IERI

Performance of complex tasks under different levels of illumination

Part I—Needle probe task

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This is the first in a series of research reports that describe the relationship between illumination level and the performance of complex tasks having selected realistic components. The task described in this article required subjects to insert a fine tipped probe into the eye-holes of ten needles in rapid succession. Results of the needle probe task and of different tasks reported by other investigators are compared.

Preface

In 1971 the Research Executive Committee of the Illuminating Engineering Research Institute (IERI) asked the author to develop a research program to study the performance of a variety of complex realistic tasks under a wide range of illumination levels. This is Part I of a series of research studies on how illumination level affects the performance of complex tasks. Advice and guidance in the selection of tasks and conduct of the research has been provided by the Technical Advisory Committee of IERI. Additional ideas and suggestions were contributed by others, including the Human Performance Subcommittee of the Illuminating Engineering Society.

The experiments have several common features. Illumination level is the major independent variable. Illumination is diffuse, uniform, spectrally broad (white) and steady. Tasks involve (1) relatively complex stimulus objects and materials having selected, realistic characteristics; (2) complete performance sequences having sensory, perceptual, cognitive and motor components, (3) performance objectives specified by instructions, or a reward system (payoff matrix) for speed and accuracy; and (4) realistic performance measures. Subjects are young adults without vision defects.

The experimental tasks are not real office or industrial tasks, nor are they simulations of any real tasks. They were designed to make particular features realistic or complex and others less so. For example, the display used in other experiments to be reported later is made of real circuit board materials processed in the normal way, but the arrangement of the displayed elements is unlike any real electronic circuit board. Likewise, the subject's response—placing a probe in a small hole—is like many required

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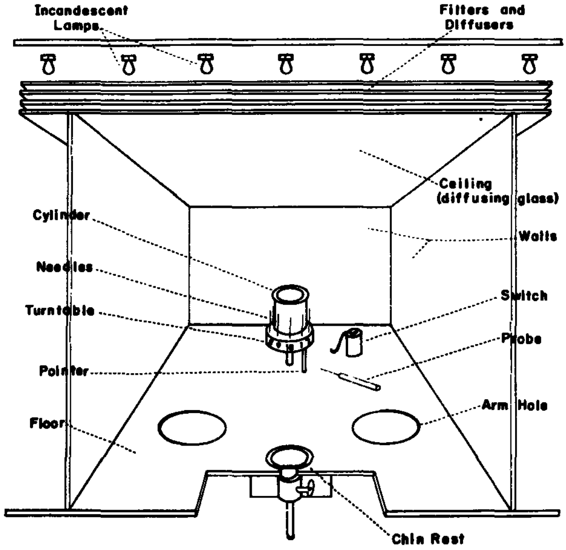


Figure 1. Drawing of task apparatus and viewing chamber.

in industrial work; but it is not usually one associated with inspection of real circuit boards. Similar comparisons could be made regarding performance objectives and measures.

Tasks like these have been used by others to compare the effects of different types of illumination.[1–3] Less realistic tasks have been used in most studies involving different illumination levels.[4–16] Basic visual detection and acuity studies are even simpler and more abstract. They involve sensitivity or threshold measures of various types.

The critical visual details of the tasks used in our current experiments are suprathreshold, as are those of most real life tasks. These experiments provide results of higher validity than do the less realistic ones. The effect of light level on the performance of these tasks and real-life tasks having similar characteristics should be comparable.

Introduction

The needle probe task requires accurate eye fixations, good visual acuity and distance judgement, precise eye-hand coordination and proper sequencing of several movement patterns. The important visual stimuli are thin, shiny, three-dimensional metallic objects (needles). The subject is to insert the tip of one needle into a small hole (the eye) of another needle, and to do this as rapidly as possible for ten needles in succession. The time required to complete the task is the primary performance measure.

