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RECOMMENDATIONS FOR MINIMAL LUMINANCE REQUIREMENTS FOR METAL AND NONMETAL MINES

Contract J0318022
Perceptronics, Inc.

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16. Abstract (Limit: 200 words) The primary objective of this research program was to recommend ranges of minimum luminance for safety in underground metal and nonmetal mining. Visual tasks critical to safety were identified and rank-ordered. Realistic, full-scale, dynamic task simulations encompassing the most important visual components of the critical tasks were installed in a large simulated workspace. Five trained observers performed the six simulated mining tasks under varying levels of luminance. Over 13,000 measurements of visual task performance were used in developing minimum luminance recommendations for the on-foot underground worker and the mobile equipment operator.			
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FOREWORD

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We wish to express deep appreciation to our panel of illumination and mining consultants, Dr. H. Richard Blackwell, Mr. C.L. Crouch, Dr. William Hustrulid, and Dr. John H. Taylor. Their expertise has been invaluable in every aspect of this research project. The program director, Dr. J. E. Uhlaner, served as chairman of the expert consultants panel.

Special thanks are expressed to the mine operators and Mine Safety and Health Administration personnel who participated in this study, and who willingly shared their knowledge and experience with us.

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EXECUTIVE SUMMARY

The primary objective of this research program was to recommend minimum luminance requirements for safety in underground metal and nonmetal mining. Minimum luminance recommendations for broad classes of mining tasks were derived from extensive measurements of visual performance database collected under varying light levels, using dynamic, full-scale mining task simulations in a large simulated underground workspace.

Adequate lighting is important to the safety of the underground worker. Available studies have shown that improved lighting can also increase morale and productivity. However, customary industrial lighting standards and practices are in many cases inappropriate for the underground environment because of the different nature of the visual tasks, the need to maintain the worker's adaptation to low light levels, the constantly changing location of the work area with each cycle of blasting and excavation, the confined spaces and harsh physical conditions, and the high cost of providing electrical power throughout the miles of haulageways. Another distinctive feature of underground work is the caplamp, which provides a local source of task illumination wherever the worker goes.

To determine the effect of luminance level on visual task performance in the underground mining environment, a direct measurement approach was developed. Visual tasks critical to the safe performance of underground mining jobs were selected for study. Observers performed simulated critical visual tasks, under a range of luminance levels. Time and accuracy measures of the observers' performance on the visual tasks were then used to quantify the relationship between visual performance and luminance.

Visual tasks important to the safety of underground workers were identified from task analysis interviews and work station observations performed in a previous study, under USBM Contract J0387230. From these tasks, a subset of tasks most critical to safety were identified in the current study from ratings of each task by 18 experienced Mine Safety and Health Administration inspectors and 6 expert consultants in mining and illumination research.

Full-scale, dynamic simulations of these critical visual tasks were installed in a realistic reproduction of a large underground workspace (15 ft wide, 30 ft deep, 11 ft high). The performance measurement methodology developed in this research program is based on the precise laboratory control made possible by working in a simulated underground work area rather than in actual operating mines.

Particular emphasis was placed on making the full-scale simulated underground workspace and the visual task simulations highly realistic, so that photometric and visual factors important in illumination engineering would match those in an actual underground mine. The validity of the task simulations, and thus the generalizability of the resulting data, was confirmed by comparing relative measures of visual difficulty for the simulated tasks and their actual counterparts in large underground mines.

To determine the functional relationship between luminance level and visual performance on safety-related tasks, five trained observers performed the simulated mining tasks under varying levels of luminance, ranging from the light level produced by a single caplamp to a high light level, above which no significant improvement in performance would be expected. Over 13,860 repeated measurement trials were conducted under carefully controlled lighting and task conditions. The simulated tasks were instrumented to provide precisely quantified performance measures, and accurately repeated presentations of visual tasks and light levels. The lighting environment faithfully duplicated actual underground mine conditions, including the important elements of caplamp lighting geometry and beam pattern (bright central spot, dim surround).

The task simulations represented broad classes of visual tasks in mining and incorporated a realistic degree of visual search. The visual components included high-acuity targets (detection of rock cracks), detection of motion (as in a jammed ore path), detection of hazards on the rib, back, and floor (rubble, hoses, holes, protruding pipes or rock bolts), and peripheral vision requirements (awareness of other workers and machines, perception of emergency escape path).

An extensive database, representing many repetitions of each task at each light level, was used to develop recommendations for minimum luminance in 43 mining jobs. The recommended luminance levels are discussed in detail in Section 4.3, pages 102-107, of this report. All of the mining jobs (a total of 38) performed by the on-foot mine worker (often with caplamp illumination only) were found to have equivalent minimum luminance recommendations that appear to be technically achievable with an improved caplamp. The other five mining jobs involve operations of mobile equipment. Most existing machine lighting systems observed in the course of this research program appear to provide light levels that meet or exceed the recommended luminance levels for tasks associated with mobile equipment.

Observations made in underground mines and the studies conducted during the present study of minimum task luminance have demonstrated the importance of other lighting factors, in addition to minimum luminance, that can affect worker safety. The additional lighting

factors include: (1) the pattern or distribution of illumination (glare and transient adaptation) (2) the source-task-observer lighting geometry (shadow definition of low contrast objects), and (3) the glare and adaptation problems that could result from a general implementation of changes in current lighting practices (e.g., improved caplamp beam patterns could cause glare to other workers).

Further research is suggested to determine the interactions between minimum task luminance and these additional lighting factors. The resulting data would provide empirically-based design specifications for an improved caplamp and better supplementary lighting systems.

The visual performance methodology developed in the present research program is strongly recommended. It combines the realism and relevance of simulated underground mining tasks with the laboratory control necessary for sensitivity and repeatability in the quantitative behavioral measures.

1. BACKGROUND OF PROBLEM

In this section we first discuss the background of the present study. Relevant prior studies of illumination in coal and metal and nonmetal mining are introduced. Second, we examine characteristics of the underground environment that require consideration in determining minimum luminance requirements. Topics discussed include the variance in both the environment and the work performed, the combination of low reflectance and low contrast, and characteristics of current luminaires. Third, we review prior work in greater detail. Both the Hitchcock (1973) study to determine minimum luminance requirements for underground coal mining, and our own previous study to identify illumination needs in underground metal and nonmetal mining are discussed. Finally, the scope of the current work is delineated and the form of the results is specified.

1.1 INTRODUCTION

Mining has been recognized officially by the Federal Government as deserving specific attention in improving the safety of its workers. This official recognition is expressed in the Federal Coal Mine Health and Safety Act of 1969, and its 1977 extension to metal and nonmetal mining. Among the major areas of concern for improved safety in mining is the illumination of underground work areas.

The importance of good lighting to the underground worker cannot be over-emphasized. In addition to the obvious benefits of improved worker morale, available studies (Trotter, 1977) have shown that good lighting reduces accidents and increases productivity. Providing a high enough level of illumination is only part of the solution. The manner in which the light is controlled (i.e., by placement of luminaires, luminaire design and shielding) is equally important. Economics will not allow the general level of lighting in a mine to approach that typically found in an industrial setting. Therefore, lighting standards should be based upon the minimum luminance necessary for adequate performance of those mining tasks critical to safety.

Basic research aimed at specifying minimum luminance requirements for underground coal mining was reported by Hitchcock (1973). With regard to specifying luminance requirements for underground metal and nonmetal mining, in a previous study we (Crooks, Drake, Perry, Schwalm, Shaw, and Stone, 1980) reported:

- (1) Descriptions of the range of visual tasks performed by underground workers.

- (2) The current illumination environment and lighting practices.
- (3) Task and background reflectances.

In the present study, the following additional work was accomplished:

- (1) Selection of critical visual tasks representative of the complete range of underground visual tasks.
- (2) Determination of the quantitative relationship between luminance level and visual performance of safety-critical tasks.
- (3) Interpretation of the resulting visual performance database by integration with data from other relevant studies and consideration of current Illuminating Engineering Society practices.
- (4) Recommendation of ranges of minimum luminance required for safety in underground metal and nonmetal mining.

1.2 LIGHTING CONSIDERATIONS IN UNDERGROUND MINING

The results of our mine visits, interviews with experienced underground workers, and illumination laboratory analyses (Crooks, et al., 1980) lead us to several distinct conclusions regarding the present illumination conditions in underground metal and nonmetal mines and to some observations regarding approaches to determining minimum luminance requirements.

Unlike coal mines, the environmental and physical characteristics of metal and nonmetal mines vary considerably both within and between mines. Relevant examples cited in Crooks, et al. include size of the opening (face), reflectance of particular ore types, and concentrations of aerosols. Equipment types and configurations of machine lighting also differ considerably, even at two or more work locations within the same mine. The work performed is also highly variable. Forty-three unique unit operations encompassing the tasks performed under 258 job titles were identified.

Underground work is performed in a visual environment that imposes severe restraints on the ability of the worker to see adequately essential visual features. Backgrounds are of low reflectance. Most faces and floors are in the 10 to 30 percent range.

Low target-background contrasts are characteristic of most work areas due to a uniform mud and dust film deposited by blasting. Specular reflection from standing water or wet surfaces is commonplace.

While mobile equipment (rubber-tired and rail) is fitted typically with several sealed beam luminaires, the worker's caplamp is often the only illumination source for many mining jobs. Because the caplamp still plays such an important role in underground illumination and is used even when other sources are present, the characteristics of current caplamps deserve consideration. Figure 1-1 shows the beam distribution pattern of a typical lamp. Some advantages of the caplamp include:

- (1) Easily aimed without use of hands.
- (2) Provides conspicuity and very important means of signalling.
- (3) Effectively eliminates glare from source to eye.
- (4) Hazardous objects suddenly increase in brightness as they approach the caplamp (inverse-square law of illumination).

These advantages are balanced by the following disadvantages:

- (1) Narrow central beam, typically 5° - 10° in diameter creates tunnel vision in which hazards may go unseen.
- (2) High luminance ratio between the small central spot and the dim surround (penumbra).
- (3) Loss of dark adaptation due to the high luminance of near objects.
- (4) Caplamp located just above eyes eliminates visible shadows that help outline objects on the mine floor (see Figures 4-3a and 4-3b, pages 111-112).

Despite the limitations of the caplamp, portable and fixed luminaires are used infrequently. Some of the reasons for low utilization include:

- (1) Portable lights require either battery or generator if electrical power is not readily available (transport requirement).
- (2) Electrical power for portable or fixed lights presents an additional hazard (except for low voltage systems).

