The Effect of Background Luminance and Contrast Upon Visual Search Performance

A research report on Project 63 of the Illuminating Research Institute.

Robert M. Boynton
Daniel E. Boss

Foreword

THERE is much experimental evidence, generally supported by everyday experience, to show that more light means better sight. For example, it has been shown that higher levels of illumination lead to reduced contrast thresholds,[1] improved visual acuity,[2] and decreased visual reaction time.[3] However, much of the relevant laboratory work has involved the use of stimuli carefully imaged upon the fovea of the eye. We now wish to extend this knowledge by using a visual task which, although it includes foveal vision as an important component, also critically requires the use of peripheral vision.

Situations exist where vision in the near periphery is actually better than at the point of fixation; these involve dim stimuli, such as stars of the weaker magnitudes, that cannot be seen when directly fixated, but which appear when the gaze is shifted slightly to one side. These situations are of relatively little interest to the illuminating engineer, who is usually concerned with photopic conditions. Although the best vision at these higher light levels always occurs exactly at the point of fixation, peripheral vision continues to be very important. This can be dramatically demonstrated by walking about with one eye covered, while holding a tube in front of the other eye that restricts the visual field to a degree or two. With such "tunnel vision," where only what is more-or-less directly fixated can be seen, all information about the potential visual content of the vastly-larger peripheral part of the field is lost, and is sorely missed.

Peripheral vision, which normally gives us the "big picture," is indistinct in the sense that we cannot directly resolve fine detail with it. This fact is easily verified by attempting to read this line of print while looking two or three lines above or below it. Yet we do not normally perceive a clear central region that is surrounded by an otherwise fuzzy visual world. On the contrary, the entire visual world seems clear to us. Why is this? One part of the answer relates to the fact that our eyes are very mobile. If an object in the peripheral part of the visual field attracts our attention, we quickly move the eye to place the image of that object squarely in the foveal center. This causes the object to be visible in greatest detail. Although we cannot any longer see the previously-fixated area as clearly as before, we do remember it, and it does not seem to us any less distinct. Indeed, we need only to look back at it to verify our clear impression and to reinforce our memory of its details. So it is that all parts of the visual field are potentially as distinct as that part which is momentarily being fixated.

Normal human vision is built up from a series of "snapshots" separated by rapid saccadic eye movements. In a static visual environment, with the head fixed in position, smooth eye movements normally do not occur and vision consists of a series of discrete fixations, each lasting from a fraction of a second to several seconds, separated by rapid eye movements that take up less than ten per cent of the total viewing time. Given that the eye must be in some particular position at a given moment, what factors determine where the next point of fixation will be? Relatively little is known in detail about the complex determinants of this process, but it is clear that peripheral vision is importantly involved. We are born with

---

AUTHORS: Center for Visual Science, University of Rochester, Rochester, N. Y.

a fixational reflex, which is a tendency to turn the eyes toward a bright object. But our attention is usually attracted toward an object not because it is bright, but rather because it is significant.[4] The informational content of a peripheral stimulus usually dominates, while the basic reflex is inhibited, as for example when an experienced driver avoids looking at oncoming headlights.

In the experiments to be reported, we have utilized a visual search task. Although necessarily oversimplified, it contains many of the essential features found in everyday photopic vision. We repeatedly presented the observer with random arrays of dark circular spots seen against an otherwise uniform background. He was instructed that on some occasions one of the spots, instead of being a circle, would be a square. His mission was to look intently for the square and either to report its presence or declare its absence, doing so in the shortest possible time consistent with nearly complete certainty and correctness. (We have previously[5] reported on the use of this method in studying adaptational problems in vision.)

In addition to varying the luminance of the background, we varied the contrast between the square and background to provide a graded level of task difficulty. In a second experiment, we also varied the size of the stimuli.

The interplay of foveal and peripheral vision in this search task, and the relative importance of each, may best be understood by describing the situation in subjective terms. When the background luminance is high, and the contrast of large forms upon it is great, we have the easiest condition of all. In this case, a square is usually seen almost immediately in peripheral vision, and is correctly recognized and reported as a square without the need for eye movements. The response time is well under a second, and consists primarily of irreducible components of visual reaction time—the time required for signals to be generated by the photoreceptors and delivered through the synaptic relays of the retina, for impulses to reach the brain from the eyes, and for other impulses to be directed outward to activate the finger muscles that depress the response switch. As the luminance of the background is reduced, and/or the target-background contrast is decreased, the subjective impression becomes that of seeing objects in the periphery whose locations are obvious, but whose shapes are only vaguely discernible. If the conditions are not too impoverished, one of the peripheral forms, prior to eye movement, may seem to be a most likely candidate for being a square. Since it is uncertain on a given trial that any of the objects are squares, and also because the observer has been motivated to be conservative about reporting their presence, he will not respond yet. Instead, he will move his eyes to fixate the suspected target. Sometimes a single eye movement may be sufficient to confirm the identification; if so, his response will follow quickly. On other occasions, of course, the initial peripheral impression will turn out to be wrong. This probability of error increases as a function of the distance between the part of the array being fixated and the location of the suspected target. For this and other reasons, a statistical distribution of response times is expected, and is found; many trials are therefore needed to establish quantitative results.

As conditions are made still more difficult by further reducing the size and/or the contrast of the squares, there will be fewer and fewer occasions when the location of even a suspected square can be discerned upon initial fixation. All forms may be seen at a glance, but they all look like circles unless one of them is nearly exactly fixated. In this case, the subject may adopt the strategy of fixating near the centroid of the most densely-grouped portion of the stimuli presented. It should be noted in this connection that stimuli are arranged randomly, and therefore not uniformly; two-dimensional random arrays produce very decided subjective clusters. If the square is in fact a member of such a cluster, it may be discriminable upon fixation anywhere within the group, although an additional fixation or two may be necessary to confirm its presence. Since it is not possible to re-fixate in less than 200 to 300 msec, each additional fixation adds significantly to the total response time. If, as may happen, a square is not a member of the first cluster, fixation must then be re-directed elsewhere, possibly at the next most densely grouped cluster.

The description of the previous paragraph is a bit fanciful and oversimplified. It ignores the fact that, other things being equal, a square that is a member of a cluster will be harder to discriminate than one surrounded by a uniform luminance. The process has also been described as if eye movements are always consciously directed, or at least controlled by a deliberate strategy that is rigorously followed. Actually, eye movements run themselves off largely without conscious control. Even the experienced subject, in the routine of the experiment, is unlikely to be concerned about, or even to know, what his eyes are doing.

Consider finally what is involved when stimuli are small and contrast is very low. Under these conditions the fovea is the most sensitive region of the retina and highly accurate fixation may be required even to see that a form is present; in the fortuitous case where a form is fixated and therefore seen, the discrimination between square and circle may nevertheless be difficult or even impossible. Fixation in this case becomes a process that is undetermined by peripheral vision or the spatial distribution of the forms; very many eye movements are made, and it is very unlikely that a

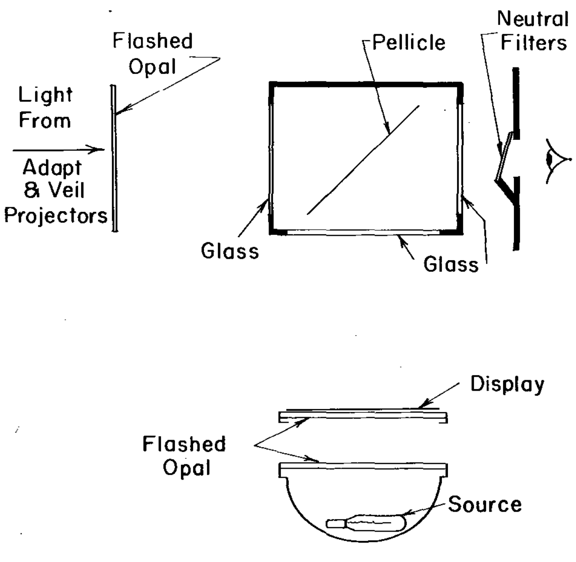

Figure 1. Schematic diagram of experimental apparatus (approximately to scale).

square will accidentally be fixated during the search period.