Many real life tasks have some of these same characteristics, for example, successful probing is necessary for sewing on a button, needlepoint sewing, lacing shoes, inserting a key into a keyhole, putting a screw driver into a screw slot, spot soldering, testing miniature electronic circuits with a probe and meter, countless assembly tasks, placing a pencil or brush at the correct spot on paper or canvas, certain aspects of dental work and surgery, and dueling with foil or rapier. Of course, the specific set of visual features, response characteristics and performance objectives is different for each task. It is assumed, however, that such differences do not affect the general relationship between light level and performance. The functional relationship determined for the needle probe task should apply to many real life tasks.

Apparatus and procedures

Figure 1 is a sketch of the apparatus and viewing chamber with the front face removed. The subject's visual environment was controlled with the aid of an adjustable chin-forehead rest which positioned the head 3.0 inches (7.6 cm) into the viewing chamber. The head opening was 7.9 inches (20 cm) wide by 9.8 inches (25 cm) high (not shown in Fig. 1 since the front face was removed). The chamber was 20 inches (51 cm) wide, 20 inches (51 cm) deep, and 11.8 inches (30 cm) high. The walls and floor were painted flat (low gloss) white. The ceiling was diffusing glass.

A 3.0-inch (7.6-cm) diameter circular turntable was located 1.0 inch (2.5 cm) above the floor in the center and near the back of the viewing chamber. The support spindle extended through the floor so that the table could be rotated with a knob from beneath the chamber floor. Ten vertical needles (Sharps' sewing needles), with the needle eyes at the top, were spaced evenly around the circular turntable near its edge. The eyes of the needles faced directly outward from the center of the turntable. Each needle was identified by a numeral (1 to 10) located on the table rim just below the place where the tip was inserted in the table top. Table I lists important dimensions of the needles at the viewing distance of 9.4 inches (24 cm) used for the task. The needles were five degrees of visual angle in length.

A vertical cylinder 2.5 inches (6.4 cm) in diameter and 2.2 inches (5.6 cm) high, centered on the turntable, served as a background field for the needles. The cylinder was covered with either black or white low gloss paper.

A vertical pointer rising from the chamber floor to the edge of the table, located one needle (36 degrees on the turntable) to the right of straight ahead (to the

Table I—Needle dimensions (visual angle in minutes of arc)

Needle ident. no.	Needle size no.	Needle thickness near eye	Eye of needle: Height	Eye of needle: Width
1	5	14.5	23.0	7.0
2	6	13.0	21.0	6.5
3	7	11.5	19.0	6.0
4	8	10.0	17.0	5.0
5	9	9.0	14.5	4.0
6	10	7.0	12.0	4.0
7	9	9.0	14.5	4.0
8	8	10.0	17.0	5.0
9	7	11.5	19.0	6.0
10	6	13.0	21.0	6.5

Table II—Background luminance values

Light level	Horizontal illumination		White background		Black background	
	fc	lx	fL	cd/m²	fL	cd/m²
I	.56	6	.14	.48	.022	.075
II	8.5	91	2.2	7.5	.33	1.13
III	120	1290	30	103	4.7	16.1
IV	940	10100	240	822	37	127

left for left-handed subjects,) indicated the position to which the needle to be probed should be rotated. A preliminary investigation showed that probing at this angle is more natural (less awkward and tiring) than head-on or 90-degree probing.

The probe consisted of a No. 10 Sharps' needle protruding from the end of a plastic rod handle. The probe tapered to a tip of about two minutes of arc visual angle when held near the eye of the needle to be probed.

Illumination was provided by rows of staggered incandescent filament lamps, a mirror system and diffusing glass plates designed to simulate a continuous luminous ceiling. Different illumination levels were achieved by using different sets of lamps and by placing mechanical filters between diffusing plates. Thus, geometry and spectral composition were the same for all levels of illumination. Four illumination levels were used in this experiment: .56, 8.5, 120 and 940 footcandles (6.0, 91, 1290 and 10,100 lx) measured at the level and location of the task. These produced the luminance values listed in Table II for the white and black backgrounds measured along the subject's line of sight.

The subject viewed the task from 9.4 inches (24 cm) (subject's dominant eye to needle eye to be probed) and at a downward angle of 15.5 degrees. Viewing was binocular with natural pupils.