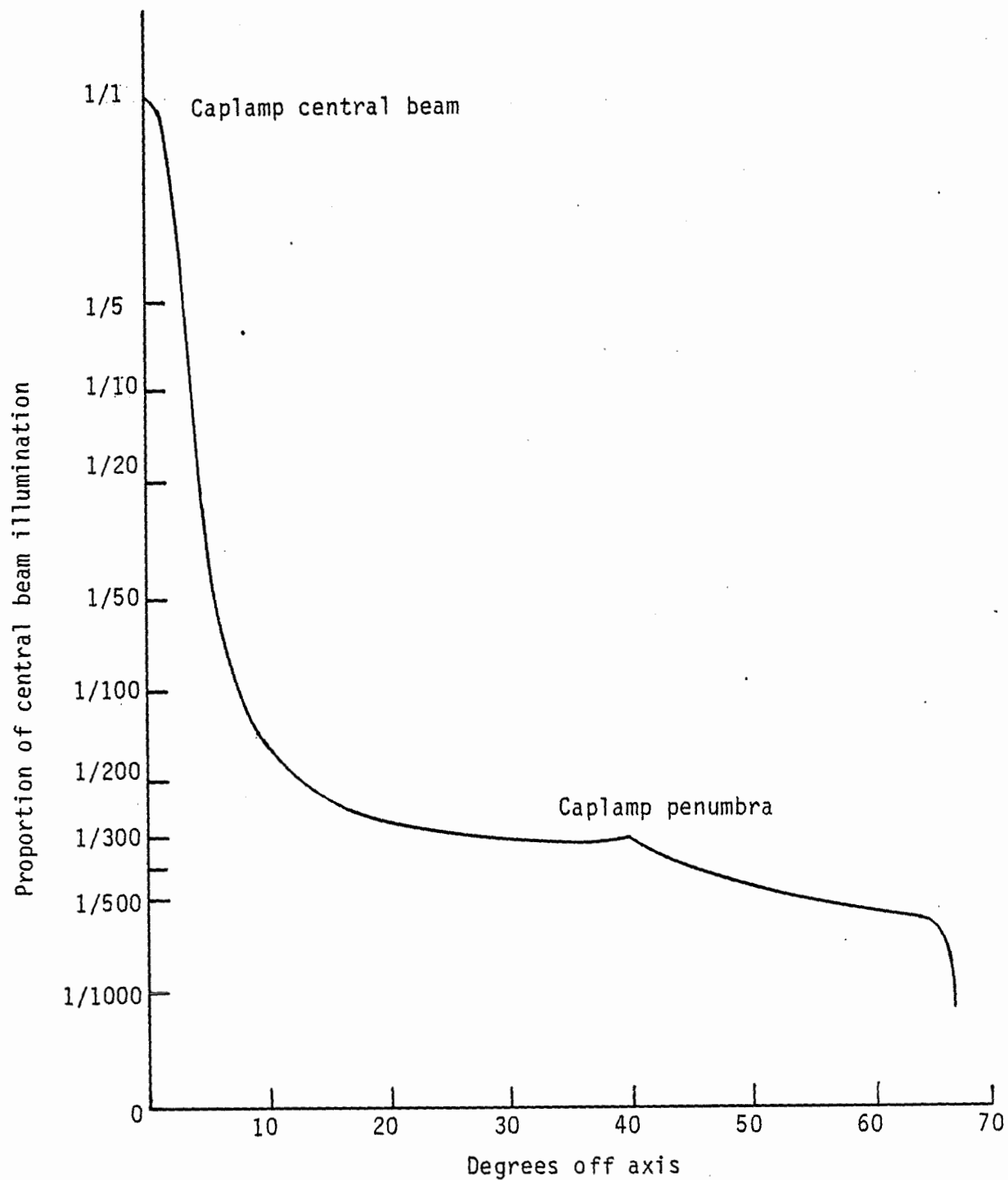


FIGURE 1-1. - Caplamp beam distribution.

- (3) Portable or fixed lighting is often installed so that glare problems defeat the additional lighting benefit.
- (4) Cost and maintenance time (installation, removal, repair).
- (5) Unshielded light may cause temporary loss of dark adaptation so that the caplamp is not adequate for detection of hazards away from the illuminated work area.

1.3 REVIEW OF PRIOR WORK

Hitchcock (1973) reported the development of minimum luminance requirements for safe job performance in underground coal mining. Eleven mining jobs in conventional, continuous and longwall mining methods were studied. The study involved two distinct phases, the first being in-mine measurements. A detailed task description was prepared for each job. Visual tasks for each job were identified. The distance, duration, object identity and luminance, and background identity and luminance were all determined. Measurements of reflectances of the opening and light transmission were also made.

The second phase was done in a full-scale simulated mine work space with full-scale machinery models. The visual tasks observed in the mine were duplicated in the simulator and the visibility levels of the visual tasks were measured using a contrast-reducing visibility meter (Visual Task Evaluator, or VTE). Mining visual tasks were referenced to threshold visibility data for 4' disks presented on uniform backgrounds in repeated 1/5 second exposures, in the standard manner used by the Illuminating Engineering Society for all application areas at the time of the Hitchcock study.

The threshold visibility luminances were then revised upward to include a 99% probability of detecting a dynamic visual task of uncertain location. The threshold luminances were then further revised upward to encompass 95% of a 55-65 year old population with no ocular pathology and with a visual acuity not less than 20/30 (corrected). To increase the general confidence level, luminance levels for each task were calculated including 50% of the experimental error.

Hitchcock next recombined the individual tasks into job categories. A group of visual tasks common to all mining jobs was assigned to a "common core." The remaining tasks were divided among the jobs as "tasks unique to particular jobs." The calculated luminance values for the common core tasks were compared to each of the unique job tasks categories. None of the unique job task categories was found to require greater luminance than the common core category. This finding was taken to support the specification of a single common minimum luminance level for all underground coal mining.

On July 1, 1978, Mine Safety and Health Administration regulations for the illumination of underground coal mines took effect. These regulations specify a minimum luminance of 0.06 foot-lamberts (fL) on surfaces to be illuminated while self-propelled mining equipment is operated in the working place. The working place is defined as the area of a coal mine inby the last open crosscut. The regulations specify the surfaces to be illuminated for various classes of equipment.

Prior work by Perceptronics is fully described in the report "Analysis of Work Areas and Tasks to Establish Illumination Needs in Underground Metal and Nonmetal Mines" (Crooks, et al., 1980). The research program consisted of three essential steps: (1) identification and description of visual tasks, (2) description of the illumination environment, and (3) measurement of task and background reflectances. These three steps were the first steps necessary to establish valid recommendations for illumination requirements. The first program step was based on detailed analyses of the jobs and work stations that occur in the underground mining environment. Nine mines representative of the range of mining methods and commodities were visited. Extensive task analysis interviews were conducted with 135 underground workers and detailed studies were made of 139 unique underground work sites.

The job and work station analyses identified a number of important dimensions of the visual tasks, such as (1) sizes of objects, (2) viewing distances, (3) object characteristics, (4) viewing angles, (5) prior visual tasks, (6) when task is performed, (7) atmospheric (dust) conditions, (8) frequency of occurrence, (9) impact of inadequate performance, and (10) common errors. These dimensions of the visual tasks provided the information necessary to characterize the full range of jobs and tasks in terms of the constituent visual tasks.

The second step in the completed program focused on describing the illumination environment. In addition to specifying the visual tasks to be performed, the analysis program focused on underground illumination as it currently exists. The research team identified the ambient luminance of the visual tasks, the lighting geometry of the work stations, and characteristics of the luminaires (geometry, placement, beam distribution, etc.). The third step in the program complemented the second step by augmenting the description of the existing visual environment. This third step involved measuring the reflectance of the objects and surfaces in the underground working environment.

These three steps were essential in establishing a logical basis for the present research to determine minimum luminance requirements for safe and efficient underground work. The tasks remaining were to:

- (1) Select critical visual tasks representative of the full range of visual tasks.
- (2) Determine the quantitative relationship between visual performance and luminance.
- (3) Integrate the results with other relevant information and current IES practices.
- (4) Specify recommended ranges of minimum luminance.

1.4 SCOPE OF WORK

The objective of the present project has been to define and recommend minimum lighting that is required to perform safely and efficiently work in all underground metal and nonmetal mines. The study included consideration of mining jobs representing the entire range of work found in underground metal and nonmetal mines. Table 1-1 lists the job titles included in the study. Table 1-2 lists the generic mining jobs or unit operations encompassing those job titles.

Visual tasks identified as critical to the safety of underground workers and representative of the complete range of visual tasks in all underground metal and nonmetal mines were included in the study. A combination of methodologies were utilized to determine the effect of luminance on visual performance. These data were then integrated with all relevant data to make sound recommendations concerning minimum luminance requirements for safe and efficient job performance.

These recommendations cover all major work in underground metal and nonmetal mines and are the most general illumination requirements possible for the entire industry. Recommended lighting practices and possible problems associated with implementing the recommendations are also provided.

TABLE 1-1. - Job titles

APPRENTICE	HANGUP TIMBERMAN	REPAIRMAN
BORING MACHINE HELPER	HEAD GATE MAN	ROOFMAN
BORING MACHINE OPERATOR	HOIST ENGINEER	RODMAN, ENGINEER
BARMAN	JANITOR	REPAIRMAN, DIESEL
BOBCAT OPERATOR	JAW OPERATOR	REPAIRMAN, ROCK DRILL
BAULKGROUND MAN	JUMBO OPERATOR	SAMPLER
CAGER (CAGERMAN)	JOY LOADER OPERATOR	SANDMAN
CRUSHER FEEDER	LABORER	SHAFTMAN
CRUSHER MAN	LOAD DISPATCHER	SHAFTMAN - SINKING
CRUSHER CONTROL ROOM OPERATOR	LOADER	SKIPPER
CRANE OPERATOR	LOADER OPERATOR	SURVEYOR
CARPENTER	LHD OPERATOR	SHAFT UTILITY MAN
CONCRETE MASONRY MAN	MINER	SKIP LOADER
CONCRETE PLACER	MECHANIC	SLUSHER REPAIRMAN
CAR CLEANER	MOTORMAN	SCREEN OPERATOR
CAVE MINER	MACHINE REPAIRMAN	SCALE MAN
CONVEYOR OPERATOR	MINE EQUIPMENT MECHANIC	SHIFT BOSS
CHUTE PULLER	MINE MAINTENANCE MAN	SQUARE-SET MINER
CHOCK ADVANCE MINER	MAINTENANCE MAN	SLUSHER OPERATOR
CONDUCTOR MINE SKIP	MIXER OPERATOR	SCRAPERMAN
CRUSHER MECHANIC	MUCKING MACHINE OPERATOR	SCRAPER OPERATORS
DIAMOND DRILL HELPER	MINER, CONTRACT	SUPPORT OPERATORS
DIAMOND DRILL OPERATOR	MASON	SHEARER OPERATORS
DIAMOND DRILLER	MOTORMAN TROLLEY HAULAGE	SUMP PUMP MAN
DISPATCHER	MINE OPERATOR, LOCOMOTIVE	SHOTCRETE CREW MEMBER
DRILLER	MINE OPERATOR, LHD	TIMBERMAN
DEVELOPMENT DRILLER	NIPPER	TOOL ROOM MAN
DRIVER	NIPPER FORM MAN	TRACKMAN
DRILLER, RAISE	OILER	TRIPPER OPERATOR
ELECTRICIAN	OPERATING DRILLER	TRUCK DRIVER
FIRE INSPECTOR	PLANT OPERATOR	TRUCK DRIVER HELPER
FORM MAN	PLUMBER	TRACTOR DRIVER
FORKLIFT OPERATOR	PIPEMAN	TRUCK AND TRACTOR HELPER
GUNITE OPERATOR	PUDDLER	TAIL GATE MAN
GYRATOR OPERATOR	PUMP AND FAN MAN	TRANSFER HAULER
HELPER	POWERMAN	TIMBERLINE CREW MEMBER
HOIST OPERATOR	PIPE VENTILATION MAN	TRAMMER
HOISTMAN	PUMPMAN	WELDER
HEAVY EQUIPMENT OPERATOR	PROSPECTOR	WOODPICKER
HANGUP MAN	PIPEFITTER	WALL BUILDER
		WINZE SKIPPER

