was surrounded by a black opaque backdrop which extended from floor to ceiling in the experimental room and was 145 cm in width. A Model 6246 Iconix timer controlled two Lafayette shutters positioned in front of the lens of each projector. The timer and shutters controlled the duration of each target presentation as well as the temporal interval between presentations from the two projectors. By depressing a hand-held switch, the observer initiated the target presentations whose duration and interval were determined by the experimenter. The choice of targets on each trial was also controlled by the experimenter by means of a remote manual control which advanced or reversed the Carousel slide tray containing the target slides. Glass-mounted neutral density filters (Kodak Wratten No. 96) or various colored filters could be placed in the target beams from each projector to control target luminance and wavelength. The colored filters used were Kodak Wratten No. 29 Red (633), No. 45 Blue (487), No. 61 Green (534), No. 73 Yellow (576), No. 75 Blue-Green (491), and No. 92 Far-Red (646), where the numbers in parentheses are the dominant wavelengths in nanometers. For 3°, 7°, and 10° eccentricity, the fixation point was a 2′ red dot (fiber-optics). For central fixation, however, it was found that a small dot in the center of the screen provided a reference point with which to compare the absolute position of the first rectangle while the second rectangle could be ignored completely. Following some pilot work, it was determined that this problem could be solved by providing a broken fixation "line" consisting of six fixation lights (each 0.7′ diameter) located 40′, 50′, and 60′ to the left of center and 40′, 50′, and 60′ to the right of center. The subjects were simply instructed to fixate the estimated midpoint of the 80′ central break in this fixation line. Although this provided less fixation precision than a fixation point, it seemed to eliminate the cues of absolute position of the rectangles.

The observer was seated approximately 2.5 m from the opal projection screen at the opposite end of the experimental room with his/her head resting against the wall. No bite-bar or artificial headrest of any kind was employed, and all viewing was done with the natural pupil. To reduce the level of stray light from the projectors which could illuminate the opal screen and reduce target contrast, a series of opaque black curtains were hung around and above the projector side of the screen. In spite of this precaution, some stray light was still present in the remaining portion of the room which permitted the dark-adapted observer barely to distinguish the opal screen from its surround.

A gap width of 4′ corresponded to a 3-mm separation of the rectangles on the screen. In order to get faithful repetitions of such small separations, we tried various projectors before selecting the type actually chosen, one with a fairly accurate slide positioning arm. Even so, we had to return one sample which was not accurate. Accuracy was checked by measuring the separation on the screen with a magnifying comparator graded in 10ths of a millimeter. Before each session, the gap width was aligned and checked. In the early experiments, the separation was checked after every 25 trials, but when we found that the separation was maintained, we only checked randomly every few blocks thereafter. Only rarely was it necessary to realign the projectors during a session, and then only because of slight (about .2-.5 mm) shifts in rectangle position. In addition to our choice of projectors, other factors which helped maintain fidelity were use of a remote control to change slides, having the projectors mounted on separate wooden stands, and not having any other part of the apparatus in physical contact with the stands or projectors.

Procedure. Stimuli were presented monocularly (left eye), with the right eye covered by an eyepatch during the experimental sessions. Before each session, the subject dark-adapted the left eye by wearing two eyepatches (an inner and an outer) over the left eye for a minimum of 45 min.

The procedure was a temporal two-alternative forced-choice experiment. The subject received two stimulus presentations about 15 sec apart. In one presentation, there was a spatial gap between the two rectangles. In the other, there was no gap. The subject was forced to decide in which of the two presentations there had been a gap. The experimenter controlled which presentation contained the gap by using random number tables. The experimenter would prepare the apparatus by changing the slide for the first rectangle for the first presentation and verbally signal the subject "ready." The subject then initiated the first presentation by pressing the shutter switch. The experimenter then prepared the second presentation and the subject gave himself another presentation. After the second presentation, the subject verbally responded either "first" or "second," indicating which presentation he thought had the 4′ gap. The experimenter gave him feedback, recorded the response, and proceeded on to the next trial.

For a given set of stimulus conditions to be described in the experiments below, a complete block of trials consisted of a series of 25 such forced-choice trials, the first five of which were considered as practice trials and were discarded from subsequent analysis. Except for those series in which the observer was able to detect correctly the gap for the first 10 consecutive trials, for which he was then assigned a perfect score of 100%, the observer's performance for a given block was assessed as the percent correct out of 20 forced-choice trials.

The duration of an experimental session varied from approximately 1 to 2 h, depending upon the number of blocks of 25 trials that were run as well as the selected luminance levels of the rectangles employed. Target luminance strongly affected the duration of an experimental session because the observer was instructed to depress his switch for each trial pair only when he was fairly certain that no afterimage (or icon) of a previous flash remained. At the highest luminance levels, this might require a 20- to 25-sec delay per flash compared to a 2-4 sec interflash interval at the lower luminance levels. Within each experimental session, there was a brief (2- to 4-min) rest period after each series of 25 trials, during which time the experimenter made the appropriate change in stimulus conditions and checked target alignment of the rectangles from the two projectors for precise gap width. For the more extensively studied conditions in which a given subject was run with an entire range of colors at each of several ISIs (e.g., 7° fixation for subject G.L.), data collection extended over a period of months. For other conditions in which fewer colors and ISIs were examined (e.g., central fixation for subject J.L.), data collection was completed in just a few weeks.