The probe and needles were brighter than the black background, but the probe appeared dark against the needles.

The needles appeared darker than the white background. The holes (needle eyes) were bright against the darker needle bodies. The probe was also of negative contrast against the background and the eye of the needle. It was slightly darker than the body of the needles. The probe was approximately horizontal and at an angle from the observer as it was moved toward the needle eye. Its appearance changed as it was moved and seen against the walls, the background cylinder and the needles.

Visual Task Evaluation[17] was performed by an experienced operator (BWS) whose calibration function closely approximated the standard Visibility Reference Function.[18] The needles were highly visible under most conditions. Visibility Level (VL) values for the needles seen against the white background ranged from 21 to 42. For the black background, VL values ranged from 62 to 76 for the three highest illumination levels, but dropped to 11.3 for the lowest level. The VL values for the more critical details of the task, the eyes of the needles and the tip of the probe, are presented in Table III. The VL needle eye values listed are for the smallest needle. VL values for the larger needle eyes were higher (the multiplying factor gradually increased to about 1.7). The VL values for the needle eye measured against the white background are slightly lower than those for the probe tip, except for Light Level IV in Table III. The reason for the low value for the probe tip under light level IV is unknown. Since it is in disagreement with the subject's phenomenal reports and a subsequent visual check, it is probably erroneous and is therefore not used in analyzing the results.

The subject sat on a comfortable adjustable stool with head properly positioned in the chin-forehead rest. The probe was held with the preferred hand through a hole in the floor of the viewing chamber. The edge of the hole was padded. The other hand was used to rotate the turntable.

After appropriate adaptation, the subject held the probe against a timing switch and lined up Needle No. 1 with the pointer. The subject initiated a trial by moving the probe from the switch toward the first needle. This started a timer. After a successful probe of the first needle eye, the second needle was rotated into position and probed. This procedure was continued until all ten needles had been probed in turn. The probe was then returned to the switch to stop the timer. The taper of the probe permitted the subject to know whether or not the probe had indeed entered the needle eye, since the probe stopped in the eye at the point where it was of the same diameter as the hole.

The subject's task was to probe the ten needles as rapidly as possible. The performance measure for each trial was the total amount of time it took to probe the ten needles in turn and return the probe to the switch.

The four luminance levels were presented in a counterbalanced order for the different subjects.

Results

The data for all three experiments were analyzed in the same way. First, the median performance time for each block of five trials was determined. Averages of these block scores were then calculated for each illumination level. Thus, an entry in Tables IV and V represents performance on 20 trials (200 probings); and in Table VI each entry summarizes the data of 40 trials. These values were used to calculate group averages.

Table III—Visibility level (VL) values

Light level	White background		Black background	
	Needle eye	Probe tip	Needle eye	Probe tip
I	5.4	6.2	8.4	—
II	8.7	10.4	38.9	4.8
III	15.7	16.1	68.3	8.4
IV	17.7	12.8	64.7	12.7

Table IV—Experiment A: black background performance time (seconds)

Light level	AW	AD	WO	DG	Subjects JK	BR	DJ	FF	JB	Average
I	25.85	28.84	32.05	25.74	20.89	41.05	25.01	24.96	27.47	27.98
II	17.06	20.75	22.99	19.23	18.40	22.88	19.42	17.92	21.85	20.06
III	16.56	18.72	20.33	17.28	16.57	19.97	17.68	16.26	20.95	18.26
IV	15.84	19.80	19.68	15.79	15.20	19.13	16.57	16.25	19.70	17.55

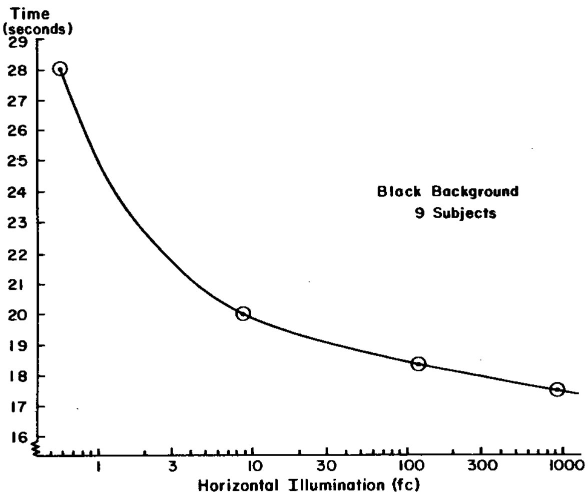


Figure 2. Relation between performance time and illumination (Experiment A).