TABLE 1-2.- Unit operation list

DRILLING

1. Feedleg Drilling
2. Raise Boring
3. Jumbo Drilling
4. Stoper Drilling
5. Ring Drilling
6. Rotary Drilling

GROUND SUPPORT

7. Rock Bolting
8. Timber Post Erection
9. Guniting/Shotcreting
10. Timberset Assembly
11. Cribbing
12. Sandfilling
13. Preparing Work Area

LOADING

14. L.H.D. Operation
15. Slusher Operation
16. Overshot Loader Operation
17. Manual Shoveling
18. Chute Pulling

HAULAGE

19. Train Operation
20. Truck Operation
21. Conveyor Operation/Maintenance
22. Tugger Operation

MAINTENANCE

23. Shaft Maintenance
24. Machine Maintenance
25. Roadway Maintenance
26. Track Maintenance

SERVICES

27. Pipe Installation
28. Ventilation Installation/Repair
29. Electrical Installation/Repair

CONSTRUCTION

30. Concrete Construction
31. Steel Construction
32. Timber Construction

BLASTING

33. ANFO Loading/Blasting
34. Stick Powder Loading/Blasting
35. Diamond Drilling
36. Surveying
37. Sampling

CONTINUOUS MINING

38. Continuous Miner Operation

HOISTING

39. Man Cage Operation
40. Ore Skip Operation

SUPERVISION

41. Super./Coordinating Workforce
42. Safety Inspection

UNDERGROUND ORE PROCESSING

43. Ore Crusher Operation

2. TECHNICAL APPROACH

In this section we first provide an overview of the technical approach. Second, we describe the procedures used to identify those visual tasks critical to safety in underground work. Third, we discuss the selection of measurement methods appropriate to the critical visual tasks.

Finally, we describe the experimental paradigm used to determine the relationship between visual performance and the level of background luminance. The simulations of the mine work space and the visual tasks are described. The procedures used for direct measurement of visual performance are delineated.

2.1 OVERVIEW OF TECHNICAL APPROACH

The basic question answered in this research project is: "How much light is needed for safety in performing underground work?" Another way of stating the intention of this project is: "Determine the minimum levels of illumination needed to eliminate lighting as a significant factor in mining accidents."

There are many factors other than lighting that contribute to the cause of a given accident. Minimum standards for illumination could not prevent some accidents, but would ensure that lighting factors play virtually no causal role.

For reasons set forth in Appendix A, our basic approach was to select the critical visual tasks that constitute the visual demands of underground mining, to determine experimentally the effect of luminance on performance of these tasks, and to use these experimental data as the basis for recommendations of minimal luminance. To accomplish this research effort, six tasks were completed, as outlined below:

- (1) Select critical visual tasks to be measured.
- (2) Select measurement methods suitable for each task.
- (3) Pilot test measurement equipment and procedures.
- (4) Determine the quantitative relationship between luminance and visual performance for each critical task.
- (5) Specify minimum luminance ranges and distribution for mining jobs.

(6) Recommend optimum lighting practices:

- lighting geometry to highlight task features
- control of glare

In the course of this project, a seventh task was added to the original research plan. Since the illumination required to achieve a given level of task luminance is a direct function of surface reflectance, we undertook development of instruments and procedures for in-mine reflectance measurement. The recommended system is described in Appendix B.

2.2 SELECTION OF CRITICAL VISUAL TASKS

Almost all visual tasks in mining are relatively easy: although contrasts are typically low, details to be seen are large, and hazards often present motion that can be detected in peripheral vision at low luminance levels.

Visual tasks associated with the safety of the operator are the focus of the present study. These tend to be detection tasks, especially peripheral detection of some hazard or change in the work area. The targets associated with these visual tasks frequently fall outside the intense central beam of the caplamp.

The miner's caplamp appears to do an adequate job of illuminating the visual targets associated with most production tasks. In most instances the miner knows the target's location and is able to illuminate it with his caplamp's central beam. The principal exception to the caplamp's adequacy for production is the relatively small number of visual tasks that have viewing distances in excess of 20 feet. Supplemental lighting is typically used in those cases. This lighting generally appears to be adequate for production and is not of primary interest in this study.

Our prior work (Crooks, et al., 1980) identified the visual tasks associated with each of 43 mining jobs or unit operations. We conducted 188 task analysis interviews with 135 underground workers and analyzed 139 unique work sites in the course of that effort.

We found that each job involves many visual tasks. For example, the unit operation "prepare work site" (barring down loose rock from the back or rib) involves such visual tasks as detecting likely areas of incompetent rock, seeing where to place the pry bar, observing the direction in which loose rock is going to fall, and maintaining a general "environmental awareness" of the immediate terrain underfoot

in order to move safely and quickly in escaping from unexpected rock falls. The unit operation "slushing" involves such visual tasks as detecting frayed slusher cables and identifying rock bolts in the muck pile.

It was neither feasible nor necessary to determine minimum luminance requirements for all visual tasks of each unit operation. To reduce the size of the study, we first identified those visual tasks that are common to a group of unit operations. For example, detection of floor hazards (holes, rubble, cables, and other tripping hazards) is common to all mining jobs that require the worker to walk about the work site. Other visual tasks such as color discrimination of color-coded wiring are unique to a single unit operation (e.g., electrical installation and repair). The complete list of 113 visual tasks is given in Appendix C. Of these, 48 were found to be common to 2 or more mining jobs while 65 were unique to specific mining jobs.

The next task was to identify the visual tasks that are critical to the safe and efficient performance of each mining job. Determination of requirements of the subset of critical visual tasks would then define the minimum luminance requirements of the associated unit operation. The procedure used to select the critical visual tasks is shown in Figure 2-1.

A Visual Task Questionnaire was used to identify those visual tasks critical to safety. A sample problem from the questionnaire is shown in Figure 2-2. Each visual task was rated for its safety impact and the potential payoff of improved lighting. Would a failure to see or to see quickly enough cause an accident? Would changes in current lighting improve the worker's ability to see the target? Questionnaires were obtained from 18 experienced Mine Safety and Health Administration (MSHA) mine inspectors representing each geographic region, mining method, and commodity. Questionnaires were also obtained from six mining researchers and consultants. For both groups of raters the mean ratings of Safety Impact and Potential Payoff were computed for each of the 113 visual tasks. The two ratings were combined to identify the visual tasks that contribute most to the safety of the underground worker and that improvements in lighting will improve most the worker's safety. The rank orders of the 113 visual tasks produced by the two rating groups (inspectors vs. researchers) were compared and found to be highly correlated (Spearman Rank-Order Correlation, $\rho = 0.841$, significant at 0.001 level). The results of the two rating groups were then pooled to determine a final rank ordering of the visual tasks.

Many of the highest ranked visual tasks are common to a large number of mining jobs (e.g., visual tasks involving "environmental awareness" are found in most of the 43 unit operations). Other highly

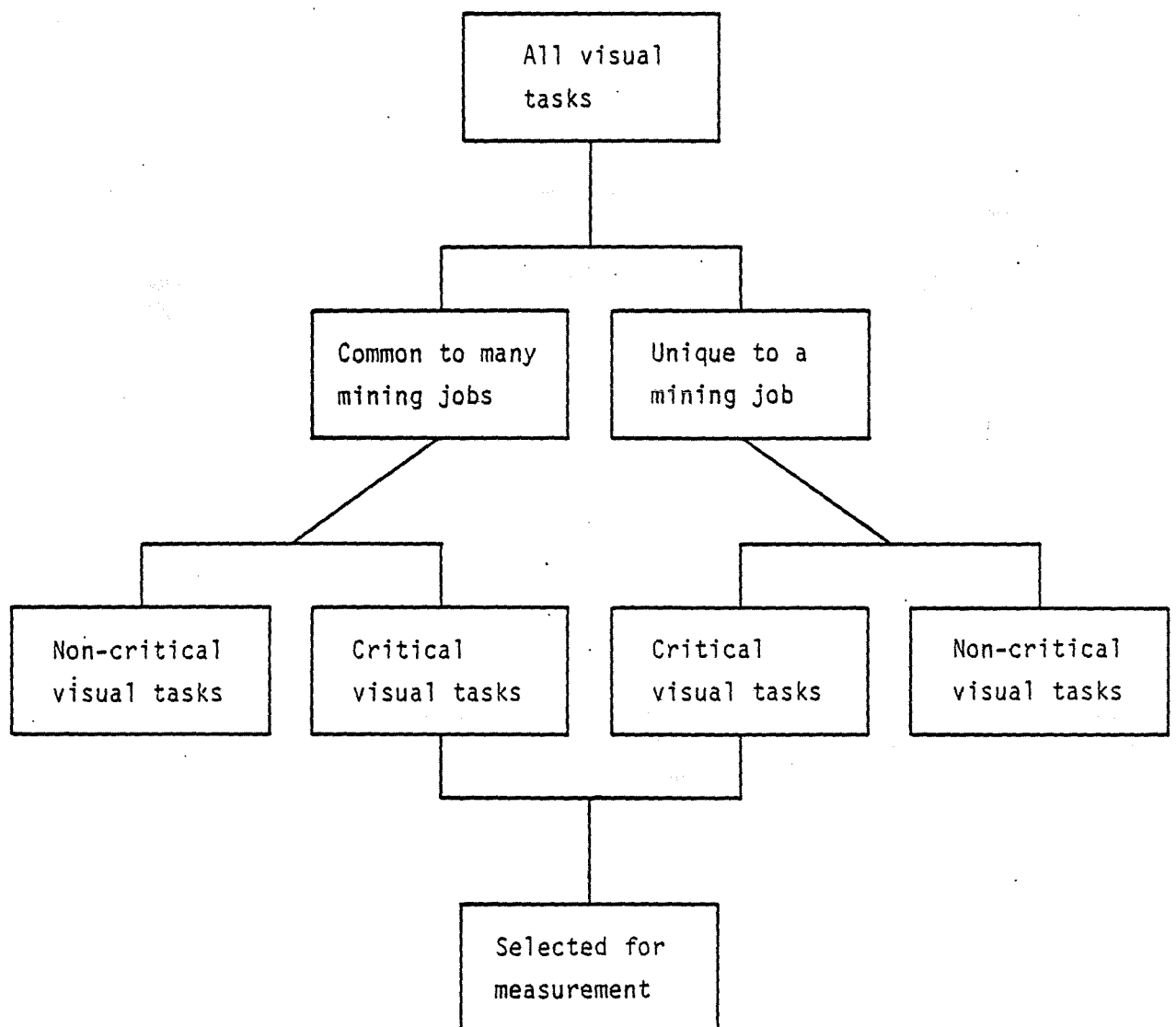


FIGURE 2-1. - Selection of critical visual tasks.

Sample Problem:

Circle the number that best describes your rating of each visual task according to the following criteria:

1. Safety Impact. How much does performance of this visual task affect the safety and health of underground workers?
2. Potential Payoff. How much can performance of this visual task be improved by changes in current lighting practices and illumination equipment?