The search task thus seems to be a reasonable analog of real-world vision, demanding the use of central and peripheral vision, and of the eye movements that critically link the two. The major purpose of this study is to determine exactly how the luminance of the background affects the efficiency of this kind of complex visual performance.

Apparatus

The apparatus was designed to provide a square field of light, subtending 20° by 20° of visual angle, in which the following events took place: (1) Prior to exposure of the stimulus display, the subject viewed, binocularly, a blank pre-adapting field of specified luminance. (2) Upon command from the experimenter, the subject depressed one of two buttons held in his hand. This caused the blank field to be extinguished, while in its place a stimulus array appeared. The background of the stimulus array was set to the same luminance as the blank field which preceded it. The forms that constituted the stimulus array were always darker than the background, but variably so, over an adjustable range of contrasts. (3) When the subject was ready to respond, he pushed the second button. This immediately turned off the stimulus field and caused the blank field to return. (4) The time between the depression of the two buttons was recorded.

These objectives were accomplished in the following way. The blank field was provided by transillumination of an 8 x 8 in (20.3 cm) sheet of flashed opal glass by light from a Carousel slide projector, containing no slide, located 24 in (61 cm) behind the glass. The opal glass is shown at the left in Fig. 1, which shows part of the apparatus drawn approximately to scale. The subject's eyes were located 22.6 in (57.4 cm) from the flashed opal glass, as shown on the far right side of the figure. Between the flashed opal glass and the eyes, a thin pellicle was positioned, oriented at 45° with respect to the subject's line of sight. The pellicle was mounted inside a box measuring eight inches high, ten inches across, and 11 inches deep (20.3 by 25.4 by 27.9 cm; depth is not shown in Fig. 1). Plate glass on three sides of the box allowed light to be transmitted and, together with solid plates on the top and remaining two sides, protected the pellicle.

The purpose of the pellicle was to reflect light from below, where the stimulus display was physically located. A lamp was fitted into the bottom of an eight-inch-diameter aluminum bowl. The top of the bowl was covered with flashed opal glass. Another piece of flashed opal glass, located three inches (7.6 cm) above the bowl, further diffused the light and provided support for the stimulus display.

The stimulus material consisted of small squares and circles, attached to eight-inch by eight-inch plastic sheets. These forms were completely opaque, so that if viewed without light being added from the veil projector, they were seen in 100 per cent contrast. This contrast could be reduced by adding light from the veil, while decreasing the luminance of the display to keep the total luminance of the two fields, excepting those regions containing stimuli, at the original value.

In order to reduce luminance at a given contrast, neutral filters were added just in front of the subject's eyes, as shown. These also reduced the light from the blank pre-adapting field. Controlling luminance in this way also ensured that the timing of the onsets and offsets of the various lamps would not differ from one luminance to another. The filters were made up from stacks of 0.6 and 1.0 log unit Wratten No. 96 sheets, mounted without glass into convenient cardboard holders. Separate mounted stacks of filters were used to obtain each of the luminance levels used except the highest, which was obtained without filters.

Timing was accomplished by a digital timer, started by the subject, which actuated relays that controlled the lighting circuits. The lamps used in the Carousel projectors were rated at 750 watts, while a 750-watt projection lamp was used in the bowl below the stimulus array. These lamps were switched on and off by the timer as desired, in such a manner as to produce the minimally noticeable artifact during the transition time. Although the transition time was an appreciable fraction of a second, it was small compared to most of the response times measured, and was minimized by the use of a trickle current through the 750-watt projection lamp.

Calibrations

The 20° field was divided into 16 equally-sized squares with the use of a sheet of the plastic material, devoid of stimulus forms, lightly ruled. The center of one of these squares was measured with a Spectra Spot photometer, five times during the first experiment, and once before and again after the second experiment. On one occasion, the luminances of all 16 squares were measured, with the reference square set at 400 fL (1370 cd/m^2). This was done for all three fields. The luminances recorded from these measurements are given in Table I. Fig. 2 shows iso-contrast contours for the condition specified as five per cent. It will be seen that the range of contrast variation is on the order of 2 to 1; five per cent is very close to the average contrast of the 16 areas that were measured.

The values of the lower luminances used in the experiment were measured with the Spectra Spot photometer, with the filter stacks successively in place. The objective was to use luminance steps that differed by a factor of 4; some unevenness of this spacing was obtained at the lower luminance levels. The actual values were used, of course, in plotting the data.

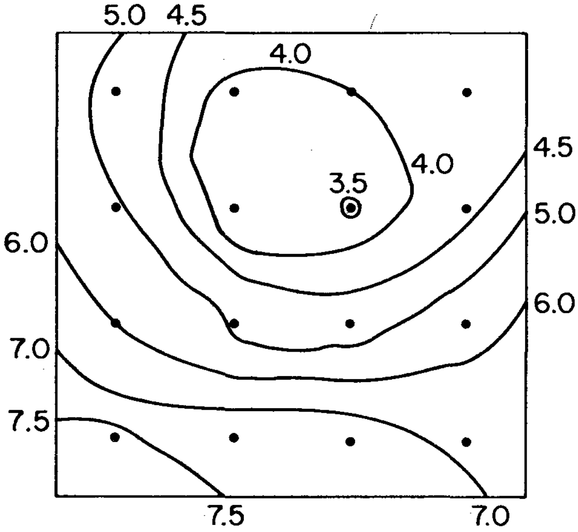

Figure 2. Iso-contrast curves across the field of the stimulus array for the nominal 5-per cent contrast condition. The solid points show the location of the actual measurements of luminance from which the following contrasts were calculated (reading from left to right and top to bottom): 4.9, 3.8, 4.0, 4.3, 5.1, 3.9, 3.5, 4.4, 6.0, 4.9, 4.7, 5.4, 7.6, 7.3, 7.2, and 6.5.

Procedure: Experiment 1

Subjects

Ten observers, four male and six female, were used in the experiment; all were undergraduate students at the University of Rochester with 20/20 visual acuity, corrected where needed.

Stimulus Materials

Eighty stimulus arrays were prepared. Each contained 16 randomly-positioned forms. Forty of the arrays contained only circles; the other 40 contained 15 circles and one square. The circular forms subtended 10 minutes of visual angle; the sides of the square forms subtended about nine minutes. A square was therefore of nearly equivalent area, but just slightly larger than a circle. The subjective area of the two classes of forms, under difficult viewing conditions where their shapes could not be discriminated with certainty, was very similar; it is doubtful that any correct discriminations were based upon differences in subjective area, rather than shape (as intended). It may be noted that the size of these forms is only twice that of a 20/20 letter in the standard Snellen acuity test, so that even under optimal viewing conditions the task of the first experiment cannot be classified as an extremely easy one.