Although the wavelength (i.e., color filter) manipulation of each ISI was performed in a nonsystematic and different order for each subject, the ISIs were always presented in an ascending sequence, with brief ISIs examined first and long ISIs last. Extensive pilot work had indicated that subjects often require considerable experience with shorter ISIs before responding comfortably and reliably at longer ones. This systematic manipulation may have resulted in some practice effects in the data to be presented, since subjects were generally more experienced by the time they received the longer ISIs, but such a procedure was considered superior to the alternative of days and even weeks of practice at all ISIs followed by a completely randomized sequence of ISIs.

The parameters that were varied during the course of these experiments were luminance, wavelength, ISI, and eccentricity. At 7° eccentricity, G.L. was run with all six colored filters, J.L. and D.V. with Nos. 73, 75, and 92. At 3° eccentricity, J.L. was run with all six filters, while G.L. was run with only Nos. 29 and 75. With central viewing, G.L. was run with Nos. 29, 61, and 75; J.L. with Nos. 29 and 75. At 10° eccentricity, only G.L. was run, using Nos. 29 and 75 filters.

Calibrations. The absolute luminance of the rectangles was measured periodically with a Leeds and Northrup Company Macbeth illuminometer. Since the light sources were ordinary projectors, the luminance level was probably fluctuating over time due to changes in the line voltage and in the lamps. For these reasons, we deliberately avoided plotting data in terms of absolute luminance levels, but instead tried to measure relative luminance levels between conditions run within a day or two of one another. Even so, as can be seen by our procedure, this was not strictly possible, so there may be sources of error due to fluctuating luminance levels. We also caution that our stated absolute levels are only approximate.

The tolerance levels for the neutral density filters we used are ±5% as specified by the manufacturer. With a United photometer, we measured the densities for the small densities (up to a few 10ths of a log unit) in situ with the various colored filters (see Sakitt, 1972, for procedure). However, we did not have enough light to measure the values of the more dense filters in situ, and we did not know the spectral transmission of the opal screen, although it appeared to be white. Therefore, we used a special technique to verify that our procedure of using the nominal values for the neutral density filters was permissible for the degree of accuracy we were interested in. This balancing procedure, described in Experiment 3, justifies our usage.

Scotopic (rod) and photopic (cone) effectiveness of a filter. The spectral transmittance of a filter (percent transmitted vs. wavelength) is usually plotted in tables supplied by the manufacturer or can be measured with a spectrophotometer. However, it is sometimes necessary, as in our experiments, to determine the overall density of a given filter for either the rod system (scotopic density) or for the cone system (photopic density). For the sake of simplicity, we first describe the procedure used to measure and calculate the scotopic (rod) density of a particular filter, say the Kodak No. 73 (yellow) in our apparatus. Later, we outline our other procedures. For a more general discussion, the reader is referred to Boynton (1966).

We obtained absolute thresholds by frequency-of-seeing procedures for both white light and with the No. 73 (yellow) filter in the beam. We insured that this was a rod function by having the subject dark adapt for 1 h prior to the experiment and by having the subject note the absence of color in the detected stimulus. We varied luminance by adding neutral density filters to the optical system.

Our result for subject G.L. was that we had to add 2.0 log units of neutral density filters to the white beam compared to the condition with the No. 73 added to the beam. It is well known that all absorbed photons have the same effect on the scotopic system (Boynton, 1966). Since placing the No. 73 filter in the beam had the same effect on the rod system as adding a neutral density filter whose density is 2.0, the scotopic density of the No. 73 filter for G.L. in our apparatus is 2.0 log units. Therefore, the Kodak No. 73 (in our system and for G.L.) had the effect of transmitting only 1% of the light to the rods. This would *not* be true for the cone system, and, in fact, we separately measured the photopic density of this same filter by doing a similar procedure on a 12-mL background. The test was a 15-msec bar 4′ × 58′. This was bright enough to favor cones over rods, as shown by the fact that the color of the test was always obvious at threshold for all the filters. The result was that the photopic density of the No. 73 filter was 1.4 log units so that this filter transmitted only 4% of the light to the cone system.

For each colored filter, the photopic and scotopic densities were determined for each subject at each eccentricity in a similar manner. As a control, we also measured the densities by determining the backgrounds needed for a fixed threshold level (either rod or cone). For the far red No. 92 filter, this was the only method used for the scotopic condition, since the absolute threshold for that filter was determined by the cones (the color red was always observed at absolute threshold). These are traditional Stiles techniques (Aguilar & Stiles, 1954; Stiles, 1959).

We also calculated the scotopic and photopic densities of the filters by using the spectral transmittance supplied by the manufacturer, the scotopic and photopic luminosity curves, and the spectral illuminance of our lamp. We ignored the spectral transmission of the opal screen which appeared white, and we approximated our bulbs to those of standard illumination A (Riggs, 1965). Still, we obtained fair agreement with these theoretical values, usually within 0.1 log units and almost always within 0.2 log units. Part of these differences might have been due to the slide glass used to mount the filters. In the graphs in the paper, we always used the experimental values, since those are the relevant ones. The theoretical check was done to verify that we were, indeed, using the proper conditions.

Later in this paper, we describe various tasks in which we compare performance with the ordinary white beam to the case in which the No. 73 (yellow) filter was placed in the beam. If we found for a particular task that the No. 73 filter acted like a 2.0 neutral density filter, we concluded that the task was more likely to have been performed by the rods than by the cones. If, on the other hand, we found that the filter acted like a 1.4 neutral density filter, we concluded that the task was more likely to have been performed by the cones.