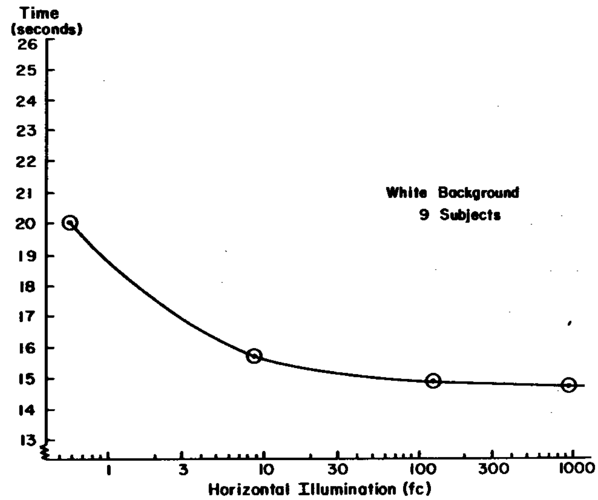


Figure 4. Relation between performance time and illumination (Experiment B).

Figure 3. Relation between performance speed and visibility level of probe tip (Experiment A).

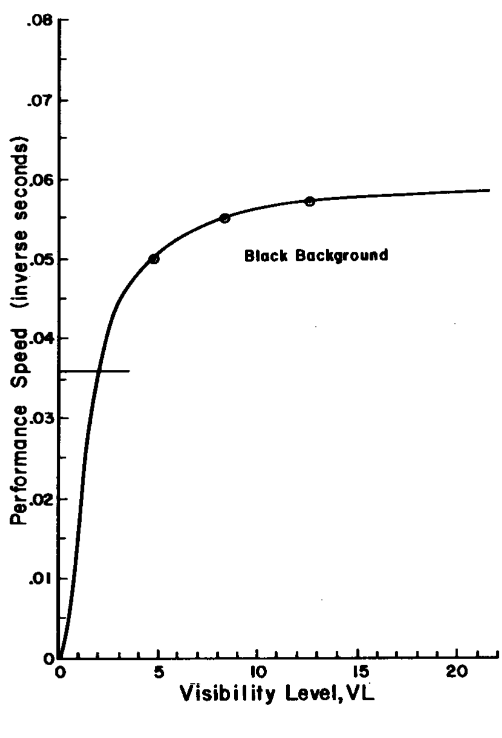


Figure 5. Relation between performance speed and visibility level of needle eye (Experiment B).

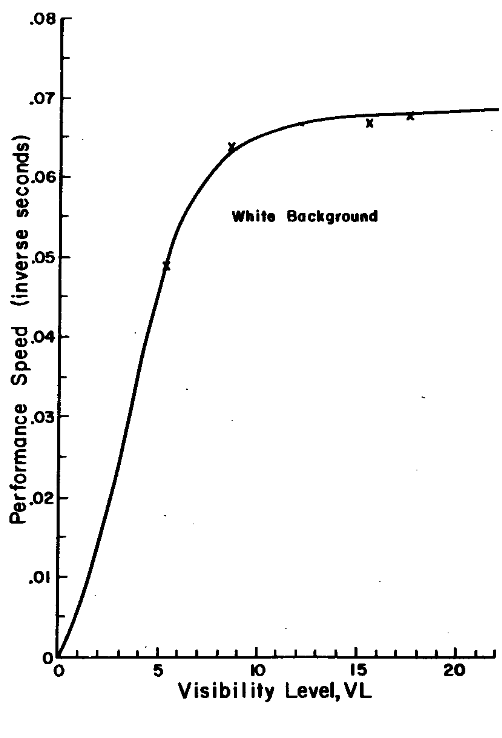


Table V—Experiment B: white background performance time (seconds)