What Must Be Seen (Target)	What Must Be Discriminated	Comments	Safety/Payoff Rating					
			Low		High			
Crack in back/ribs	Detect (discon- tinuity in dust coat, shadows)	Often caplamp only; often no shadow modeling of rock surface	Safety	1	2	3	4	5
			Payoff	1	2	3	4	5

Figure 2-2.- Visual task questionnaire.

ranked visual tasks are unique to a specific mining job (e.g., the visual tasks associated with chute pulling and clearing blocked finger raises are unique to that job). The three highest ranked visual tasks were selected as the minimum to be measured for each mining job. Selection of the 17 highest ranked tasks provided a minimum of three critical tasks for 42 of the 43 mining jobs. Two additional tasks (tied rank of 28.5) were included to provide the minimum of three for the job of shaft maintenance. The 19 critical visual tasks are described in Table 2-1. A matrix of mining jobs and the critical visual tasks is shown in Table 2-2.

2.3 SELECTION OF MEASUREMENT METHODS

Our prior work (Crooks, et al, 1980) enabled us to identify a number of constraints on the selection of measurement methods and procedures. Foremost of these was the impracticality of providing even, diffuse lighting at most underground work sites. Glare (both reflected and source) and transient adaptation must be highly significant variables in any consideration of underground lighting. The Illuminating Engineering Society (Kaufman, 1972, p.3-23) suggests that:

"It will be found impractical to study some tasks, such as those encountered in roadway lighting, under the reference lighting conditions of a photometric sphere. It will prove convenient to study other tasks such as highly specular industrial tasks under more realistic types of lighting than the diffuse lighting of a photometric sphere."

Further, we recognized that the miner's caplamp would always be present and must, therefore, be considered. We had also observed that lighting geometry and shadow modeling greatly affected the visibility of many visual targets. These complex and interactive lighting factors made the use of a full-scale, realistic simulation facility essential. Such a facility allowed us to use realistic lighting appropriate to each task situation and incorporate effects of glare, transient adaptation, shadow modeling, and lighting geometry while retaining the very important capability for accurate trial-to-trial replication.

Four candidate methodologies were considered for determining minimum luminance requirements. The four were:

- (1) Measure task performance under varying levels of illumination (direct performance measurement approach).

TABLE 2-1. - Critical visual tasks

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
1	Prepare work site (detect and remove loose; inspect muck pile)	Back and ribs near area being barred	Detect loosening of rock (keystone effect).	Often caplamp only, may be in penumbra, often no shadow modeling of rock surface.
2	Environmental awareness (detection and awareness of hazards while on foot)	Supported/unsupported ground	Detect location of unsupported ground. Maintain awareness of location/update as necessary.	Worker may be handling heavy objects. Often caplamp only.
3	Prepare work site (detect and remove loose; inspect muck pile)	Slabs and rock protrusions in back/ribs	Detect (appear "abnormal" or out of place).	Often caplamp only, often no shadow modeling of rock surface.
4	Chute pulling and clearing blocked finger raises	Rocks in chute or raise	Detect movement (in time to get out of the way).	Usually caplamp only, often must lean out in front of chute to see cause of jam.
5	Prepare work site (detect and remove loose; inspect muck pile)	Crack in back/ribs	Detect (discontinuity in dust coat, shadows).	Often caplamp only, often no shadow modeling of rock surface.
6	High speed tramming of mobile equipment (rubber-tired and rail)	Hazards on rib/back (pipe, rock bolts, vent tubing, timber sets, low headings)	Detect location, judge/adjust path of machine to avoid hazard.	Machine lighting. Operator may have to stop or may choose to duck to clear hazard.
7	Continuous miner operation	Back condition	Detect cracks, discolorations and other indicators of unsafe conditions.	Machine lighting; dust may reduce visibility.

TABLE 2-1. - Critical visual tasks (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
8.5	High speed tramming of mobile equipment (rubber-tired and rail)	Haulageway hazards (people, equipment, rubble, hoses, cables, holes, etc.)	Detect location, judge/adjust path of machine to avoid hazard.	Machine lighting. Blind spots may be extensive, especially to side opposite operator.
8.5	Prepare work site (detect and remove loose; inspect muck pile)	Rock surface	Detect changes in grain pattern or "slips".	Often caplamp only, dust obscures much of desired detail.
10	Environmental awareness (detection and awareness of hazards while on foot)	Hazards on rib/back (loose rock, protrusions, low headings, etc.)	Detect location. Maintain awareness of location at work site.	Worker may be handling heavy objects. Often caplamp only.
11	Ground support activities (rock bolting, timbering, sandfilling, shotcreting, etc.)	Oversize slabs	Detect presence and boundaries (slab given extra support if too large to bar down)	Often caplamp only, often no shadow modeling, may be in penumbra of lamp.
12	Prepare work site (detect and remove loose; inspect muck pile)	Falling loose and loose sliding down bar	Detect beginning of fall, judge probable path (to decide whether evasive action is required).	Often caplamp only, may be in penumbra, often no shadow modeling of rock surface.
13	Environmental awareness (detection and awareness of hazards while on foot)	Floor hazards (holes, rubble, hoses and cables, etc.)	Detect location on floor. Maintain awareness of location at work site.	Worker may be handling heavy objects. Often caplamp only.
14	Prepare work site (detect and remove loose; inspect muck pile)	Face after blasting ("bootholes", ANFO or stick powder)	Detect bootholes, ANFO or stick powder in holes, ignite wires or caps.	Often caplamp only, often no shadow modeling of rock surface.

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
15	High speed tramping of mobile equipment (rubber-tired and rail)	Front & rear clearance during turns, backing, and maneuvering	Judge clearance, adjust path of machine to avoid impact with hazards front, rear, or to sides.	May require simultaneous monitoring of spatial relationships on all sides.
16	Environmental awareness (detection and awareness of hazards while on foot)	Area behind worker (hazards, escape route)	Detect clear path for escape. Maintain awareness of escape route/update as necessary.	Worker may be handling heavy objects. Often caplamp only.
17	Prepare work site (detect and remove loose; inspect muck pile)	Stick, caps, igniter wires, blasting lines, drill steel	Detect in muck pile.	Often caplamp only.
28.5	Shaft maintenance	Girders, timbers	Detect cracks, rot, etc.	Caplamp only, cage is usually moving.
28.5	Shaft maintenance	Guides	Detect excessive wear, absence of grease.	Caplamp only, cage is usually moving.

TABLE 2-2. - Critical visual tasks of mining jobs

		Mining Jobs																																											
Rank	Visual task	Feedleg drilling	Raise boring	Jumbo drilling	Stoper drilling	Ring drilling	Rotary drilling	Rock bolting	Timber post erection	Gunite/shotcreting	Timber set assembly	Cribbing	Sandfilling	Prepare work area	LHD operation	Slusher operation	Overshot loader operation	Manual shoveling	Chute pulling/clearing raises	Train operation	Truck operation	Conveyor operation/maintenance	Tugger operation	Shaft maintenance	Machine maintenance	Roadway maintenance	Track maintenance	Pipe installation/repair	Ventilation installation/repair	Electrical installation/repair	Concrete construction	Steel construction	Timber construction	ANFO loading/blasting	Stick powder loading/blasting	Diamond drilling	Surveying	Sampling	Continuous miner operation	Manage operation	Ore skip operation	Supervising/coordinating workforce	Safety inspection	Ore crusher operation	
1	Keystone effect	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									X	X					X	X	X					X			
2	Unsupported ground	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X									X	X					X	X	X					X			
3	Slabs/protrusions													X																															
4	Rock motion (chute)														X				X																										
5	Cracks in rock														X					X																									
6	Rib/back (tramming)															X				X							X																		
7	Condition of back																			X																									
8.5	Haulageway hazards															X				X																									
8.5	Pattern slips														X																														
10	Rib/back (walking)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																									
11	Oversize slabs							X	X	X	X	X	X																																
12	Falling loose														X																														
13	Floor hazards	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																									
14	Bootholes	X		X	X	X	X							X																															
15	Vehicle clearance														X					X																									
16	Escape path	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																									
17	Muck pile hazards														X	X	X	X																											
28.5	Shaft guides																																												
28.5	Shaft timbers																																												

- (2) Determine luminance level required for threshold detection by varying the level of illumination (direct task visibility approach).
- (3) Determine visibility of task with contrast-reducing visibility meter (VTE) and determine minimum luminance requirements by reference to standard visual task performance data (indirect task visibility approach).
- (4) Predict minimum luminance requirements from angular size of critical details and inherent contrasts (analytic illumination engineering approach).

While each method has been used successfully in other lighting studies, we elected to rely primarily on the first method listed, in part for reasons discussed in Appendix A. This method allowed us to incorporate realistic glare and transient adaptation effects and uncertainties of target appearance and location into the measurement process.

In consultation with our panel of illumination and mining experts (see Appendix D for a list of panel members and their professional affiliations) we developed the following measurement approach:

- (1) Measure visual task performance with varying levels of task luminance.
- (2) Concentrate data collection on a restricted number of simulated tasks that broadly represent generic classes of motion, contrast, resolution, and depth perception.
- (3) Use visually realistic simulations of actual mining tasks, including dynamic visual search factors.
- (4) Include glare and adaptation factors appropriate for each task, such as the caplamp's central spot.
- (5) Provide standardized replications from trial to trial.
- (6) Record response time measures and errors.
- (7) Use a visibility meter (VTE) to obtain relative measures comparing the simulated tasks with their actual underground counterparts.
- (8) Use a VTE to obtain visibility measures for tasks that do not lend themselves to performance testing.

VTE measures, and their implications for minimum luminance recommendations, are discussed in detail in Appendix A.

2.4 MEASUREMENT OF VISUAL TASK PERFORMANCE

2.4.1 Simulation of Mine Work Space. The total effect of any given lighting system depends on the characteristics of the surrounding space. Light energy reflects back and forth in a complex way between the task objects and the interior surfaces of a work space (IES, 1981). The realistic full-scale simulation of both a large and small underground work space was essential for ensuring that the total lighting effects obtained in visual performance testing would be the same as if the tests were conducted in an actual underground work area.

The plan of the Mine Research Facility is shown in Figure 2-3. The large work space or opening is 15'W x 11'H x 30'D and allows testing of visual tasks associated with longer viewing distances and large, open areas in the mine. The smaller work space is 7'W x 7'H x 12'D and is used for the simulation of visual tasks associated with smaller openings and lower degrees of mechanization.

The interior surfaces of both openings simulate the appearance of a typical mine. After testing a variety of surface simulation techniques, a heavy gauge aluminum-foil/kraft-paper laminate (sold commercially as "builder's foil") stapled to wood framing was found to give reasonable fidelity at modest cost. Large sheets of the laminate are crumpled and then unfolded to produce contours remarkably like those of blasted rock. These surfaces are then covered with several coats of primer and low reflectance (10-15%) matte-finish paint. Various non-uniformities in the painted surface are added to simulate the complex visual patterns typical of most mine interior surfaces. The large opening is shown during construction in Figure 2-4 and after completion in Figure 2-5.