The difference between the photopic (cone) and scotopic (rod) densities of the various filters varied from small to quite large. Some filters were more dense with respect to the rods (like the red filters), but others (like the No. 75 blue-green) were more dense with respect to the cones. This variety made it easier to interpret the results, as will be seen later.

Results

For each stimulus condition (eccentricity, color of beam, and ISI) and for each subject, the percent correct in a two-alternative forced-choice experiment was plotted against the log luminance of the rectangles. Figure 2 shows J.L.'s results at 3° eccentricity for

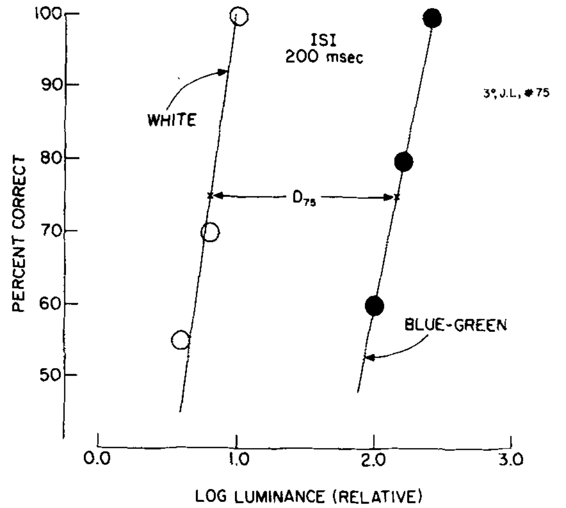

Figure 2. Open circles are percent correct (40 trials each) for detecting the gap with the white beam plotted against the log relative luminance of the stimulus. Filled circles (20 trials each) are percent correct with the Kodak No. 75 (blue-green) filter in both beams. ISI was 200 msec; eccentricity, 3°; subject, J.L. Log luminance of 3 on this scale is roughly 870 mL, or 2.94 log mL. The difference between the 75% correct levels (thresholds for gap detection), D_{75}, represents the effectiveness in log units of this filter for this task.

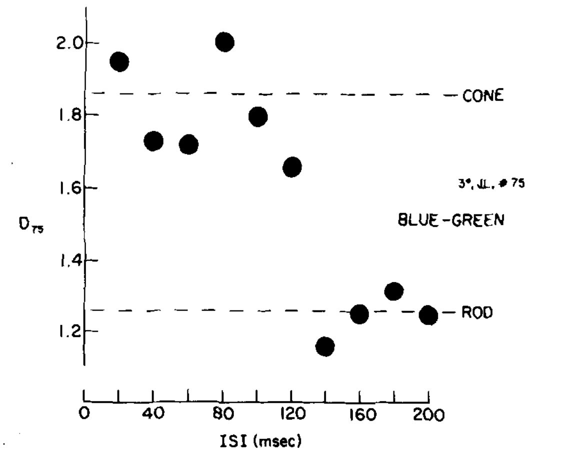

Figure 3. Filled circles are the experimental values of D_{75} (effectiveness of Kodak No. 75 filter) plotted against ISI. The dashed lines are the values of D_{75} predicted from the assumptions that the task was either pure cone function or pure rod function, as described in the text. The subject was J.L.; eccentricity, 3°.

both white and blue-green light (Kodak No. 75) for a 4′ spatial gap between the rectangles and an ISI of 200 msec. The lines were fitted to the data points by a least-squares procedure. The separation between the 75% correct points, D_{75}, is the effective density of this filter for this subject on this task. Similarly, D_{75} values were determined for other ISIs, other colored filters, other eccentricities, and other subjects.

Figure 3 combines the results of many such experiments by plotting D_{75} vs. ISI for the 4′ spatial gap at 3° eccentricity for J.L. The point at 200-msec ISI represents the value of D_{75} shown in Figure 2. The dashed lines labeled "cone" and "rod" were obtained by experimentally determining the photopic (cone) and scotopic (rod) densities of this same filter. This technique is described in the Methods section. If this task was performed solely by the rod system, then the experimental values of D_{75} should lie on the dashed line labeled "rod" which indicates the scotopic density of this filter. If the task was performed solely by the cones, then the filled circles should lie on the line labeled "cone."

The results indicate that for ISI up to 100 or 120 msec, the 4′ spatial gap was detected predominately by the cones, but for ISI of 140 to 200 msec, the gap was detected by the rods. Figure 4 shows the results for another subject, G.L., at an eccentricity of 7° for yellow light (Kodak No. 73). For an ISI of 20 msec, the cones detected the gap, but for ISIs of 100-400 msec, the rods detected the 4′ spatial gap. Similar results were found for all three subjects with all colors tested. That is, at short ISIs, the gap was detected by the cones, but as ISI increased there was a shift so that the rods detected the 4′ spatial gap. Comparing Figures 3 and 4, we note that the No. 75 (blue-green) filter is more dense for the cones and the No. 73 (yellow) filter is more dense for the rods, so that the shift is in opposite directions for the filters. However, for both filters, the shift is still from cones at short ISI to rods at longer ISIs.