Light level	AW	AD	WO	DG	Subjects JK	BR	DJ	FF	JB	Average
I	18.23	20.84	22.96	19.68	19.50	24.98	16.61	16.07	24.59	20.38
II	14.58	14.91	18.89	14.48	14.28	19.90	13.77	13.10	17.60	15.72
III	14.13	15.29	17.60	13.27	13.73	16.04	14.00	13.61	16.30	14.89
IV	13.51	14.35	16.47	12.22	14.12	17.64	13.51	13.81	16.40	14.67

The element of the visual task having the lowest visibility is assumed to be the most critical. Accordingly, VL values for the probe tip are used for the black background condition and VL values for the needle eye are used for the white background condition. Since the VL values with the white background for probe tip and needle eye are nearly the same, data analyses would differ little if the probe tip VL values were used throughout.

Experiment A. Nine subjects participated in this experiment. The needles were viewed against the black background collar. Table IV contains the data for individual subjects, and Fig. 2 shows group averages. The curve in this and all other graphs was fitted to the data points visually.

These results show that performance continually improved as illumination level increased to about 1000 footcandles (11,000 lx) The consistency of the effect is clearly evident in Table IV. The data for every subject are essentially the same. There was only one reversal (subject AD for the two highest light levels.)

In Fig. 3 performance speed, the reciprocal of performance time, is plotted against visibility level. Since VL was indeterminate (but less than 3.6) for the lowest light level, performance speed is indicated by a horizontal line rather than a data point. The curve is drawn to the zero-zero point under the reasonable assumption that it would be impossible to perform the task in the dark.

Experiment B. The experiment was repeated with the same subjects, but with the white background collar substituted for the black collar. Table V and Figs. 4 and 5 present the results in the same way as for Experiment A. Performance in this experiment also improved as light level increased. However, since the effect was smaller for the white than for the black background, the data for individual subjects appear to be less consistent due to random variability.

In spite of considerable preliminary practice, the performance of some subjects continued to improve during Experiments A and B, making direct comparisons between the experiments (backgrounds) invalid.

Experiment C. This experiment was designed to permit direct comparisons of performance with the black background and with the white background. Three new subjects were selected and given extensive preliminary training and practice. Illumination levels and backgrounds were presented in counter-balanced order. In addition, the number of blocks of trials for each condition was increased from four to eight.

The data are presented in Table VI and Figs. 6 to 8. As in the previous experiments, performance improved with increased illumination and visibility. When performance is compared for the two background conditions at the same levels of illumination (see Fig. 6), the white background is better; but when the comparison is made for equal adaptation levels (luminances of Fig. 7), the black background is superior. This apparent contradiction merely reflects a difference in perspective. To a lighting specialist or applied engineering psychologist the comparison using illumination is more interesting. The white background collar would be preferred over the black one for conserving energy. On the other hand, vision experts are more interested in luminance because it is more directly related to visual performance. Since visibility level is a visual performance measure, the results of the VL analysis should agree with those of the adaptation analysis rather than those of the illumination analysis. Fig. 8 confirms this by showing that performance was better with the black background when plotted against visibility level. The difference in performance for the two background conditions diminished as illumination increased.

Additional data analyses. In all three experiments, linear scales were used in Figs. 3, 5 and 8 to

Table VI—Experiment C: performance time (seconds)

	Subject JH		Subject FG		Subject TM		Average	
	Background		Background		Background		Background	
Light level	Black	White	Black	White	Black	White	Black	White
I	22.45	17.45	20.97	18.77	16.46	16.69	19.96	17.64
II	17.91	15.47	15.23	14.90	13.61	12.92	15.58	14.43
III	14.93	13.66	14.19	13.45	12.41	12.10	13.84	13.07
IV	14.05	14.02	13.64	12.53	11.65	11.32	13.11	12.62