Procedure

Within Sessions. Prior to the beginning of data collection, a subject was exposed for five minutes to the adapting field. He then initiated the presentation of a stimulus array by depressing a green button and searched for the possible presence of a square target somewhere in the array. Immediately upon finding a square, or following his decision that no square was present, he pressed a red button which caused the stimulus array to be replaced again by the adapting field. (There was no need to look at the buttons, one of which was held in each hand.) He then told the experimenter whether or not he had seen a square. After a variable interval of 10 to 20 seconds (sufficient for the experimenter to change the stimulus array, record the response, and, where appropriate, give a reward) the experimenter told the subject to press the green button again. When ready, the subject did so and the process was repeated for 40 trials in random sequence, 20 where the stimulus arrays contained a square (target trials) and 20 where they did not (no-target trials). Response time is defined as the interval between the depression of the red and green buttons, measured to the nearest 0.1 second (rounded downward). If the subject failed to respond after 20 seconds, the trial was automatically terminated and a "no-target" response time recorded, for purposes of analysis, as 20.1 seconds. Two sessions of this kind were run for each experimental condition.

Rewards. A reward procedure was used to stabilize motivation and keep the level of "false positives" (reporting a non-existent square) at a minimal level.

Each trial stood a 0.375 chance of being specified in advance as a "reward trial;" if so, the subject was rewarded afterward, provided that his response was correct regarding the presence or absence of a square (unless his "square" response was very slow—see below). The subject did not know whether a particular trial was to be a reward trial. Since the numbers of reward trials varied somewhat from one session to another, he could not count them in order to deduce when the supply of such trials had been exhausted. This would have been difficult to do in any case, since no feedback of any kind was ordinarily given to the subject when he failed to find a square that was actually present. The opposite "false alarm" type of error was penalized 10 cents on all trials where it occurred.

Rewards for correct responses, when a square was present, were either 0, 5, 10, or 15 cents. The amount was contingent upon the response time in the following way. On the basis of results obtained in the preliminary sessions, a particular luminance condition was designated, for a given subject, as "high," "medium," or "low" in difficulty. Rewards were adjusted in order to keep earnings reasonably constant across conditions. The twenty seconds of possible response time were divided into four zones, separated by three boundaries. For the "easy" conditions, these boundaries were approximately 1.0, 2.0, and 5.0 sec. In order to prevent the subject from developing a time sense with respect to these boundaries (which might have biased his response times) a deliberate variability was set into the boundary times. This was done by randomly selecting the boundary time for each trial from a population of such times having a mean value as specified above, and a standard deviation of 0.5 second. (This results in some negative times for the shorter boundaries, so that a subject would be incapable of earning the maximum reward on such trials.) The relation of the mean boundary times to task difficulty, showing the amount of reward pertain-

Table I—Measured Luminances for 16 Positions in the Stimulus and Veiling Fields at the Nominal 400-fL (1370-cd/m^2) Condition, and Calculated Contrasts.

Stimulus Field				Veil				Contrast			
Nominal Contrast = 100%											
265	345	330	240	000	000	000	000	100	100	100	100
340	450	440	360	000	000	000	000	100	100	100	100
375	490	495	395	000	000	000	000	100	100	100	100
430	530	540	395	000	000	000	000	100	100	100	100
Nominal Contrast = 40%											
160 fL Av. (548 cd/m^2)				240 fL Av. (822 cd/m^2)				40% Av.			
106	138	132	96	160	270	260	170	40	34	34	36
136	180	175	145	200	360	380	250	40	33	32	37
150	195	197	158	190	300	320	220	44	39	38	42
170	210	215	157	160	210	220	180	52	50	49	47
Nominal Contrast = 20%											
80 fL Av. (274 cd/m^2)				320 fL Av. (1096 cd/m^2)				20% Av.			
53	69	66	49	210	355	340	220	20	16	16	18
68	90	88	73	260	470	500	330	21	16	15	18
75	98	99	80	250	395	420	290	23	20	19	22
86	106	108	80	210	275	290	235	29	28	27	25
Nominal Contrast = 10%											
40 fL Av. (137 cd/^{2}m)				360 fL Av. (1233 cd/m^2)				10% Av.			
26	35	33	24	240	410	390	255	10	8	8	9
34	45	44	36	300	530	570	375	10	8	7	9
37	49	49	40	285	445	480	330	11	10	9	11
43	52	54	40	240	310	330	270	15	14	14	13
Nominal Contrast = 5%											
20 fL Av. (69 cd/m^2)				380 fL Av. (1301 cd/m^2)				5% Av.			
13	17	17	12	255	430	410	270	5	4	4	4
17	23	22	18	315	560	600	395	5	4	4	4
19	24	25	20	300	470	505	350	6	5	5	5
21	26	27	20	255	330	350	285	8	7	7	7

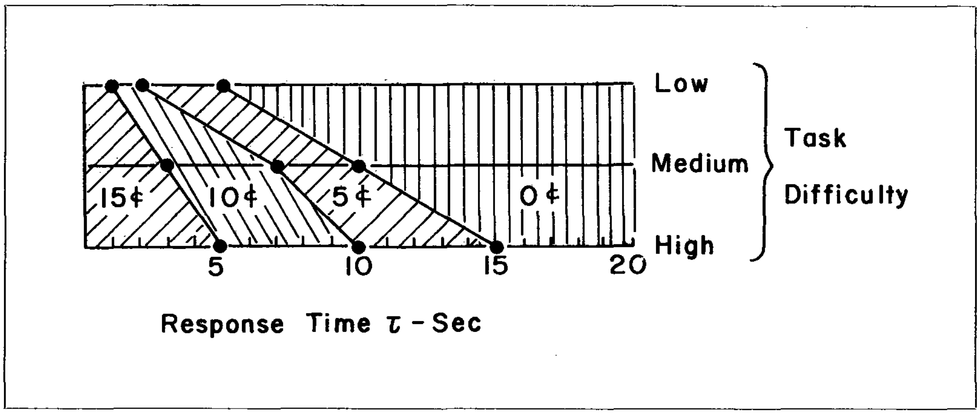

Figure 3. How rewards were distributed in time for target trials. See text for explanation.

ing to each time zone, is shown in Fig. 3. Correct "no square" responses were rewarded with 5 cents and a 10-cent penalty was assessed for incorrect "square" responses, both without regard to response time. No penalty or reward was attached to not finding a square that was actually present. These reward conditions were designed to elicit the fastest possible "square" response while keeping the false alarm responses at a minimal rate.

On those trials where the subject concluded that no square was present, the reward conditions provided no extra incentive for quick response. There was, nevertheless, a non-monetary reward value for a rapid response, since it immediately terminated the trial and thus shortened the experiment.

Experimental Design. Each subject served in two sessions at all or most background luminances. A criterion was adopted to exclude impossibly difficult conditions. When it became clear during preliminary testing, or from the first several trials of a planned session, that the subject would fail to see at least 50 per cent of the targets and/or yield a median response time of more than ten seconds, then the subject was not examined under that condition, which was accordingly judged to be too difficult.

The conditions that were examined, specified in terms of that portion of the display nearest the average of the 16 areas sampled, were as follows: (a) 400 fL (1370 cd/m^2) at 100, 40, 20, 10, and 5 per cent contrast; (b) 100 per cent contrast [in addition to 400 fL already specified under (a)] at 105, 23, 5.8, 1.50, 0.20, 0.055, and 0.012 fL (360, 79, 20, 5.1, 0.69, 0.19, and 0.041 cd/m^2). These conditions are represented in Table V (see *Results*) as those producing the data in the top row and left-hand column, part of a much larger matrix of stimulus conditions involving combinations of these contrasts and luminances. The remainder of the matrix was examined in Experiment 2.