Figure 5 summarizes the cone-to-rod shift for all subjects. Figure 5a plots D_{75} (the density of the filter for the detection of the 4′ spatial gap) against the photopic (cone) density of the filter. Each point in Figure 5a is for a single subject, single filter, and single ISI. All results for ISIs of 20, 40, and 60 msec are shown for all subjects and all filters used. Simi-

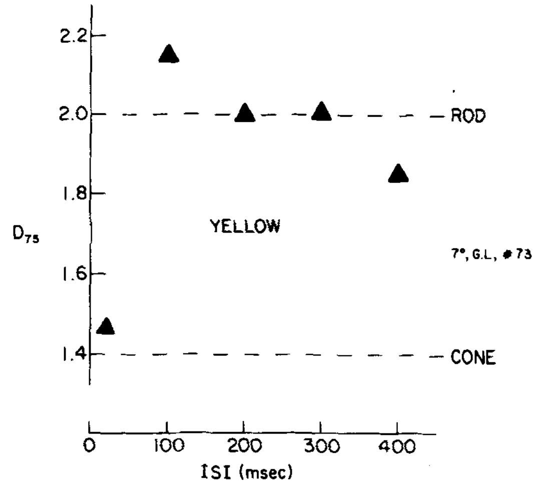

Figure 4. Triangles are the experimental values of D_{75} for the Kodak No. 73 filter for subject G.L. at 7° eccentricity. Dashed lines are predicted rod and cone values of D_{75}, as described in the text.

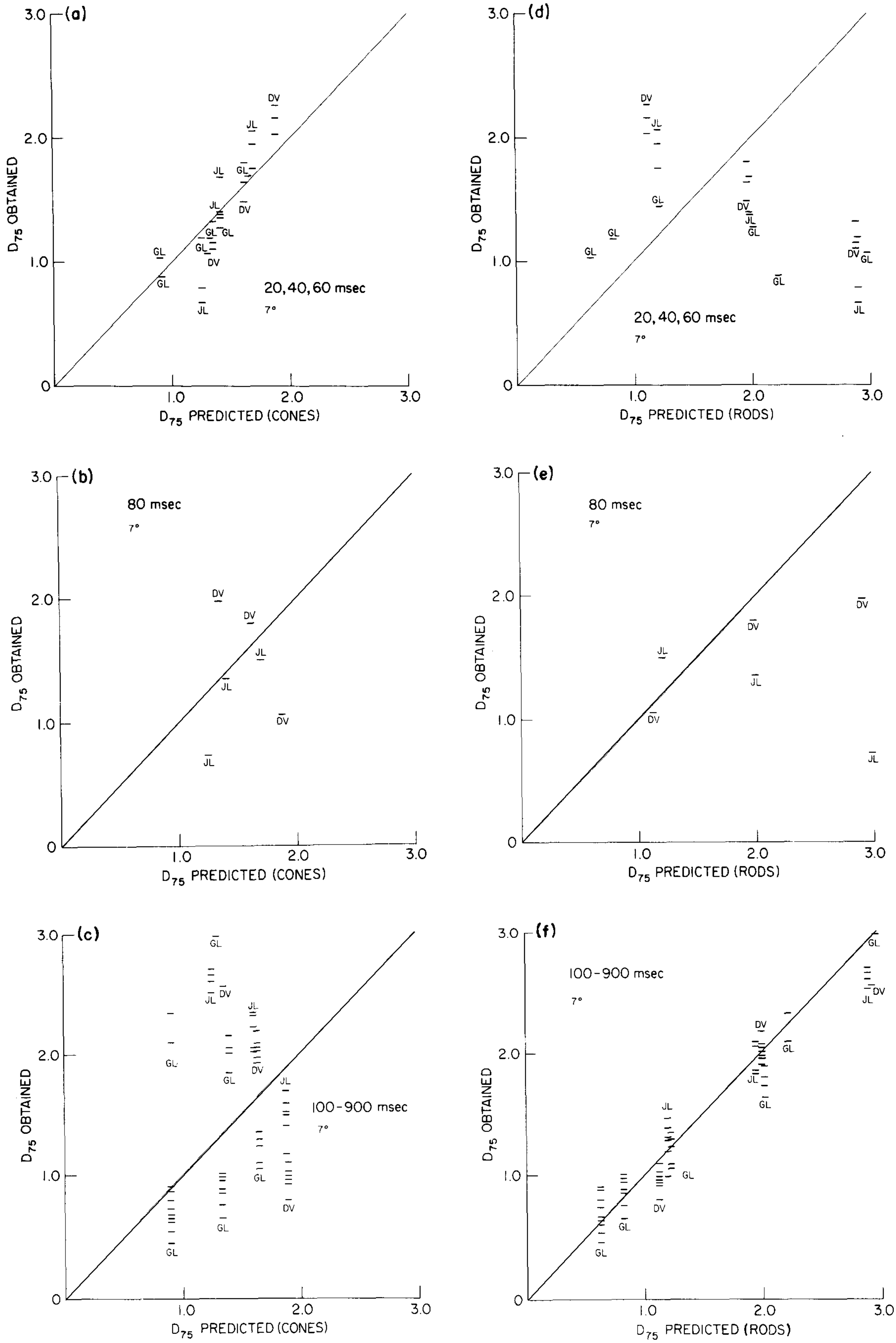

Figure 5. Scatter plots comparing experimental D_{75} values with D_{75} values predicted from pure cone (a, b, and c) and rod (d, e, and f) functions, as described in text at 7° eccentricity for three subjects at ISIs of 20, 40, and 60 msec (a and d); at 80-msec ISI (b and e); and for all ISIs tested from 100 to 900 msec (c and f).

larly, Figure 5b shows the results for ISI equal to 80 msec, and Figure 5c shows the results for ISIs from 100 to 900 msec. These three figures containing 87 points represent all our data taken at 7° eccentricity and represent the results of 87 curves similar to those of Figure 2. The three curves on the right, Figures 5d, 5e, and 5f show the same data, but here the data are plotted vs. the scotopic (rod) density of the filter for each subject.