2.4.2 Simulation of Visual Tasks. Based on our analysis of the critical visual tasks, we identified five laboratory simulations that encompassed the most important visual aspects of the tasks and lent themselves to a performance testing approach:

- (1) Crack detection
- (2) Rock motion detection
- (3) Floor hazard detection

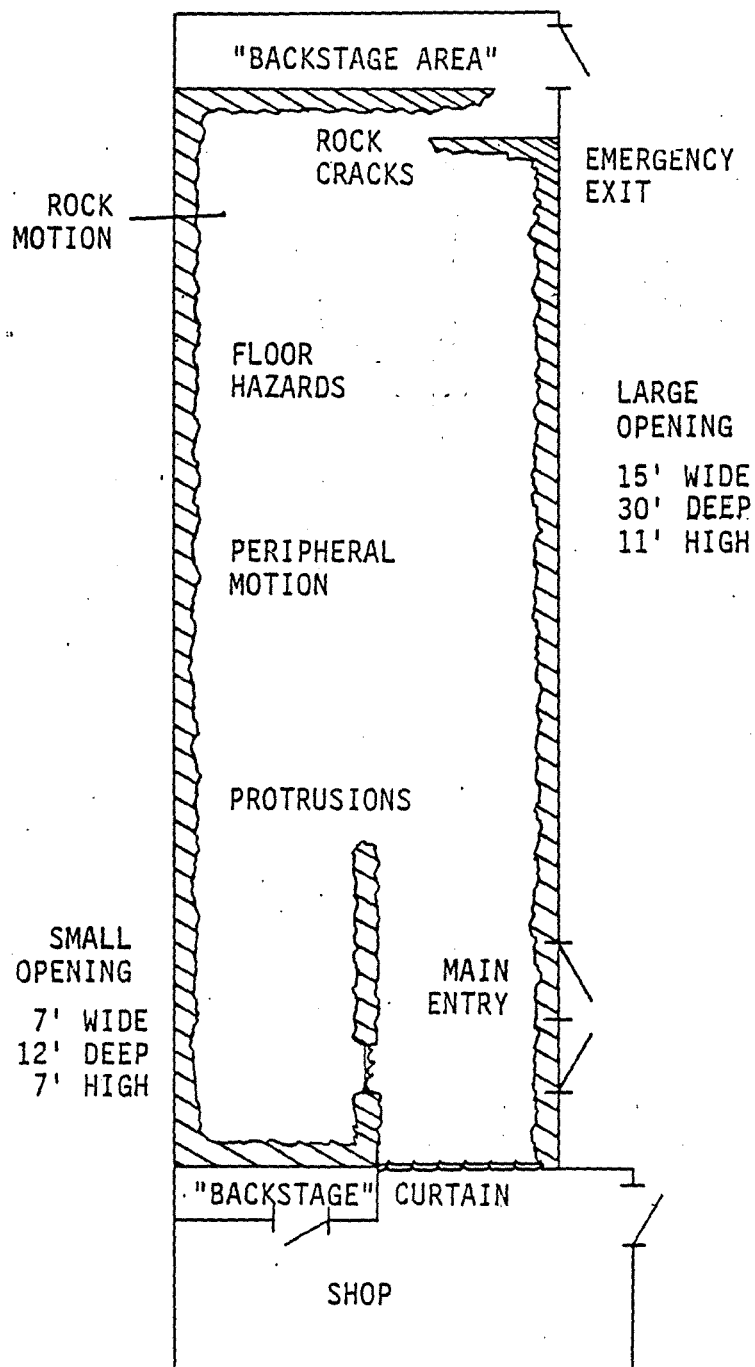


FIGURE 2-3. - Mine research facility.

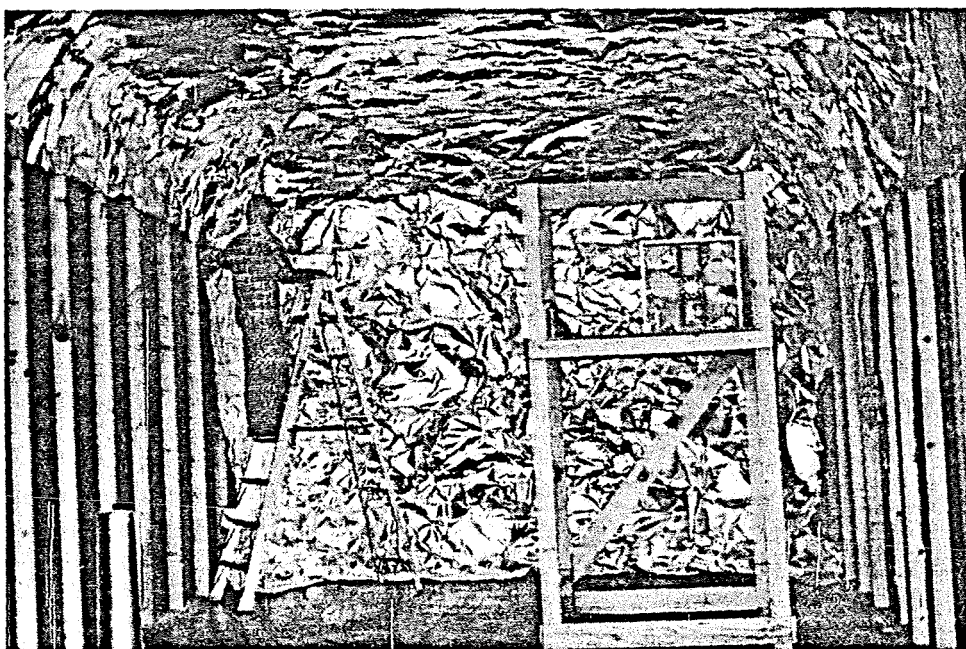


FIGURE 2-4.-Mine work space during construction.

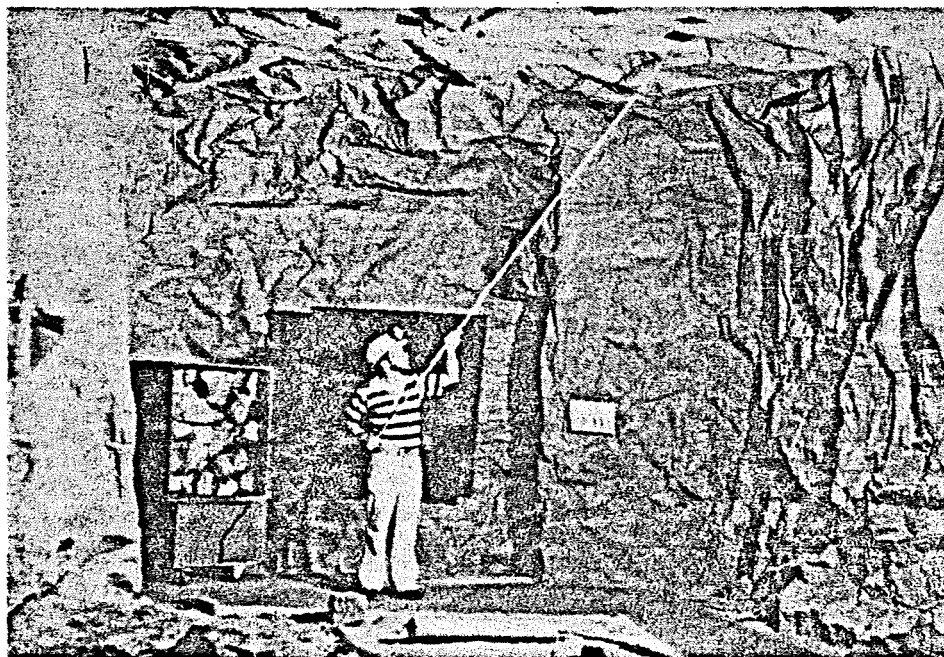


FIGURE 2-5.-Completed mine work space (pole in photo is 10 ft long).

(4) Protrusion detection

(5) Peripheral motion detection

As compared with actual underground mining tasks, these five simulated tasks have in common (1) the very important capability for accurate trial-to-trial replication of the visual stimulus delivered to the subject, and (2) the capability for measuring both response time ("seeing time") and errors as a function of target and background luminance levels. In addition, the five simulations contain generic visual components (resolution, contrast, motion, peripheral detection, depth perception) that represent the broad range of visual tasks found in underground work.

Some of the critical visual tasks could not be simulated readily or else did not lend themselves to a performance testing approach. Our plan was to collect VTE measures for these tasks as shown in Table 2-3. In the use of tasks involving targets too large for the VTE's field of view (e.g., oversize slabs), we planned to determine the visibility of target details on the assumption that the entire target would be at least as visible as its details. We also planned to use the VTE to obtain relative measures comparing the five laboratory simulations with their actual counterparts in underground mines.

The five simulations are described in the following subsections:

Crack Detection. Loose rock (rock that is loosely attached and likely to fall) must be detected and removed prior to beginning other tasks. Loose rock is visually identified primarily by the presence of cracks between the loose rock and the firm rock making up the ribs (walls) and back (roof) of the work site.

The apparatus for simulating rock cracks is shown in Figure 2-6. Six electrically activated rock cracks are arranged in an irregular hexagonal array around a central area where a caplamp beam can be focused. In the photo, the three uppermost cracks are open and the three lower ones are closed. The simulation is 48 inches wide and 54 inches high. Figure 2-7 shows a closeup of an open simulated crack and Figure 2-8 shows the same crack in the closed condition. The six simulated cracks are all approximately 12 inches in length. The width of each crack can be varied. The crack shown in Figures 2-7 and 2-8 is approximately one-quarter inch in width and represents a relatively easy crack detection task. The simulation can be rotated in 90° increments. On each trial the observer searches the target board to determine which one of the six cracks is open. The experimenter records the response time and the accuracy of the position reporting.