Procedure: Experiment 2

The purpose of the second experiment was to obtain data pertaining to the inside cells of the matrix of luminance and contrast conditions, and to investigate the influence of target size in the stimulus array. Two subjects from Experiment 1 were selected for testing under this more extensive range of conditions.

Both subjects (No. 4 and No. 10 from Exp. 1) were run in all cells of the matrix of Table V for which they were able to meet the criterion of greater than 50 per cent detection or a median response time of ten seconds.

Stimulus displays were prepared as in the previous experiment, except that two sizes of forms (10 minutes and 30 minutes) were used. Each display contained 16 forms, eight small and eight large. Forty target displays were used; 20 of these contained one large target square, seven large circles and eight small circles; the other 20 contained one small target square, seven small circles and eight large circles. There were also 40 no-target displays that contained eight small circles and eight large circles. Locations were again determined by random assignment.

Each subject was run for 5360 trials. Half of these were no-target trials, a quarter were large-target trials, and a quarter were small-target trials. Luminance was held constant within each session; approximately one third of the 20 trials for each of the five contrasts were run in each session, for each target size, while approximately twice that number of no-target trials were mixed in, yielding on the order of 210 trials per session, 25 sessions per subject.

Reward conditions were equated for diagonals (bottom left to top right) of the matrix of Table V, and adjusted as in Experiment 1.

Some Miscellaneous Aspects of Procedure

The 80 stimulus arrays used in Experiment 1 were always presented in the same order, although the experimenter began sessions at different parts of the sequence. There were four possible ways to insert the array into the apparatus; all were used in unpredictable order. In the first experiment, only one luminance level was used in each session; in some of the sessions of the second experiment, two or more luminance levels were used, and in some cases three sessions were collapsed into two sittings. In such cases five minutes of adaptation time was allowed to elapse at each change in luminance.

The sequence of experimental trials, including all stimulus and reward parameters, was set up by computer and the output extracted in the form of punched cards. The cards were fed through a key punch during the experiment, one card for each trial, and the subject's response time (and an indication of whether the response was correct) was punched by the experimenter, who read the times from the digital timer. Data processing was done later by computer, using the cards as input.

No record was kept of which particular stimulus array had been used, in which of its possible positions, on a given trial. The only indication on the computer card, pertaining to stimulus array, was whether a square was present, and if so, its size.

Experiment 2 was set up by affixing large squares and circles in place of some of the small ones that had been used in Experiment 1, using therefore the same basic random patterns and pieces of plastic. The second experiment was completed in three days for one subject and, following this, in one week for the other, with as many as seven long sessions in a single day for a subject. Despite the intensity of the experimentation, there was no indication that the two subjects who participated were able to memorize patterns or profit in any way from the fact of having seen the arrays so many times before. The pace during the first experiment was much more leisurely from the subject's standpoint: typically he participated in only two or three 40-trial sessions per day, and the experiment was spread over a total of two or three weeks.

Results

Experiment 1: Target Trials

Some of the raw data of Experiment 1 are given in Fig. 4, which shows a set of *target acquisition curves* for the ten subjects. The ordinate indicates the percentage of trials on which a square was reported by the time τ indicated on the abscissa. For example, the arrow on the graph shows that subject No. 1, after seven seconds of search, had reported a square on 20 per cent of the trials where a square was present (eight of 40). There are ten conditions of the experiment for which full data are available, and each of these is divided into target and no-target trials. Consequently, 20 sets of functions like those of Fig. 4

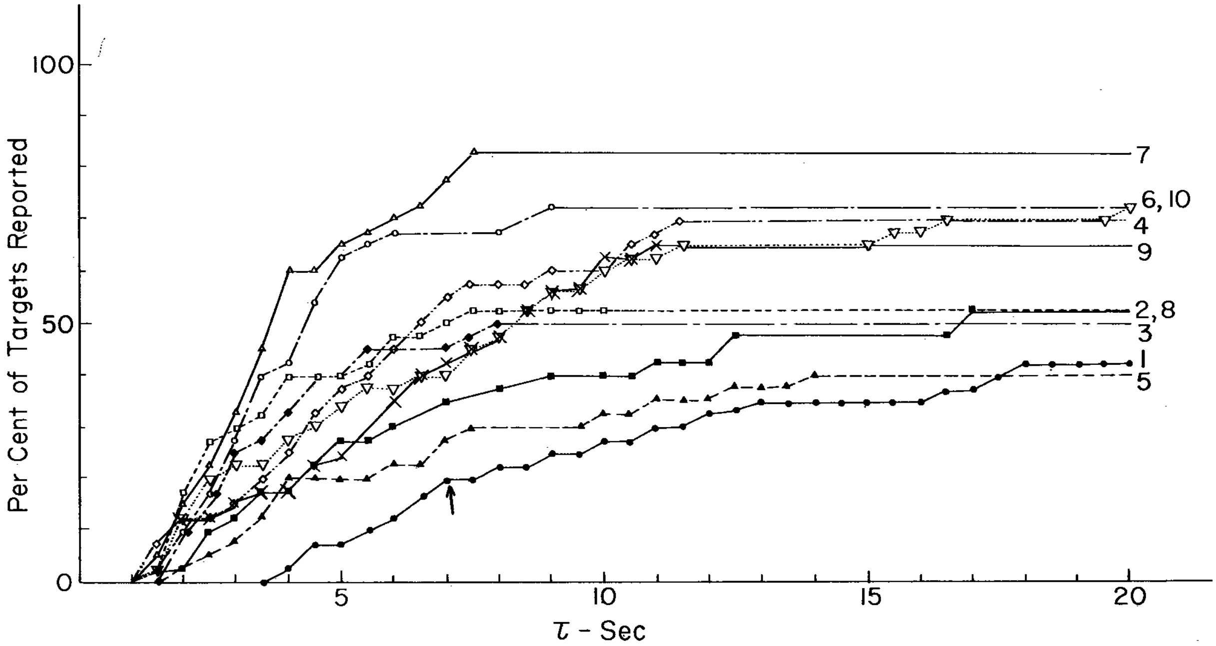

Figure 4. Target acquisition curves for individual subjects (identification numbers shown) at 0.20 fF (0.69 cd/m^2), 100 per cent contrast. Arrow is directed at a particular point on the curve, discussed in the text, for subject No. 1.

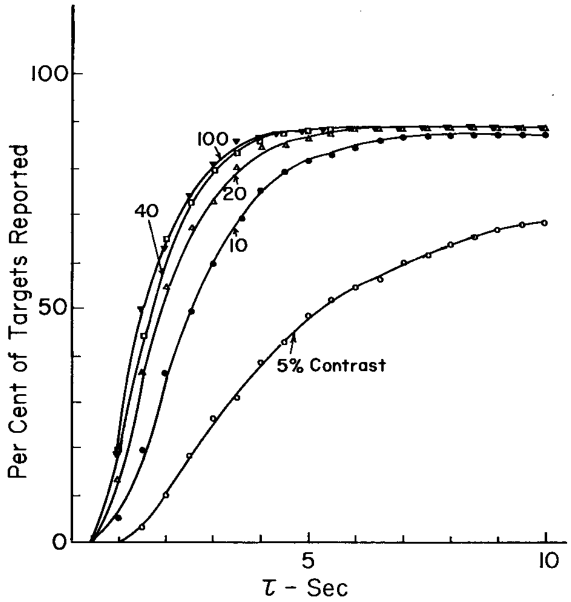

Figure 5. Average target acquisition curves for 10 subjects in Experiment 1, for 400 fL (1370 cd/m²) and contrast shown.