In all six parts of Figure 5, a straight line has been drawn at 45° so that the lines on Figures 5a, 5b, and 5c represent the prediction for the results if cones alone were performing the task. The lines of Figures 5d, 5e, and 5f represent the prediction for the results if rods alone were performing the task. For ISIs below 80 msec, the data fit the cone prediction (Figure 5a) but the rod prediction is poor (Figure 5d). Conversely, for ISIs from 100 to 900 msec, the cone prediction is poor (Figure 5c) but the rod prediction, shown in Figure 5f is good. It is clear from these curves that for ISIs less than 80 msec the cones are performing the task and that for ISIs greater than 80 msec the rods are performing the task. At an ISI of 80 msec, the results are ambiguous. Therefore, we conclude that the shift from cone detection to rod detection occurs at about 80 msec ISI at 7° eccentricity.

We found that the ISI at which the shift from cone to rod performance occurred varied with eccentricity. At each eccentricity and at each ISI, we compared the D_{75} values with the predicted rod and cone values. At brief ISIs, the results were clear-cut just as they were at 7° eccentricity. Similarly, the results at longer ISIs were also clear-cut. For each eccentricity, we found the ISIs where the cone-to-rod shift was taking place. Figure 6 shows the results where the symbol "R," at a particular ISI and eccentricity, indicates that the experimental values fit the rod prediction quite clearly. The symbol "C" indicates that the experimental values fit the cone prediction quite clearly, and the symbol "X" indicates that the data could not be fit to either the rod or the cone prediction. Each symbol represents all subjects and colors run for a single ISI and eccentricity. The lines are drawn as an estimate of the ISIs at which the shift from cone-to-rod function takes place as a function of eccentricity. At central viewing, the cones operate up to 200 msec. The point labeled R at 300 msec is probably due to an inadvertent eye movement which permitted rods near the fovea to do the task when the foveal cones could no longer do so. At 3° eccentricity, the shift takes place at 120 msec. At 7° and 10° eccentricity, the shift takes place at 80 msec. That is, the value of ISI at which the shift occurs changes with eccentricity.

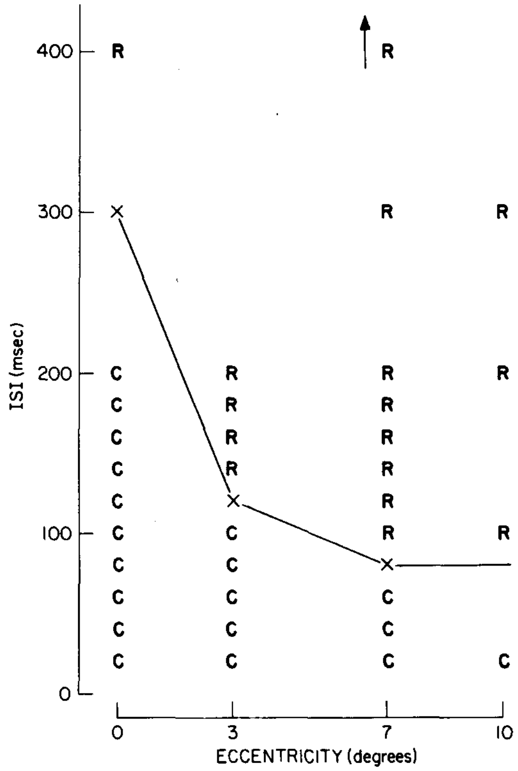

Figure 6. Symbols R, C, and X refer to a fit of the scatter plots to rod, cone, or mixed predictions. Each symbol is for three subjects and a single ISI. Lines are drawn for estimates of ISI for cone-to-rod shift as a function of eccentricity.

Discussion

In order to detect a spatial gap between two rectangles that are not presented simultaneously, there must be, by definition, some visual storage of the information about the first rectangle. In fact, our subjects report using a visual image (icon) in order to "see" the gap. Our results indicate, for example, that, at 7° for ISI of 100 msec or greater, the storage mediating gap detection is in the rod system, whereas for ISIs up to 80 msec, it is the storage in the cone system that provides the information.

Even though we found a cone-to-rod shift for the gap task, all our stimuli were photopic. We know this from the simple fact that the subjects could always detect the color of the rectangles, even at the lowest luminance used for the gap task. Also, in Figure 2, the 75% correct point for white light for the gap task at 200 msec occurred at about 5 mL, a photopic level. Even though we only knew our luminance levels approximately (see Method), the general trend was that, as ISI increased, more light was needed to do the gap task so that, at about 600 msec, the 75% level was roughly 90 mL. At long ISIs, the rods performed the task even though the highest luminance levels were used. Therefore, these photopic stimuli were exciting both rods and cones. These photopic luminances produced cone icons that were relatively short (about 80 msec, in this case), whereas these same photopic stimuli simultaneously produced much longer lasting rod icons, of hundreds of milliseconds, depending upon luminances used. This is consistent with an earlier finding (Sakitt,

1976) that the subjective duration of the icon, as estimated by matching to auditory stimuli, was determined by the rod system for a range of luminances beginning with the absolute threshold and going up to 9 log units higher than this value. This luminance range spanned both scotopic and photopic luminance levels, but the subjective duration of the icon was determined by the rods, not the cones. This implies that under conditions of dark pre- and postexposure fields, the rod icon is usually longer than the cone icon.