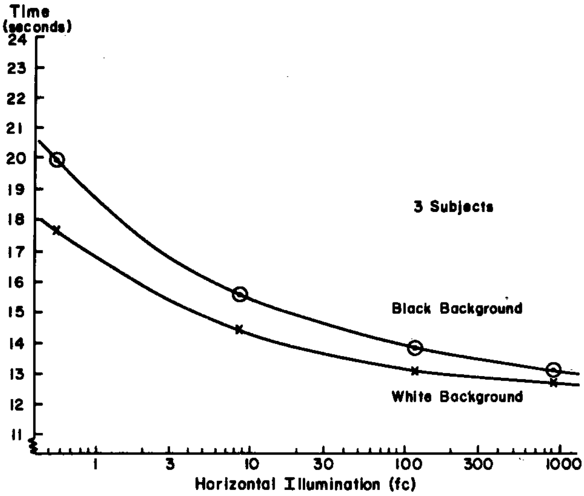


Figure 6. Relation between performance time and illumination (Experiment C).

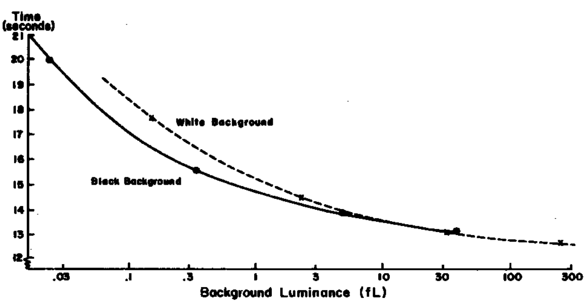


Figure 7. Relation between performance time and adaptation level (Experiment C).

show the relationship between performance time and visibility level. These data have been replotted on a double logarithmic grid in Fig. 9 to correspond with the presentation of other research.[19] A VL level of 2.0 was used for Light Level IV with the black background collar. This value was derived from the curves in Figs. 3 and 8—both cross the performance score lines at that value. The curves for the two backgrounds differ considerably in shape. This comparison is facilitated by using per cent of maximum performance for the ordinate, as shown in Fig. 10. The agreement of the data of the three experiments is remarkable—especially in view of the differences in practice levels and subjects.

The results of these Needle Probe Task experiments are shown in Fig. 11, together with those of Bodmann,[5] Boynton and Boss,[6] and Weston,[14] as plotted by Blackwell.[20,21]

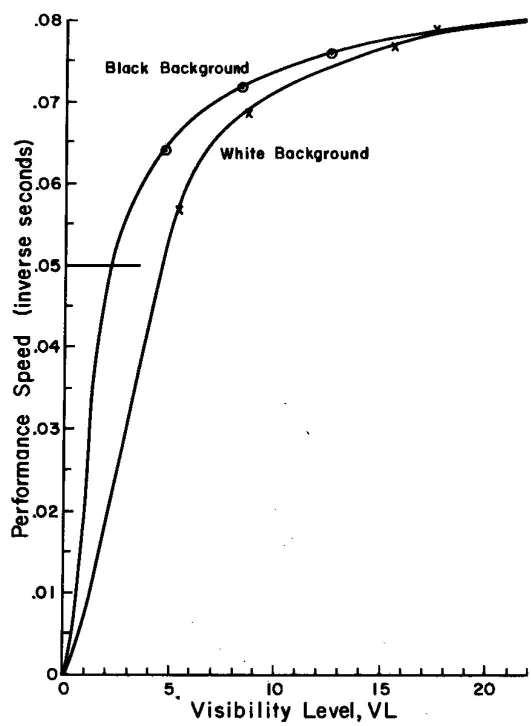
Discussion

The improvement in performance of this task with increased illumination is similar to that reported for many others ranging from real tasks to basic visual detection—improvement is rapid at the lower levels and gradually decreases as illumination increases. In this study, performance improved by 3.25 seconds, or about 17 per cent, between 1.0 and 10 footcandles (11 and 110 lx) for the black background condition (Experiment C.) From 10 to 100 footcandles (110 to 1100 lx) improvement was about 10 per cent, and from 100 to 1000 footcandles (1100 to 11,000 lx) it was about six per cent. Comparable values for the white background were 15 per cent, eight per cent and four per cent.