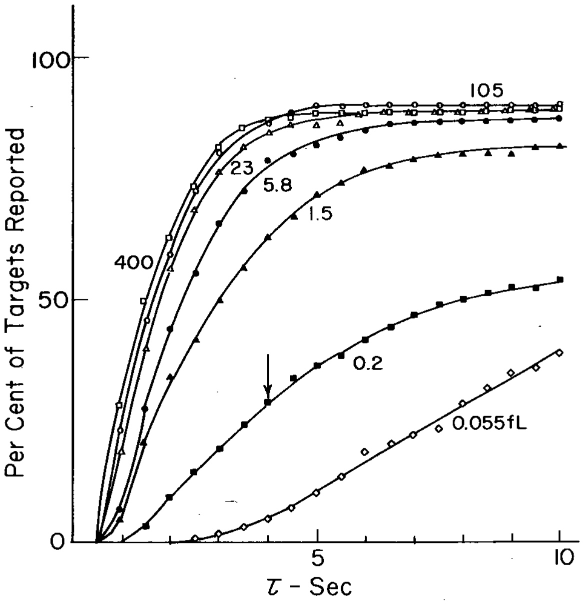

Figure 6. Average target acquisition curves for 10 subjects in Experiment 1, for 100-per cent contrast at the luminance shown.

would be required to present all data of Experiment 1 in graphical form. It should be noted that, for all subjects, target acquisition is nearly complete after ten seconds of search. Therefore, in further plots of this type, only the first ten seconds of such curves typically will be shown.

Group Data. Average data for target trials are given in Figs. 5 and 6. In Fig. 5, the separate curves are for the five contrasts employed at 400 fL, while in Fig. 6 they represent the six luminance levels examined at 100 per cent contrast. (The 400-fL, 100 per cent contrast condition is represented on both graphs.) To illustrate the meaning of these values, consider in Fig. 6 the curve for 0.2 fL at a response time τ of four seconds (indicated with an arrow). The ordinate value is 28.5 per cent. This means that, after four seconds of search, a square had been correctly identified on 114 trials of a possible 400. But the data point tells us nothing about how these target acquisitions are distributed across subjects. There are two endpoints on a continuum of possibilities. These extreme possibilities are (1) that, by four seconds, each subject detected the square on 11 or 12 trials of 40; (2) that two subjects detected squares on all 40 trials, a third found 34, while the other seven subjects reported none. In the first case, the group data would be closely representative of the performance of individual subjects, while in the second case they would not. The actual distribution of results, which of course lies somewhere between these extremes, will be presented and discussed later for this same example.

The following features should be noticed concerning the average data. (1) There are no major surprises. As expected, the effect of reducing either luminance or contrast is to impair visual performance. (2) At 100 per cent contrast, luminance has a very small effect upon performance in the range from 105 to 400 fL (360 to 1370 cd/m²). (See Fig. 6). Further lowering of luminance has a significant and progressively-accelerating negative effect upon performance. For the lowest luminance used, 0.055 fL (0.19 cd/m²), half the subjects could not perform the task at all. For this reason, the curve shown, which is from data averaged for the remaining five subjects, is biased upward. (3) There is little effect of contrast variation in the range from 40 to 100 per cent (see Fig. 5). A slight decrement occurs at 20 per cent (especially for the shorter response times) and a very significant performance drop occurs between ten and five per cent contrast.

The curves in Figs. 5 and 6 appear at first glance to belong to the same family. If so, it would follow that, for a task of a particular intermediate difficulty level (whether obtained by reducing contrast below 100 per cent or luminance below 400 fL), the function describing target acquisition with time should be more or less the same. This is, however, not true in detail. For example, if superposed upon the curves of Fig. 6, the curve from Fig. 5 for ten per cent contrast starts below that for 1.5 fL, crosses the latter at $\tau = 2$ seconds, rises substantially above it, and finally joins the curve for 5.8 fL at response times of 6.5 seconds and beyond. It is therefore inappropriate to expect that any point on these curves may be taken as an index of the entire function, except approximately.

Individual Data. For the efficient presentation of data for individual subjects, an attempt must be made to reduce the target acquisition curve to a single statistic. Unfortunately, this cannot be done without losing information, but the alternative—which is to present more than 100 curves—is clearly untenable.

One possible statistic is the total number of targets acquired during the 20-second search period. However, it should be borne in mind that 20 seconds is an arbitrary figure, selected *a priori* as being probably sufficient to reveal at least the most important part of the acquisition function. It is therefore unlikely that target acquisition over the entire 20-second search period would provide the most meaningful and sensitive indicator of performance.

Mean target acquisition curves for two of the 100 per cent contrast conditions, one easy (400 fL, 1370 cd/m^2) and one difficult (0.2 fL, 0.69 cd/m^2), are shown again in Fig. 7. For the easy condition, the final value of 88.5 per cent has been reached in less than six seconds; for the difficult condition, the final value (60 per cent) has not yet been reached after ten seconds. The curve for the easier viewing condition rises more steeply and reaches its high upper limit quickly, while that for the difficult condition rises in a more nearly linear fashion. This is a typical finding, one which applies also to the data of individual subjects. Given that both curves must by definition start at zero, this means that there is a particular time where the separation between the two curves is greatest, at $\tau \approx 3$ sec, and it therefore seems possible that target acquisition by this time might be an optimal selection of a summary statistic.

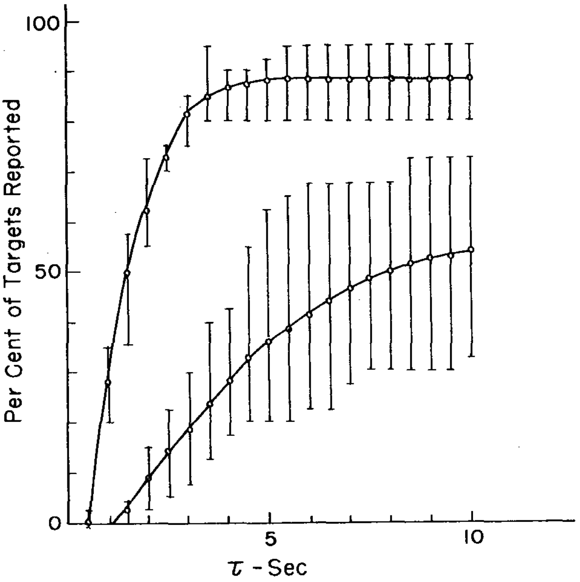

Figure 7. Average target acquisition curves for two conditions at 100-per cent contrast. Top curve: 400 fL (1370 cd/m^2); bottom curve: 0.2 fL (0.69 cd/m^2). Vertical bars represent the range of individual scores, excluding the two extreme values.

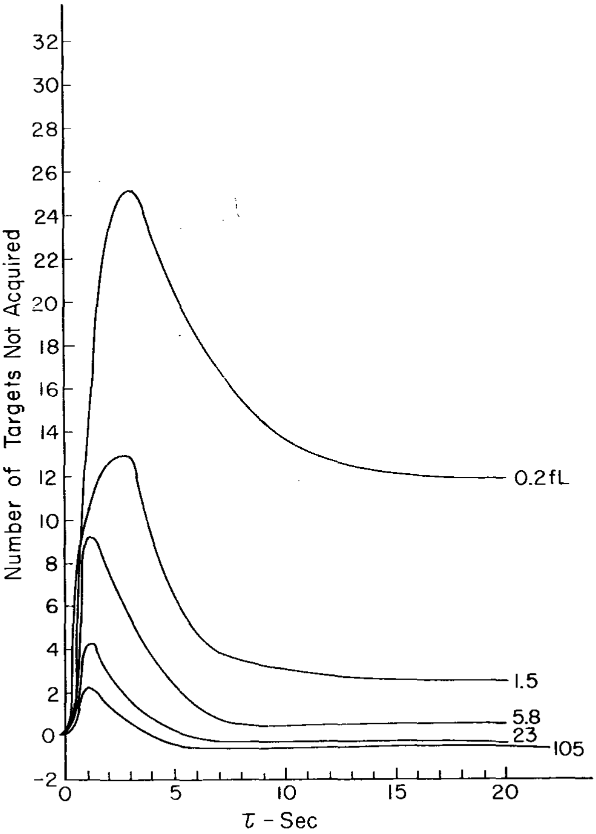

Figure 8. Visibility loss curves for Experiment 1, average data, 100-per cent contrast. Curves show the number of targets not seen, at the luminance indicated, in comparison to performance under the 400 fL condition.