The results reported here demonstrate that the rod system can resolve a 4′ spatial gap even at retinal locations as far as 10° from fixation. Conventional measures of acuity (see Millodot, 1966) as a function of eccentricity give lower values of acuity, so that, at 7° and 10°, subjects can resolve 3′ and 10′ gaps in a Landolt C. However, our task essentially involves seeing a black line against a white background, albeit the "seeing" is of an icon. This type of resolution is closer to the task of Hecht and Mintz (1939), who showed that, with foveal vision, subjects could resolve a thin black line that was only .5′′ wide. Of course, this is because of intensity discrimination, not true resolution (see Westheimer, 1972, for review). Therefore, our results cannot be used to deduce the true spatial resolution of the rod system. However, we do note a few relevant points here. First, the resolution of a thin black line does correspond to reading parts of letters. Second, the spatial summation properties of the rod system are not necessarily linked to the acuity of the system. In fact, it has been shown (Sakitt, 1971) that the rod system reacts differently to stimuli with different configurations, even if the stimuli lie within the Ricco area of complete spatial summation. Third, using the information in the icon provides a long time over which information may be integrated, and it is not clear what role that may play.

EXPERIMENT 2
EFFECT OF GAP SIZE ON TASK

Method

Subjects. Three subjects, two male (J.R. and G.L.) and a female (E.W.), served as observers in this portion of the research. Two of the observers were involved in the experiments as part of an undergraduate course in supervised research; the other observer was the second author, G.L.; subjects G.L. and E.W. wore their normal-correction spectacles during all sessions, subject J.R. had uncorrected vision. All three subjects were used extensively over a 3-month period, with four to five 1-h sessions per week. The subjects also alternated as experimenters.

Stimulus and Apparatus. The stimuli were identical with those used in Experiment 1, with the single exception that the width of the first rectangle of each flash pair was varied in order to provide a gap width between successive rectangles of .5, 1.0, 2.0, 3.0, or 5.0 mm (.69′, 1.38′, 2.76′, 4.14′, 6.90′ of arc, respectively). A brief control study indicated that subjects could not discriminate successive 15-msec rectangles on the basis of size for differences of less than 9′ under the conditions used in this study. Rectangle luminance was maintained constant at about 2.81 log mL. This was lower than that of Experiment 1 by 0.13 log units, but, as pointed out there, the absolute luminance level was not constant over time and is only approximate. No colored filters were used. In contrast to the previous study, the level of background (stray) light was somewhat higher due to the absence of black curtains around the projectors.

Procedure. The general procedure was identical to that of Experiment 1. For a given gap width (beginning with the smallest and progressively increasing), the observer received successive blocks of 25 forced-choice trials at increasing ISIs between rectangles until his/her performance fell to a chance level (50%). For the smaller gap widths, ISI was increased in rather small steps of 20 msec, while for the larger gap widths 40-100-msec steps were used. Hence, the obtained results should be taken more as a qualitative description of gap size effects over ISI rather than as a very precise quantitative statement of the effect of increasing ISI for each of several gap sizes. This latter point is further emphasized by the fact that, at the longer ISIs and for the larger gap widths, observers were therefore more practiced than at the briefer ISIs and for the smaller gap widths.

One final difference between the current procedure and that employed in the previous series of experiments concerns the level of adaptation of the three observers. While, in the previous work, all subjects were dark-adapted (monocularly) for a period of 45 min prior to each experimental session, the subjects were dark-adapted (monocularly) for only 15 min prior to the present manipulations. Hence, once again, the point is stressed that the results of the present study should be considered as an overall, rather rough description of a general effect rather than a precise statement of absolute levels of performance for the visual system under a given set of conditions.

The above manipulations were first performed under conditions of central fixation in which observers were instructed to fixate the approximate center of the opal screen prior to each flash presentation. After all gap size data had been collected under this condition of central viewing, the identical manipulations for the three subjects were repeated with a 7° fixation point provided.

Results

Figures 7 and 8 plot the percent correct in the forced-choice procedure for detecting the spatial gap as a function of ISI for central viewing and at 7° eccentricity. The different symbols refer to different gap sizes.

Before we analyze these results, we caution that various problems in the procedure make some types of analysis impossible. First, subjects dark-adapted for only 15 min instead of 1 h, and this might have reduced overall performance. Second, and far more important, the data represented on these graphs were collected during experimental sessions over a course of several weeks. For reasons pointed out in the Method section of Experiment 1, absolute luminances on this projector system cannot be reliably compared across sessions. That is, although the nominal luminance was the same for all the points, the actual luminance probably varied. Nevertheless, in spite of this caution, the overall trend can still be determined. For each gap size, the percent correct tends to decrease as ISI is increased. This is to be expected under almost any interpretation of iconic storage.