It is not surprising that the performance of this complex task (and most others having significant visual components) is affected in this manner by illumination. The basic visual functions that determine the visual performance aspects of all such tasks have this same general form. Contrast detection, most types of acuity or spatial resolution, temporal resolution and color discrimination are prime examples. The absolute values and exact form of the relationship vary, depending on the combination and relative importance of the underlying basic visual factors. Non-visual factors also affect performance, but not in ways directly related to illumination.

There are exceptions. Some tasks can be performed better at intermediate than at high values of the basic visual variables. Consequently, they might also be performed better under intermediate than high light levels. Harmon[22] and Harmon and Julesz[23] have demonstrated that the recognition of faces (in pictures processed in special ways) is improved by blurring the image (for example, by squinting, de-

Figure 8. Relation between performance speed and visibility level (Experiment C).



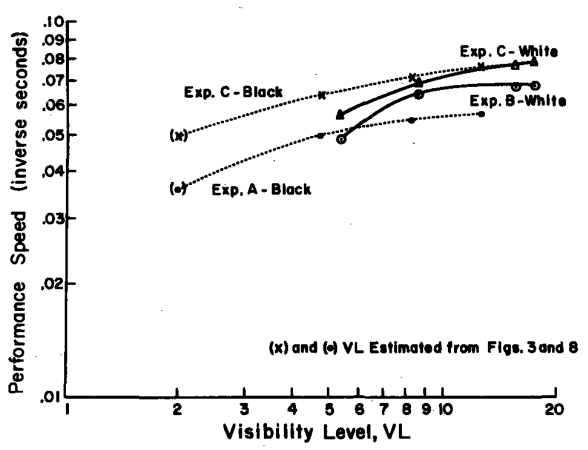


Figure 9. Relation between performance speed and visibility level plotted on a double logarithmic grid (Experiments A, B and C).

focusing, or viewing at a distance). Reducing illumination has the same effect. There is an optimum resolution (or light level) for this task with lower and higher values producing poorer performance. Similar results are reported by Yonemura and Kohayakawa[24] for observers who judged the "clarity" of sine and square wave gratings of various average luminances. The extent to which such effects occur in real life situations is unknown. In general, we believe that the performance of most tasks improves as basic visual information increases (and consequently, as light level increases.)

At first thought the needle probe task may seem simple; in fact, it is quite complex. The appearance of the probe tip changed as it was moved and seen against the background, needle body and needle eye; the probe tip, needles and needle eyes looked quite different against the two different backgrounds; the critical or important visual cues used to perform this task may vary among individuals and from time-to-time; also, needle size, exact angle and direction of probe movement, position of hand used for probing, type of probing movement, etc. would affect performance for tasks like this. These and other factors might help explain differences in performance scores. In spite of these complexities, the results of these experiments are probably representative for a wide range of tasks of this same general type.

Although visibility analysis does not take into account all of the visual characteristics of complex tasks, it provides a useful metric, especially in cases where physical measures are difficult, impossible or meaningless. Dynamic factors (what happens as the probe is moved) and differences between monocular visibility measurements and binocular task performance are examples of factors neglected in the assessment of visibility levels for the needle probe task. However, the visibility of the probe tip and needle eye are undoubtedly the main critical visual details upon which performance depends, and they were the features measured in the visibility analysis.

Since the visibility analysis did not completely rectify (cause the data points to fall on the same curve) the results for the two background conditions, variables not included in the analysis must have been effective. Transitional adaptation is an obvious possibility. The results, however, are in the opposite direction from predictions on this basis. Transitional adaptation effects are deleterious (for detection at least), yet performance with the black background where these effects would be maximum is actually superior to performance with the white background (see Fig 8.) Another possibility is that tasks involving multiple critical visual details are more difficult than tasks having a single critical detail. From Table III it can be seen that for the black background the probe tip is the only critical detail that has low visibility, whereas for the white background the probe