TABLE 2-3. - Data sources for critical visual tasks

Rank	Visual task	Performance measures					Psychophysical measures	
		Rock cracks	Rock motion	Floor hazards	Protrusions	Peripheral motion	VTE (in-mine)	VTE (in-lab)
1	Keystone effect	X	X				X	X
2	Unsupported ground						X	X
3	Slabs/protrusions							X
4	Rock motion (chute)		X					X
5	Cracks in rock	X					X	X
6	Rib/back (tramming)				X	X	X	X
7	Condition of back	X					X	X
8.5	Haulageway hazards			X		X	X	X
8.5	Pattern slips						X	
10	Rib/back (walking)	X			X	X	X	X
11	Oversize slabs							X
12	Falling loose		X			X		X
13	Floor hazards			X			X	X
14	Bootholes						X	
15	Vehicle clearance						X	X
16	Escape path			X	X	X	X	X
17	Muck pile hazards						X	X
28.5	Shaft guides							X
28.5	Shaft timbers							X

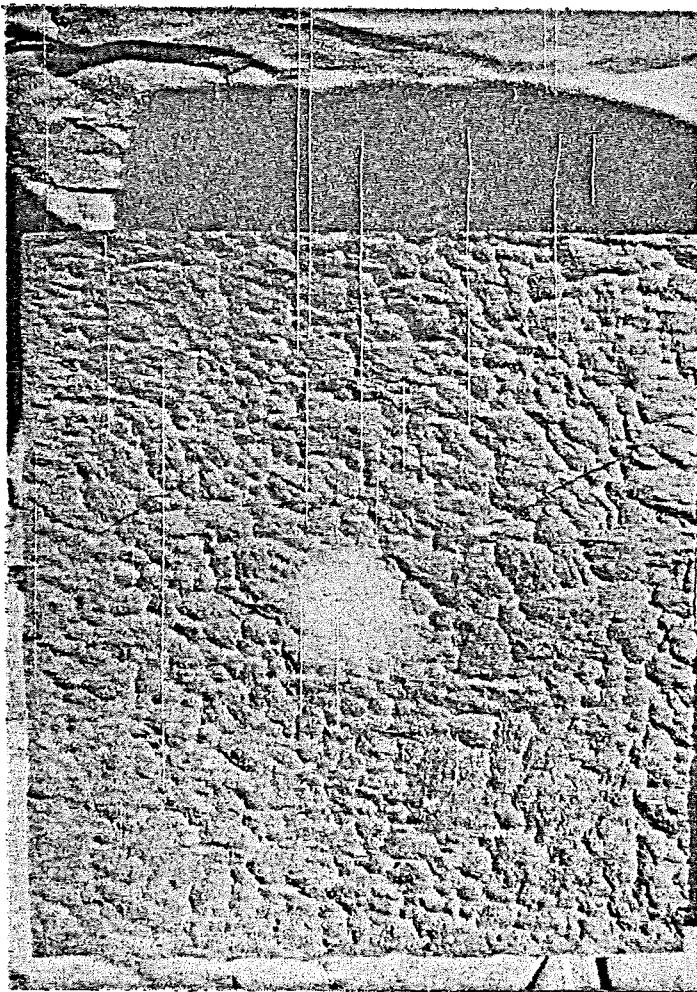


FIGURE 2-6. - Simulation of rock cracks.



FIGURE 2-7. - Crack detail (open).

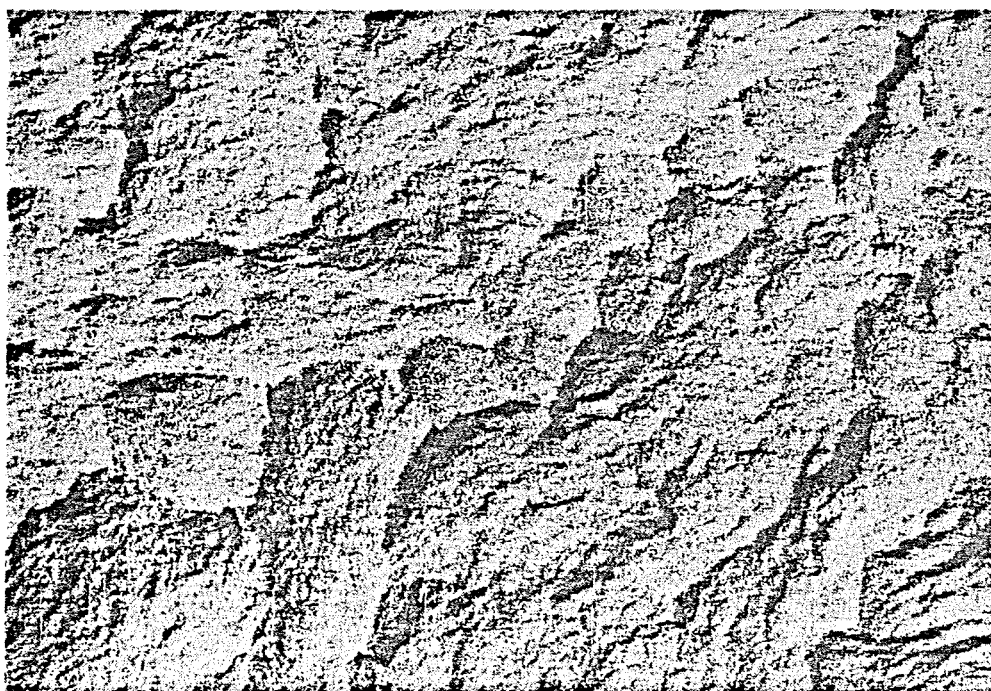


FIGURE 2-8. - Crack detail (closed).

Rock Motion Detection. This simulation apparatus was designed for two highly critical visual tasks. The first task involves seeing the first moment when rocks begin to move as a worker attempts to unblock a "jammed" loading chute or finger raise. The second task is to detect motion of overhead rocks when inadvertently barring down a "keystone" rock.

Figure 2-9 and 2-10 show the rock motion simulation. Six moveable rocks (identified by number in Figure 2-9) are arranged in a hexagonal pattern in a 4'x4' simulated chute. The six movable rocks are surrounded by similar, fixed rocks. Each movable rock jumps toward the observer approximately two inches (and moves laterally a smaller distance) when its solenoid is activated.

The observer's position is shown in Figure 2-10. While seated in front of the simulated chute or rock pile with his caplamp beam focused on the center of the display, the observer's task is to report any movement of the rocks. Response times and failures to respond (errors) are recorded.

Floor Hazard Detection. Another type of visual task rated as being highly critical to safety is the detection of various hazards found on the floor in the underground work environment. Stumbling or tripping hazards are particularly dangerous for workers who are carrying heavy equipment (such as feedleg drills) or handling materials. In the event the worker must rapidly flee the work site, quick identification of an escape path through the floor hazards is essential.

Figures 2-11 and 2-12 show the experimental set-up for the floor hazard simulation. Six potential hazards are shown on the rotating display although target items were always presented one at a time during the experimental trials. The observer is seated on an elevated platform that raises him to standing eye height above the simulated mine floor. The observer's caplamp is rigidly mounted in the normal caplamp position just above the observer's eyes. The point-source supplementary luminaire is similarly mounted as close as possible to the caplamp in order to test the effects of an improved caplamp penumbra. Scene luminance is continuously monitored with the Pritchard photometer seen in the photographs. The position of the target (hole, rubble, pipe, etc.) is controlled from the experimenter's console. The observer's task is to search the display until the target is located. The experimenter records the response time and the accuracy of the reported position. Figures 2-13 and 2-14 show several of the targets as seen from the observer's position. The photograph in Figure 2-13 was taken using caplamp illumination geometry -- the light source was immediately above the camera. Note

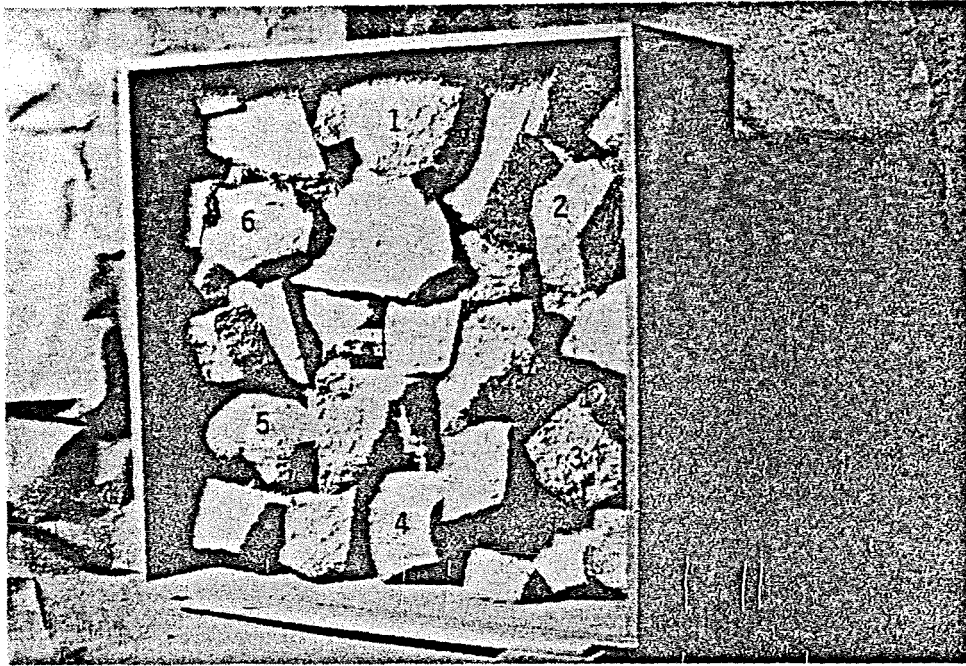


FIGURE 2-9.-Rock motion simulation.



FIGURE 2-10.-Observer position for rock motion detection.

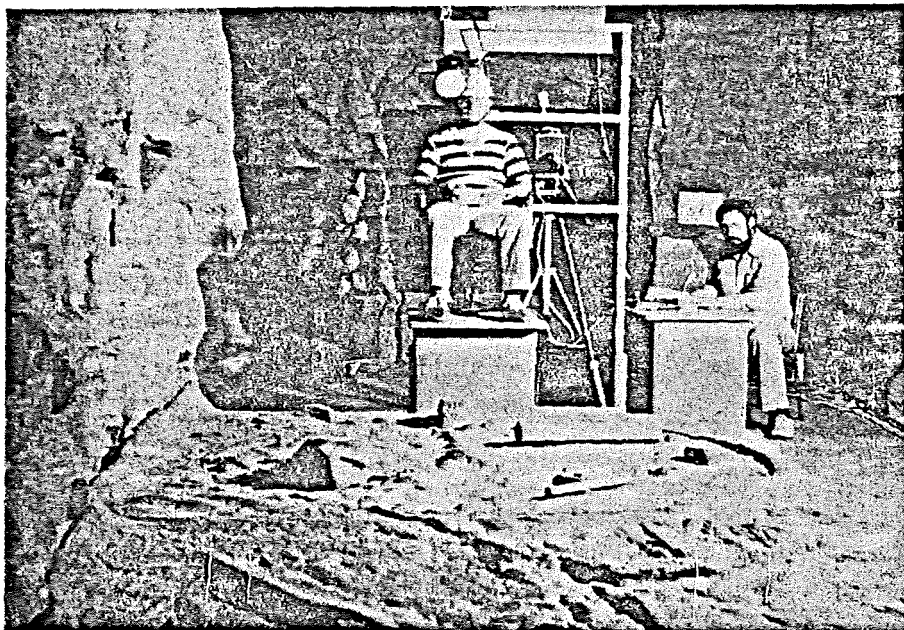


FIGURE 2-11. - Floor hazard simulation and experimental set-up.