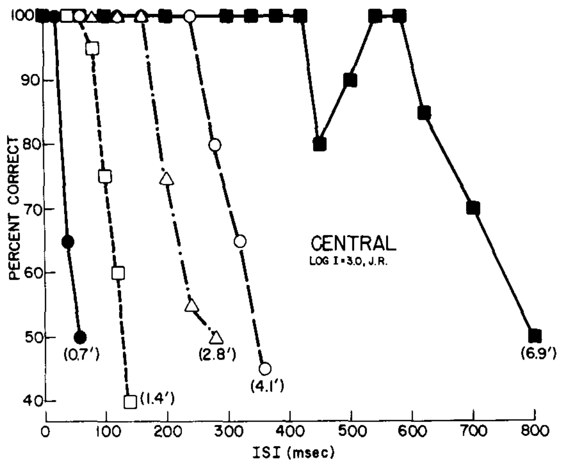

Figure 7. Percent correct as a function of ISI between rectangles for five gap widths for subject J.R. with central viewing. Each point is the mean of 20 trials.

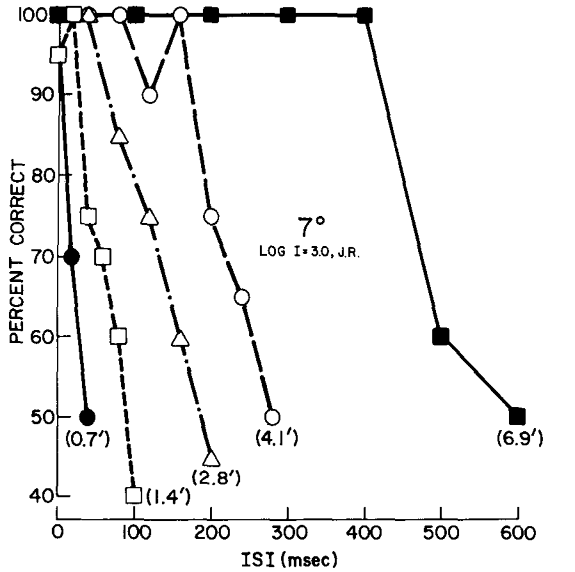

Figure 8. Percent correct as a function of ISI between rectangles for five gap widths for subject J.R. at 7° eccentricity. Each point is the mean of 20 trials.

The other aspect to the result is that, for any fixed ISI, the percent correct tends to increase with gap size. These results were true for both central and 7° viewing. Similar results were found for the other two subjects.

Discussion

First we address ourselves to the question of why it is easier to detect a larger gap than a smaller gap in the icon and whether or not this result is consistent with a photoreceptor interpretation of iconic storage. If one imagines all receptors signaling for a fixed time after the first rectangle is extinguished (an oversimplification), then, to a first approximation, we would expect that the effect of gap size on iconic performance should be similar to the effect of gap size on any acuity task. It is well known (Pirenne, 1967; Riggs, 1965) that acuity depends upon luminance in ordinary visual tasks. That is, the brighter the light, the better the acuity. Or, conversely, the larger the target to be resolved, the lower is the required luminance. Therefore, a photoreceptor interpretation of iconic storage would predict that for a fixed strength icon (essentially equivalent to a fixed ISI), the larger the gap, the better the performance. Similarly, as ISI increases, the strength of the icon would tend to diminish, and therefore the acuity of the icon would tend to get worse. Therefore, the results involving gap size are to be expected from a photoreceptor icon.

Earlier in the paper, we pointed out that there might be a problem in explaining why eccentricity should influence the value of ISI for which the performance shifted from cones to rods. We suggest that this is related to the acuity problem. In general, for any eccentricity, the cones probably have better acuity than the rods. Therefore, for a fixed-strength icon (fixed ISI), the cones would be expected to resolve a gap better than the rods. But it isn't clear how luminance differentially produces rod and cone icons. Therefore, these two factors of luminance and acuity have to be considered. Whatever these factors are, they should be independent of ISI. But the results show that, although cones detect the gap at short ISIs at threshold, they can't do so at longer ISIs. This means that the cone icon fades quickly so that it can no longer detect the gap. Once the cone icon is gone, or greatly impoverished, the rod icon will provide the storage. Our results indicate that by 80-140 msec, except for central viewing, the cone icon is so impoverished that the rods provide the storage for detecting a gap that is even as small as 4′ of arc.

We suggest that the reason eccentricity plays a role in determining the extent over which the cone icon can be utilized is that acuity falls off with eccentricity for cone vision. Our task was essentially a threshold task for detecting a spatial gap. Since the cone icon seems to be briefer than the rod icon, the shift from cone to rod performance will occur when the cone icon is too impoverished to detect the gap. This is equivalent to arbitrarily setting a functional criterion for the end of the cone icon. Since acuity falls off with eccentricity, for a fixed criterion of iconic clarity, the ability to perform will fall off with eccentricity.

In Sperling (1960) experiments, the letters are usually larger than 1°. In ordinary reading, letters are often between 0.5° and 1° and words usually span several degrees. The rod-free area of the retina has been estimated as being between 0.5° and 2.0°. Its dimensions are not known accurately, but it is usually estimated as being 1° (Duke-Elder, 1968, p. 545; Pirenne, 1967). Therefore, it is clear that in typical Sperling experiments the rods are usually being stimulated. As we pointed out in the previous paper, photopic luminances generally stimulate both rods and cones and usually produce robust rod icons. We also point out here that it is unusual to have more than one letter in the rod-free part of the fovea, even when reading, and in typical experimental situations all letters are outside this region.