The vertical bars in Fig. 7 provide an indication of inter-subject variability. They represent the range of scores for the individual subjects, excluding the highest and lowest values. For example, examination of the raw data reveals that the ten subjects had acquired the following numbers of targets after four seconds: 1, 16, 13, 10, 8, 17, 24, 7, 7, and 11. The two extreme values (1 and 24) have been eliminated, and the remaining range (7 to 17) has been plotted, on a percentage basis. This analysis reveals another fact about $\tau = 3$ seconds which is helpful: the spread of scores is relatively small here, especially when compared to longer search times.

The difference between the two functions of Fig. 7 is plotted as the uppermost curve in Fig. 8, with the ordinate expressed as the mean number of targets lost per subject. The peak of this curve indicates that, on the average, 25 targets are lost by reducing lumi-

Table II—Target Acquisition (Percentage of Trials on Which Square is Identified) By the End of Three Seconds, for Each Subject.

Condition	Luminance fL	Luminance cd/m²	Contrast Per cent	Subject 1	2	3	4**	5	6	7	8	9	10**	Mean
1	400	1370	100	75	72	77	95	87	85	82	80	82	80	81
2	105	360	100	77	80	72	80	82	87	87	70	80	87	80
3	23	79	100	75	82	67	80	77	85	70	80	65	82	76
4	5.8	20	100	62	62	52	80	65	65	62	60	82	65	65
5	1.5	5.1	100	27	50	50	67	57	52	62	45	40	42	49
6	0.2	0.69	100	0	30	25	15	7	27	32	12	15	22	18
7	0.055	0.19	100	*	0	*	0	*	0	2	*	*	0	*
9	400	1370	40	72	80	82	82	80	75	80	85	77	77	79
10	400	1370	20	62	57	72	67	82	70	72	80	85	77	72
11	400	1370	10	60	62	60	67	52	45	80	55	70	52	60
12	400	1370	5	22	35	30	30	27	27	25	20	35	10	26

* Conditions too difficult for these subjects.

** Subjects used in both experiments.

nance from 400 to 0.20 fL. That is, these 25 targets would have been acquired after three seconds at 400 fL, but are not acquired after three seconds when the luminance is reduced to 0.20 fL. After ten seconds, this difference has dropped to about 14; by the end of the full search period, it is less than 12. As the conditions of visibility improve, the amount of visibility loss becomes less (as expected) and the peak visibility loss shifts toward one second.

From the foregoing facts, plus the examination of many such visibility loss curves for individual subjects, a decision was reached to use target acquisition by the end of three seconds as the main performance index. These data are presented for individual subjects in Table II. Some attention has been paid to the correlations of subject rankings between conditions. They are generally low and unrevealing. This is partly because the differences between subjects are not large. There are also a few idiosyncracies of individual performance, which lower such correlations, that are worth noting. There is some indication that, relative to the remainder of the group, subject No. 1 is unusually strongly affected by reductions in luminance. Yet his performance is nearly average under the lowest-contrast condition. Contrariwise, subject No. 10, who is one of the better performers under conditions of low luminance, is markedly adversely affected by the lowest contrast used. Under optimal viewing conditions, subject No. 4 is very outstanding, yet she is only average, or even slightly below, under many of the remaining conditions.

Despite these idiosyncracies, it seems reasonable to conclude that the mean data do provide a performance summary which, although not representative of any particular subject, is at least generally consistent with the performance of individuals.

Experiment 1: No-target Trials

An important function of the no-target trials, in addition to the data that they generate in their own right, is to yield a "false-alarm" measure: this is the number or percentage of occasions on which a subject incorrectly reports a non-existent target square. These percentages, averaged across subjects, are given

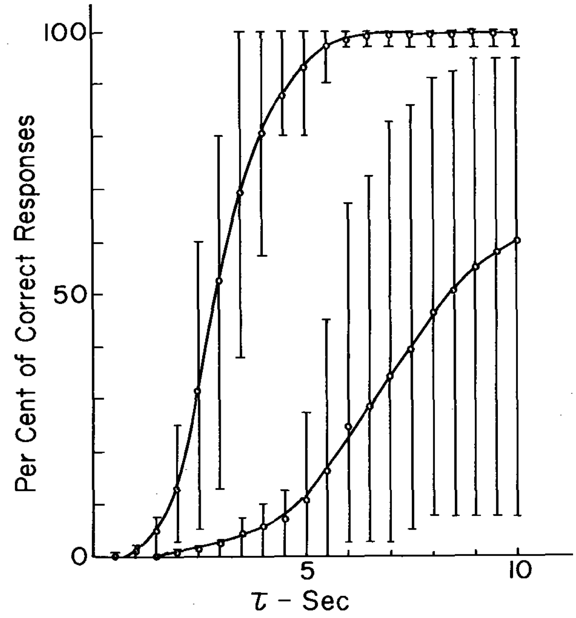

Figure 9. Average percentage of correct responses on no-target trials at 100-per cent contrast. Top curve: luminance of 400 fL (1370 cd/m²); bottom curve: 0.2 fL (0.69 cd/m²). Vertical bars represent the range of individual scores.

Table III—False-Alarm Responses for the Various Conditions of Experiment 1. Values are Based on Totals for All Ten Subjects.

Condition	Luminance fL	Luminance cd/m²	Contrast Per cent	Squares Incorrectly Reported Number	Squares Incorrectly Reported Per cent
1	400	1370	100	1	0.25
2	105	360	100	0	0.00
3	23	79	100	0	0.00
4	5.8	20	100	3	0.75
5	1.5	5.1	100	9	2.25
6	0.2	0.69	100	18	4.50
7	0.055	0.19	100	24	12.00*
9	400	1370	40	0	0.00
10	400	1370	20	0	0.00
11	400	1370	10	3	0.75
12	400	1370	5	18	4.50

* Based on only five subjects. The other five subjects did not participate in these trials.

in Table III.

It will be seen that, for the easier conditions, false-alarm responses are virtually non-existent. This means that the subjects followed the instructions and/or were influenced as we desired by the reward schedule. Although it was decidedly to their financial advantage to report the presence of a square as soon as possible, they suffered financially if such a report was incorrect. Therefore, they did not report a square until virtually certain of its presence.

As the viewing conditions became more difficult, the percentage of false-alarm responses, although larger, is still small. We may conclude that these are very probably "honest" mistakes and that, although incorrect, the subjects really thought they saw squares on these few difficult occasions. Indeed, the increasing rate of false-alarm responses, as viewing conditions are progressively impoverished, may be considered as another index of the deleterious effects caused by luminances or contrasts that are too low to support good vision.