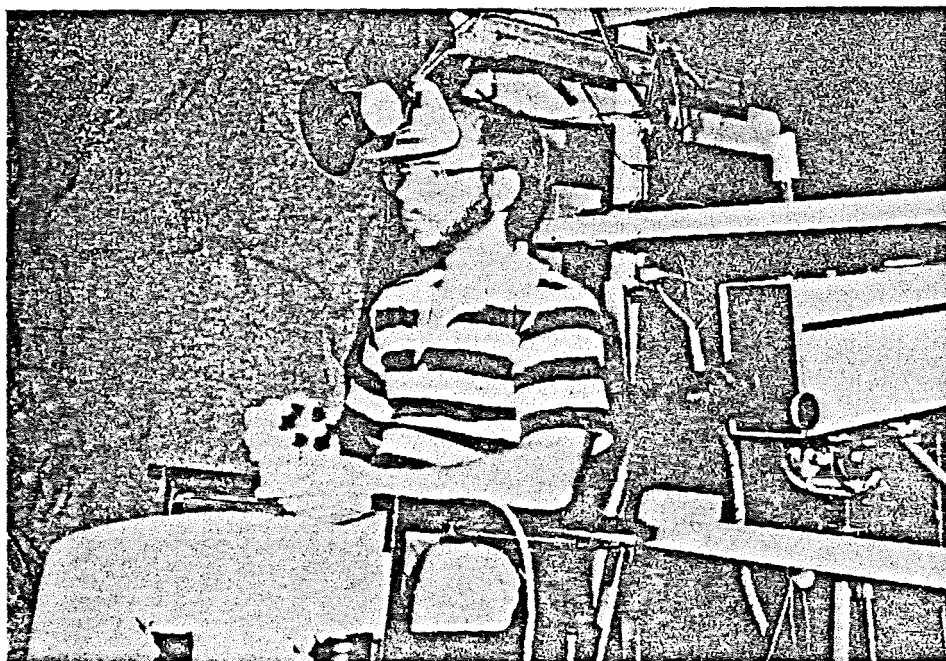


FIGURE 2-12. - Details of observer's position.

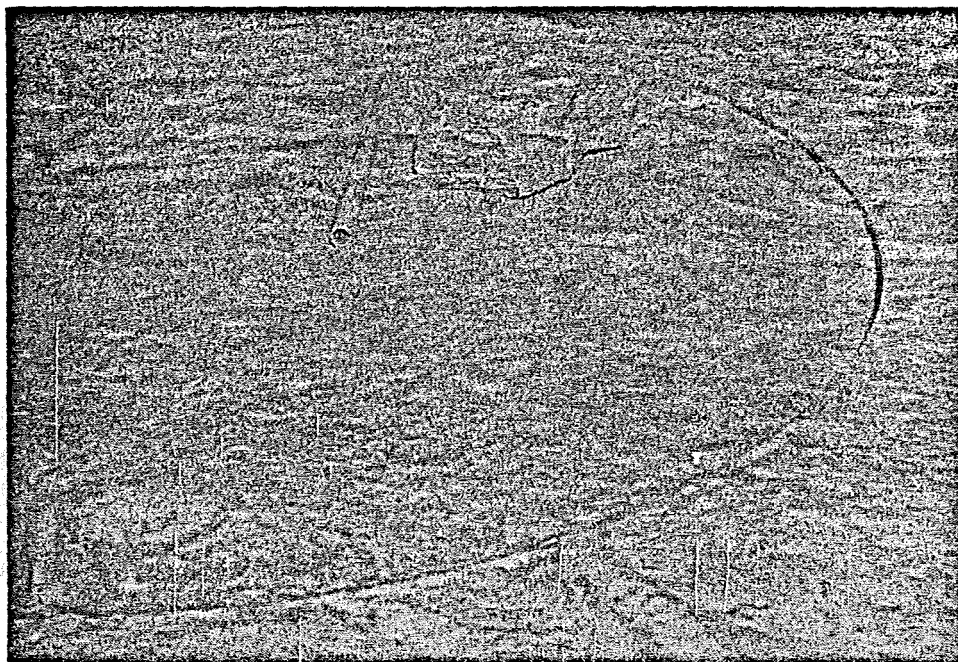


FIGURE 2-13. = Various floor hazards seen under caplamp illumination geometry.



FIGURE 2-14. - Various floor hazards seen with shadow modeling (same luminance).

the absence of any shadow modeling of the terrain and the low visibility of the one-foot diameter hole. The same scene is shown in Figure 2-14 with the light source moved approximately four feet to the side, illustrating how changes in lighting methods, as well as improvements in lighting intensity, can greatly enhance task visibility.

Protrusion Detection. This apparatus simulates the visual task of detecting hazardous protrusions such as rock bolts that have slipped down from the back or from the rib, or pipes that protrude from the rib. These can cause severe injury to a worker walking or riding in the mine. Although other objects protruding from the back or ribs (e.g., timbers, slabs, ventilation tubing, etc.) are also potentially hazardous, small-diameter pipes and rock bolts are the most difficult to detect visually. Thus, the subclass of pipes and rock bolts serve well to represent the total class of protrusion hazards.

Using the same conceptual approach taken in the simulation of rock cracks and moving rock, an array of six potential protrusion hazards, three from the rib and three from the back was used. Figures 2-15 and 2-16 show the back and rib protrusion simulation installed in the small opening (7'W x 7'H x 12'D) of the Mine Research Facility. Four of the six possible simulated "slipped" rock bolts are extended in Figure 2-15. Figure 2-16 shows three of the bolts under conditions of significant visual impairment due to glare and shadowing.

The experimenter extends a single protrusion target on each trial. The observer is seated on an elevated platform that raises him to standing eye height. The observer's task is to search the back and rib until the target is located. The experimenter records the response time and accuracy of the position reporting.

Peripheral Motion Detection. This apparatus simulates the task of detecting the presence of large moving objects (such as mobile equipment or other workers) in the peripheral visual field. Noise in the underground work environment frequently masks the sound of an approaching truck or loader. It is therefore critical to the safety of workers that they be able to detect motion in the periphery even when performing a central visual task, such as drilling or barring down loose rock.

The experimental set-up is shown in Figures 2-17 and 2-18. The targets used are two 12-inch diameter, four-foot tall cylinders vertically mounted on revolving bases. Each target simulates the motion of a generic piece of mining equipment whose original yellow paint is now chipped and dust covered. Details of one of the targets are shown



FIGURE 2-15. - Back and rib protrusion simulation in small opening.

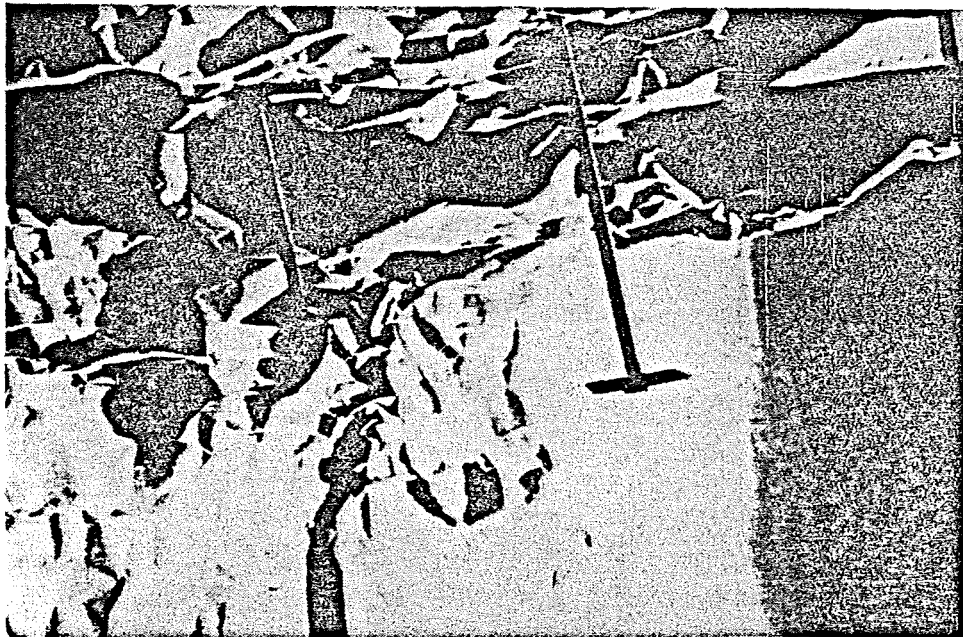


FIGURE 2-16. - Three "slipped" rock bolts seen under conditions of significant glare.

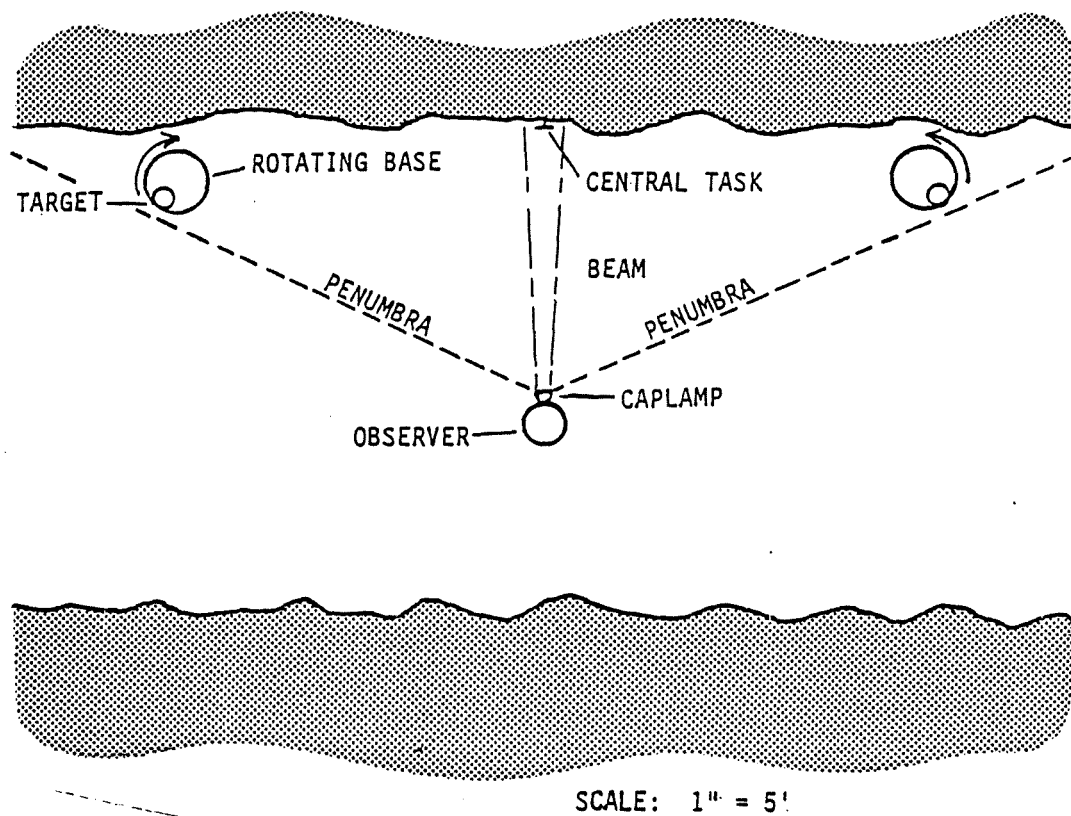


FIGURE 2-17. - Peripheral motion detection experimental set-up.