Our experiments used a threshold procedure. But, in typical Sperling experiments and in real-life situations, the luminances are above those that just permit gap detection. In those cases, probably both long-lasting rod icons as well as short cone icons will be produced. Although the cone system will have better acuity, the rod icon will tend to be longer and can be processed longer. This might permit the rod system to detect gaps even at short ISIs. Therefore, we conclude that our results indicate that, under typical brief viewing conditions, the rod system is probably the only source of storage after 100-200 msec, whereas, for shorter times, it is unknown how much the rods and cones each contribute to iconic storage.

EXPERIMENT 3 BALANCING METHOD TO CHECK THE ASSUMPTION ABOUT USING NOMINAL VALUES FOR THE NEUTRAL DENSITY FILTERS

This method simply involves using the *same* physical filters for frequency-of-seeing curves at threshold and for the gap detection task. Although we used this method for all filters, for simplicity, we describe the procedure in detail for one example, G.L. at 7° eccentricity for the No. 73 (yellow) filter. For example, Figure 9 shows the frequency-of-seeing curves at absolute threshold for the white beam and for the same condition with the No. 73 (yellow) filter inserted in the beam. The values listed next to the curves are the nominal values of the filters positioned in the beam. Since we could calibrate only the low-density filters, we can't be sure of the absolute values, but we can be sure that the curves are indeed that close to one another, since the differences depend upon the small filters which we could measure. That is, the result means that the scotopic density of the No. 73 (yellow) filter is the same as that of the filter whose nominal value is 2.0 log units within 0.1 log units.

Figure 10 shows the results for detecting the gap with a 200-msec ISI for both white light and with the No. 73 (yellow) filter added to the stimuli. The important point is that the white beam has the physically identical neutral density filters added to it as in Figure 9. The density of the No. 73 filter for this task is that of the same nominal 2.0 filter used in Figure 9, within 0.1 log units. This was true even though the luminance level was much higher for the gap detection task than for the frequency-of-seeing curve. Therefore, no matter what the actual value of the 2.0 filter is, comparison of Figures 9 and 10 indicates that the density of the No. 73 filter is the same for the absolute threshold as for the gap detection. We conclude that the rod system was probably detecting the gap. We used this balancing method

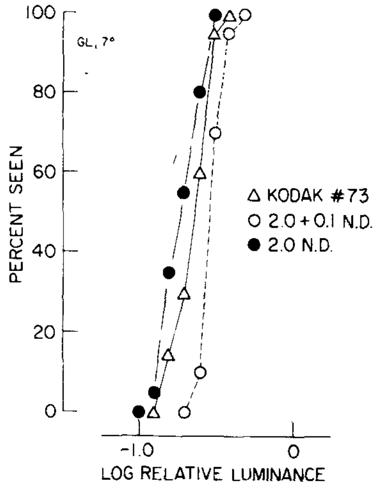

Figure 9. Percent seen vs. log relative luminance for G.L., 7° eccentricity. Same luminance scale as in the rest of the paper. Open triangles are with the Kodak No. 73 in the beam; filled circles are with the 2.0 neutral density filter in the beams; and the open circles are with the 2.0 and the 0.1 neutral density filters in the beams. Each point is based on 10 trials. Absolute threshold with the 2.0 neutral density filter in the beam is roughly .001 mL. Stimulus was a 15-msec 47′ × 56′ rectangle.

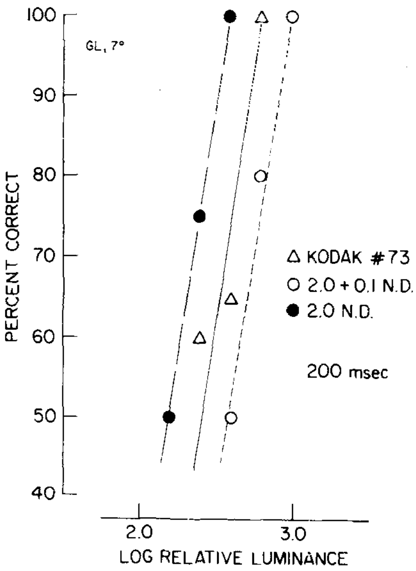

Figure 10. Percent correct for gap detection vs. log relative luminance for G.L., 200 msec ISI, 7° eccentricity. Each point is based on 20 forced-choice trials. Luminance scale is the same as elsewhere in this paper, such that 3.0 corresponds to roughly 870 mL (2.94 log mL). Threshold for gap detection with the 2.0 neutral density filter in the beam is roughly 218 mL. Symbols have the same meaning as in Figure 9.

for all the colored filters at one rod and one cone condition. The results were always consistent with what we obtained using the nominal values of the filters.

In the rest of this paper, where we have used the nominal values for the neutral density filters, we may have introduced some error. However, on the average, we would introduce the same error in both the predicted and the experimental values for the scotopic and photopic effectivenesses of the various filters. Therefore, even though the nominal values may not be accurate, the fit to our data is not likely to be changed, since the same error will be introduced in both the predicted and experimental values (equivalent to a vertical shift of both experimental and theoretical values in the figures).

We add that we found that the calculated values for the scotopic and photopic densities agreed moderately well with the values obtained from the threshold technique. This lends support to our justification for the use of nominal values. Also, we compensated for our lack of knowledge about the precise values for illuminance and densities by obtaining data on a wide range of ISIs and over a wide range of wavelengths. To the extent that the large amounts of data we collected show a systematic effect, as seen in our figures, our approximate techniques are justified.

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