Fig. 9 shows a pair of functions (analogous to those of Fig. 7) which represent data for those trials on which no square was present. They are not "target acquisition" data, since there was no target. Instead, a response indicates the point in time when the subject decided to say "no target" and was correct. Note the relatively more sigmoid shape of these curves compared to the target data of Fig. 7. Responses accumulate more slowly during the early seconds than is the case for target acquisition. Another difference is that all no-target functions, even those for very difficult viewing conditions, eventually attain an asymptote very close to 100 per cent. This results from the instructions and rewards given the subjects. On target trials, a response of "target present" reveals that the subject has determined, almost always correctly, that a square is in the array. He has really seen it. On no-target trials, a response may reveal—and clearly does so under easy viewing conditions—that the subject is very nearly certain that no square is present, and is therefore willing to say so quickly and thus terminate the trial. On the other hand, a no-target response frequently signifies that the subject has "given up." After searching for a while, he comes to feel—without any strong conviction about whether or not a square is there—that if there is a target, he is not going to find it.

Fig. 9 reveals that the range of scores among subjects is very much greater than for target trials, and this too is probably due mainly to the relative looseness of the motivating conditions, and the resultant

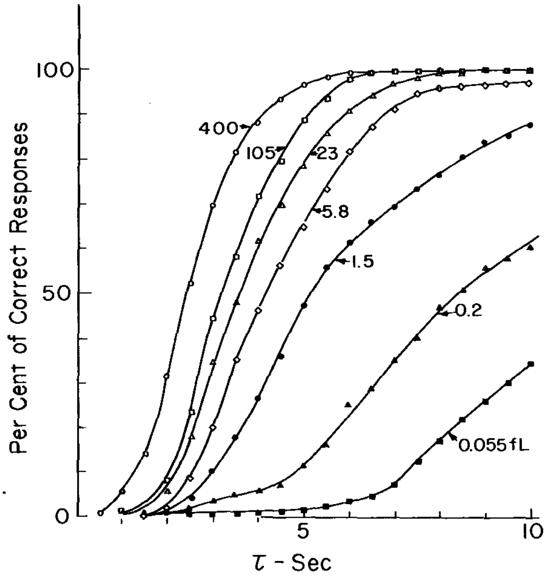

Figure 10. Average percentage of correct responses on no-target trials for 100-per cent contrast at luminance indicated.

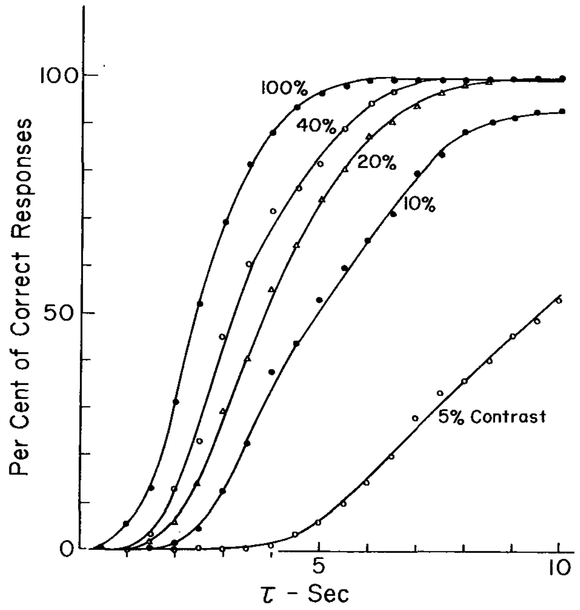

Figure 11. Average percentage of correct responses on no-target trials at 400 fL (1370 cd/m²) and contrast indicated.

multiple meaning of "no target" responses.

Figs. 10 and 11, which present the mean no-target data in full, are analogs of Figs. 5 and 6. Although relative to the target trials, the mean data here must be considered as less representative of what any individual subject has done, their regularity is nevertheless very great.

Another point to be noted is that there is a much clearer separation of the curves at the higher contrasts and luminances than was true for the target acquisition curves. This means that the very high luminances and contrasts (above 23 fL and 40 per cent) are relatively more advantageous for helping a subject to decide to respond correctly that no square is present, than to decide correctly that one is. Whereas an increase in luminance from 23 to 400 fL produces *at the most* an eight per cent increase in target acquisition, there is, in the no-target case, nearly a 50 per cent performance change, for some values of τ.

Finally, we note that, for no-target trials, the maximum separation between the uppermost reference curve (400 fL, 100 per cent contrast) and the other curves occurs more nearly at five seconds than three; this could be shown, but is not, in plots like those of Fig. 8. For this reason, the analysis of individual performance for no-target trials is based upon τ = 5 seconds, and these individual results are given in Table IV.

Experiment 2: Target Trials

All of the extensive data for each of the two subjects were graphed and inspected. It was concluded that the individual differences were small enough to average the subjects for further analysis. As for Experiment 1, the analysis is based upon target acquisition by the end of three seconds of viewing time. The mean data for the two subjects are given in Table V.

Inspection of Table V indicates that diagonal values, reading from lower left to upper right, are roughly comparable, showing that some kind of a tradeoff relation exists between luminance and contrast. Within the sensitive range of measurement, where targets are seen with a probability of more than zero but less than 100 per cent, it is virtually always true that, at any contrast, performance is lowered by reducing luminance, and that, at any luminance, performance is lowered by reducing contrast. And for any luminance-contrast combination in the sensitive range of measurement, performance

Table IV—Percentages of No-Target Trials on Which Subjects Correctly State That Target is not Present, By the End of Five Seconds.

Condition	Luminance fL	Luminance cd/m²	Contrast Per cent	Subject 1	2	3	4	5	6	7	8	9	10	Mean
1	400	1370	100	92	100	95	100	80	97	100	95	100	77	93
2	105	360	100	70	100	92	100	50	100	100	90	100	85	88
3	23	79	100	25	97	82	92	35	100	100	95	87	70	78
4	5.8	20	100	37	100	80	97	35	100	72	35	80	10	64
5	1.5	5.1	100	0	72	75	65	7	72	92	5	65	15	47
6	0.2	0.69	100	0	45	12	0	0	27	7	2	12	0	10
7	0.055	0.19	100	*	0	*	5	*	2	0	*	*	0	1
9	400	1370	40	17	100	95	95	55	100	100	100	100	57	82
10	400	1370	20	12	90	87	100	30	100	100	75	100	45	74
11	400	1370	10	0	67	57	87	2	95	100	2	100	12	52
12	400	1370	5	0	27	0	2	0	17	15	0	0	0	6

* No measurements made.

Table V—Data From Experiment 2. Values Indicate the Mean Number of Targets Acquired, for the Two Subjects, By the End of Three Seconds of Search Time. Conditions Marked * Were Not Examined.

Small Target Present (Ten Minutes)

	Luminance							
Contrast	400	105	23	5.8	1.5	0.2	0.06	0.012 fL
Per cent	1370	360	79	20	5.1	0.69	0.19	0.041 cd/m²
100	18.5	17.0	16.5	13.5	12.5	5.5	0.0	0.5
40	18.5	16.0	16.0	9.5	6.5	0.5	0.0	0.0
20	16.0	15.5	6.5	5.0	1.0	0.0	0.0	*
10	11.5	11.0	4.5	1.0	0.5	0.0	*	*
5	2.5	3.0	0.0	0.5	0.0	*	*	*

Large Target Present (30 Minutes)

	Luminance							
Contrast	400	105	23	5.8	1.5	0.2	0.06	0.012 fL
Per cent	1370	360	79	20	5.1	0.69	0.19	0.041 cd/m²
100	19.5	20.0	18.5	18.5	16.0	15.5	7.0	3.0
40	19.0	18.5	18.5	17.5	15.5	13.5	3.5	0.5
20	19.0	19.0	18.5	17.5	14.5	11.5	2.5	*
10	19.5	16.0	15.0	14.5	11.0	7.0	*	*
5	14.5	10.5	10.0	9.0	2.5	*	*	*

may be lowered by reducing target size.