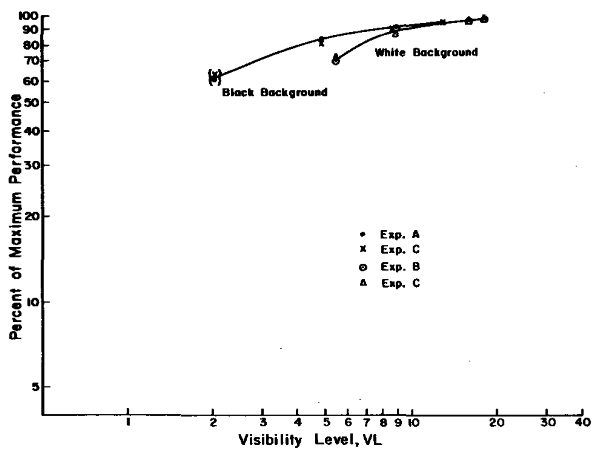
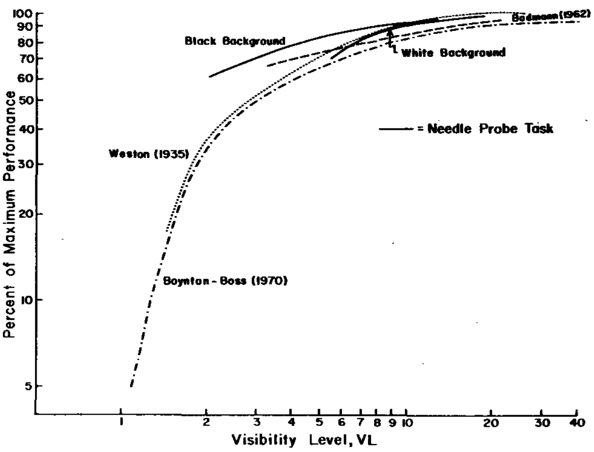


Figure 10. Relation between per cent of maximum performance and visibility level plotted on a double logarithmic grid (Experiments A, B and C).

Figure 11. Relation between per cent of maximum performance and visibility level plotted on a double logarithmic grid. Comparison of data from several studies.



tip and the needle eye are of about the same visibility. Thus, a subject doing the task with the black background always sees the needle eye very clearly, and must merely line up the probe to insert the tip in the eye. On the other hand, the subject doing the task with the white background has difficulty seeing both the needle eye and the probe tip. This interpretation is supported by the fact that the difference between the performance with the black and with the white background decreases as luminance and visibility level increase (see Figs. 7, 8 and 10).

The results of this study can be related to the present IES method for prescribing illumination.[25] At VL 8 (the IES visual performance criterion level) performance was 90 per cent of maximum with the black background, and 86 per cent of maximum with the white background. Luminance and illumination levels at the VL 8 performance criterion value were 8.7 footlamberts (29.8 cd/m^2) and 223 footcandles (2400 lx) for the black background condition, and 5.0 footlamberts (17.1 cd/m^2) and 19.8 footcandles (213 lx) for the white background condition. Veiling reflections, disability glare and transient adaptation have not been evaluated in this analysis.

Summary and Conclusions

The task used in the experiments required subjects to insert a fine tipped probe into the eye-holes of ten needles in rapid succession. Nine young adult subjects with normal vision served in the first experiment. The needles and probe were viewed against a black background under four levels of uniform white illumination. The second experiment was identical to the first except that a white background was used. For the third experiment, three new subjects were selected and given considerable practice. The two background conditions (black and white) were presented along with the same four illumination levels in counterbalanced order.

Performance in all three experiments improved, but at a decrease in rate, as light level increased to about 940 footcandles (10,100 lx). Performance was better with a white background than with a black one under the same illumination. However, for equal luminances or visibility levels, performance for the black background condition was superior. Transitional adaptation was discounted as an explanation of the differences in performance with the black and white backgrounds. A possible explanation for the difference is that the visibility of the probe tip and needle eye-holes were about equal for the white background condition, whereas only the probe tip was difficult to see for the black background condition. The results are compared with those of Bodmann,[5] Boynton and Boss,[6] and Weston.[14]

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