These interactions can be seen better in Fig. 12. This figure was derived by first plotting families of curves (not shown) showing target acquisition ($\tau = 3$ seconds) as a function of contrast, with luminance as a parameter, and a converse set (generated from the same data) of target acquisition as a function of luminance, with contrast as a parameter. The data points were fit by eye with smooth curves, and luminance-contrast combinations required to elicit 50 per cent target acquisitions were read from the graphs. These data are plotted in Fig. 12. The line fit to the small-square data, excepting the curved portion, fits the equation $C\sqrt{L}$ equals a constant, having a slope of —0.5 (note the expanded contrast scale).

For trials on which a large square was presented, the relationship between luminance and contrast is very different, being clearly curvilinear on the log-log plot. At high luminances, where contrast must be low to keep performance at criterion, luminance is not a potent variable: large changes in luminance can be compensated by small changes in contrast. At lower luminances, where contrast must be high, luminance is a very important variable, and large contrast changes are required to compensate very small changes in luminance.

Extreme reductions in contrast cannot be compensated by further increases in luminance and *vice versa.* Although we do not have supporting data, it is almost certainly true that, if the targets were made small enough, their discriminability would be unconditionally lost and not compensatable by upward changes in luminance and/or contrast.

Experiment 2: No-target Trials

Each trial where a square was not present was designated by the experimenter as either a "large no-target" or a "small no-target" trial. Since each had eight large and eight small circles, there was no difference between them so far as the subject was concerned, and it is not possible to evaluate the effect of area upon "no-target" performance.

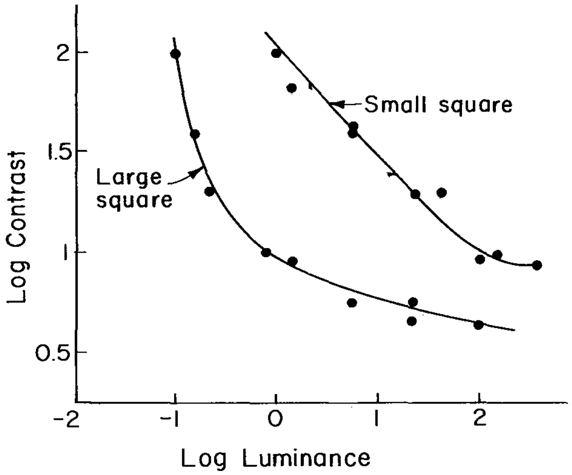

Figure 12. Contrast-luminance combinations (Experiment 2, target trials) required to elicit a criterion performance of 50 per cent.

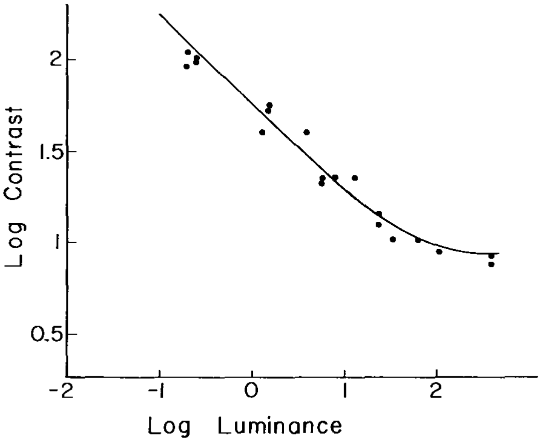

Figure 13. Contrast-luminance combinations (Experiment 2, no-target trials) required to elicit a criterion performance of 50 per cent.

The data shown in Fig. 13 are analogous to those of Fig. 12. The linear portion of the fitted function has a slope of —0.5 and thus most closely resembles the small-target curve of Fig. 12. It seems probable that, under most of the conditions of search, the question of whether or not one of the eight large forms was a square was readily resolved in the negative, so that the "no-target" decision rested mainly upon examination of the small forms.

The two subjects who participated in the second experiment repeated themselves wlel under similar conditions between the two experiments.

Discussion

Possible tradeoffs between luminance, contrast, and target size were pointed to in the *Results* section. It should be emphasized again that such compensations are possible only within a *sensitive range* of visual performance measurement that is clearly above zero and below 100 per cent. Take, for example, performance at 0.012 fL (0.041 cd/m^2). It is clear that, for the size targets used, the task is simply impossible at any contrast. Thus, for example, just because performance is zero at ten per cent contrast, it must not be assumed that it can be improved by increasing contrast even to 100 per cent. Although further increases in target size probably might restore performance to the sensitive range at this luminance level, there are surely other luminance levels, lower than this, at which such compensation will be impossible. Similarly, there are contrasts so low that the task would not be possible, no matter how large the target nor how high the luminance. We did not extend our measurements into this range due to the difficulty of maintaining uniform contrast across the stimulus field, and cannot say anything quantitative about this.

At the other extreme, there are conditions initially so favorable that they are highly resistant to seemingly enormous reductions in luminance or contrast. Our easiest viewing condition is for large targets at 100 per cent contrast at 400 fL. Starting with this, the task can stand a reduction in luminance to 5.8 fL, *or* a reduction in contrast to ten percent, *or* a reduction of target area to one ninth—each without measurable effect. But if all of these individually-tolerated changes are presented in combination (see in Table V the condition for small-target, ten per cent contrast, 5.8 fL), performance can be nearly wiped out. So it is clear that the individual changes in conditions, each of which appears when used alone to be without effect, is definitely having some effect, but one too small to be measurable (or of negligible visual significance so far as performance is concerned).

Thus it would have been incorrect to overgeneralize from Experiment 1, as so easily could have been done, that luminance is without effect above 100 fL, or that contrast makes no difference above 40 per cent. The second experiment, which filled in the remainder of the luminance-contrast matrix, has enabled us to show that neither of these generalizations is correct.

Summary

A visual search and recognition task, believed to involve important features of both central and peripheral vision, has been used to assess visual performance. Luminance, contrast, and target size have been systematically varied. Performance data are presented for ten young subjects for eight luminance levels (0.012 to 400 fL) at 100 per cent contrast, and five contrasts (five to 100 per cent) at 400 fL, using targets subtending ten minutes of arc. Two of these subjects participated in additional experiments using ten-minute and 30-minute target sizes, where the full matrix of these luminance and contrast combinations was explored. Within the limits explored, visual performance was found to be maximal at the highest contrast and luminance used. Whether or not small downward changes in either or both of these variables will reduce performance depends upon the initial task difficult. The most significant performance losses begin to occur when luminance is below 23 fL and/or contrast is below ten per cent.

References

1. Blackwell, H. R., "Contrast Thresholds of the Human Eye," *Journal of the Optical Society of America*, Vol. 36, 1946, p. 624.
2. Hecht, S., "The Relation Between Visual Acuity and Illumination," *Journal of General Physiology*, Vol. 11, 1928, p. 255.
3. Pieron, H., *Physiology of Vision*. (Traite d'ophthalmologie, Vol. II, p. 497-768.) Paris, Masson, 1939.
4. Yarbus, A. L. *Eye Movements and Vision*. Plenum Press, 1967.
5. Boynton, R. M. "Visibility Losses Caused by Sudden Luminance Changes," Paper No. 67.07, *Proceedings of the International Commission on Illumination*, 1967, p. 171.