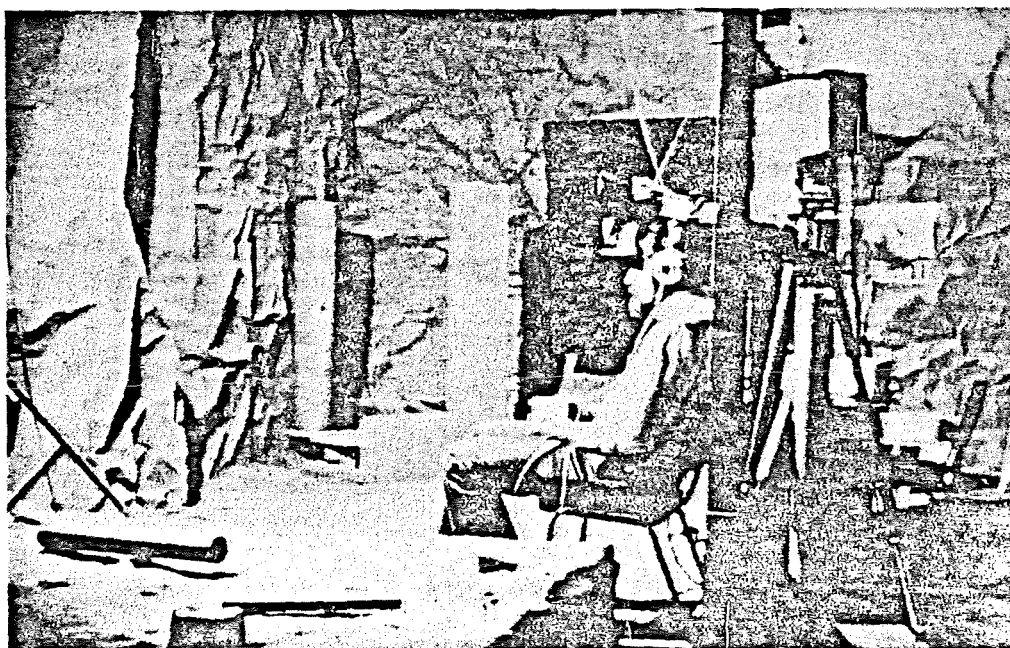


FIGURE 2-18. - Peripheral motion target and observer position.

in Figure 2-18. These targets represent a commonly occurring, more difficult detection task situation.

The targets are positioned just within the observer's caplamp penumbra at a viewing distance of approximately twelve feet. When activated by the experimenter, the target form moves in a circular path defined by rotation of the base. A central task is used to keep the observer looking straight ahead. The observer watches a small target in the caplamp spot. Whenever he observes it rotating, he presses a switch to stop the rotation. Multiple central task trials are presented between each presentation of one of the peripheral targets. At relatively random intervals a peripheral target is activated. When the observer detects the target, he presses a second switch to indicate he has detected the target. Elapsed time between activation of the target and the observer's response is recorded.

2.4.3 Direct Measurement of Visual Performance. Nearly all underground workers use individual caplamps with an intense central beam and a relatively dim surround or penumbra. The small, central beam (about 5-10 degrees in diameter) is over 100 times brighter than the wide-angle penumbra, creating an adverse ratio of luminance in the visual scene. Glare and transient adaptation caused by the central beam make it difficult to see small or low-contrast targets in dimly lighted areas outside the central beam.

If minimum luminance levels were determined with observers fully adapted to low levels of even illumination, unrealistically low thresholds could be obtained due to the absence of glare and adaptation effects caused by the ubiquitous caplamp. An initial series of pilot experiments confirmed the importance of including realistic glare and adaptation factors when conducting visual performance studies (Merritt, Perry, and Peak, 1982). A report of the experiments is included in Appendix E.

In searching for visually difficult targets such as cracks that indicate loose rock overhead or on ribs, the worker will move the caplamp beam around by moving his head. His eyes, however, will move in a scan pattern much more complex and extensive than that of the head-aimed caplamp spot. In some instances, the worker will be looking directly in the central spot, but at other moments his eyes will be looking just outside the spot, where the surfaces are much dimmer. It takes several seconds for the "after-image" of the bright central spot to fade away for adequate visual performance in the dimmer caplamp penumbra; during these seconds the visual scan pattern could pass over significant visual targets without their being seen. Furthermore, the worker cannot on placing the relatively narrow caplamp spot on every 5-degree area of the mine surfaces. He must rely on near-peripheral vision to perform its normal function of

detecting significant items for detailed examination by central vision.

With the current caplamp, peripheral vision may not adequately perform this function of steering central vision, since the luminance of the peripheral visual field is so much lower than that of the narrow central visual field. This may produce a state of "functional tunnel vision" in which many significant hazards go undetected.

In addition to the problem of adaptation to the caplamp central beam, the beam, is a highly luminous glare source always near the center of the visual field, thus further reducing the adequacy of the dim penumbra luminance. Although the caplamp itself is not a glare source for the miner who is wearing it, the bright spot it produces on close surfaces can be relatively very intense (e.g., 27 fL on a 20% reflectance surface viewed at a distance of 4 ft), and it can produce a significant visual deficit for peripheral vision in the dim penumbra (e.g., 0.03 fL on a 20% reflectance surface at 15 feet).

Because that the caplamp determines the minimum level of dark adaptation in most mine work environments, we have concluded that it is important to include these effects in the testing method used to determine minimum luminance for safe job performance.

One way to restate this problem is to ask, "Given that the worker is adapted to the relatively high luminance of the caplamp central spot, what luminance levels are required in the surrounding area to ensure timely detection of hazards in the dim penumbra? If more light is needed than that now provided by the caplamp penumbra, how much is required in supplemental lighting in order to eliminate illumination as a significant factor in accident causation?: Experimental data on disability glare and adaptation effects due by the caplamp central spot are presented in Appendix E.

The following assumptions were made in the development of procedures for direct measurement of visual performance under varying levels of luminance:

- (1) The task difficulty (determined by target size, reflectance, contrast, viewing distance, etc.) represents the commonly occurring, more difficult cases.
- (2) The lowest luminance level to be tested is that provided by an end-of-shift (low voltage) caplamp.
- (3) The caplamp is mounted on the observer's hard hat (for most targets the resulting absence of shadow modeling makes this the commonly occurring, more difficult case).

- (4) Higher levels of luminance are achieved by addition of a point-source light immediately adjacent to the caplamp (simulating a caplamp with enhanced penumbra while preserving the caplamp illumination geometry).
- (5) Targets located near (but not in) the caplamp spot must be detected by central or near-peripheral vision immediately after the worker has transiently lost dark adaptation by looking at targets in the spot.
- (6) Visual performance (detection time and/or errors) is a function of target luminance, transient adaptation (from alternately looking in and out of the caplamp spot), and glare (from hotspot near the target).

The general experimental paradigm is as follows:

- (1) The observer fixates an adaptation caplamp beam for ten seconds. The adaptation beam is positioned near the target apparatus but far enough away to preclude detection of the target prior to trial onset.
- (2) A relay switches the adaptation caplamp "off" and the target caplamp "on" to signal onset of the visual search task.
- (3) The observer searches among six possible locations for the target.
- (4) The observer presses a "STOP" pushbutton to indicate that he has located the target. He then presses the button on his response box that corresponds with the target location.
- (5) Response time and any location errors are recorded for each trial.
- (6) Each target is presented randomly seven times in each of the six positions (42 trials at each luminance level).
- (7) Six luminance levels are used in each of two replications. The order of presentation (ascending or descending) is counter-balanced.
- (8) The observers are allowed to adapt completely with each change of luminance level.

Five trained observers were used in the visual performance experiments. Three were young (age 18-19) males and two were the experimenters (Merritt and Perry, age 42 and 37, respectively), all with no ocular pathology and with wall chart visual acuity not less than 20/30 corrected. The observers were extensively trained on the experimental tasks prior to data collection, to represent the skill levels of regular underground mine workers.

3. RESULTS

The data reported in this section were obtained by directly measuring the visual performance of five trained observers working on six simulated mining tasks with varying luminance levels, under the closely controlled lighting conditions of the mine illumination laboratory.

Average response times are reported as a function of luminance level for each observer and across observers. For the rock motion detection task, data for errors (missed detections) are also reported.

In addition to direct measures of visual task performance as a function of luminance level, measures of task visibility (an index of relative visual difficulty) were obtained with a Visual Task Evaluator (VTE), both in actual underground mines and in our mine illumination laboratory's simulated underground workspace. These VTE data, reported in Appendix A, are used to compare the relative visual difficulty of our simulated mining tasks with their actual counterparts in underground mines.

3.1 DIRECT PERFORMANCE MEASURES

Over 13,000 measurement trials were conducted to determine how visual performance on six simulated mining tasks would be affected by various levels of task background luminance. Over 2500 data points, representing many repetitions at each luminance level, were collected to determine the effect of luminance level on the detection of rock cracks. Similarly, over 5000 measurement trials were conducted for two kinds of floor hazards, and over 4000 measurement trials were run to measure the effects of luminance on the timely detection of rock motion in an ore path. The effect of luminance level on the detection of protrusion hazards and on the effectiveness of peripheral vision was studied with over 2000 measurement trials.

In addition to these "official" experimental trials, a number of preliminary experiments were conducted to establish the ranges of luminances to be tested. A corollary research study showed the effects of glare and adaptation caused by the central hotspot of the miner's caplamp (see Appendix E), thus demonstrating the importance of incorporating actual caplamp lighting in the laboratory simulations.

3.1.1 Crack Detection. Response times were obtained for six levels of background luminance ranging from 0.01 fL to 0.2 fL at an average viewing distance of eight feet. The targets were three wide (mean width 0.25 in.) and three narrow (mean width 0.125 in.) cracks. The experimenter presented one of the six cracks on each trial, each crack appearing randomly seven times in each position for each sequence of 42 trials. Between trials the observer fixated an adaptation caplamp spot on the surface below the target board for a minimum of ten seconds. Headphones (with continuous music) were worn to mask the opening and closing of the solenoid-actuated cracks. A trial began when a relay switched off the adaptation caplamp spot and switched on the observer's caplamp. A digital clock was simultaneously started to measure response time. The observer's caplamp was aimed at the center of the hexagonal array of potential target cracks. It was a source of both task luminance and disability glare.

When the switch from adaptation caplamp to observer's caplamp signalled the start of the trial, the observer shifted his gaze to the target board and visually searched to determine which crack was open. When he located the crack, he pressed the stop button on his response box. This action stopped the digital timer and switched power back to the adaptation caplamp. The observer then indicated which of the six cracks was open by pressing the corresponding button on a hexagonal array of his response box. The experimenter recorded the response time (to the nearest hundredth of a second). Feedback was provided regarding incorrect judgments as to location. Only six incorrect location reports were made during 420 trials at the lowest luminance level. No such errors occurred at the higher luminance levels. Because the error rate was negligible, errors were ignored in the subsequent data analysis.

For all six simulated tasks, the luminance produced by the penumbra of a standard miner's caplamp was taken as the lowest light level to be tested. In the case of the crack detection task, however, pilot experimentation showed that the observers were unable to detect reliably the three narrow cracks at the 0.006 fL background luminance level produced by the observer's caplamp alone. Therefore, the lowest level tested was 0.01 fL, obtained by supplementing the caplamp penumbra with a co-located auxiliary point-source luminaire. This supplementary source, which provided a variable amount of penumbra illuminance to produce the various luminance levels tested, was mounted as close to the observer's caplamp as possible in order to preserve the source-target-observer geometry that is characteristic of typical caplamp use.

The target board could be rotated to change the locations and angles of the six cracks. Four crack-board orientations were employed

during the study. Two were used during practice sessions and during an investigation of the glare and adaptation effects of the caplamp (see Appendix E). The other two were used in a counterbalanced fashion for the actual performance testing. Each time the luminance level was changed, the target board was rotated to the alternate orientation. This was done to minimize the amount of learning of the appearance and position of each crack, thus maintaining a more realistic requirement for visual search, as in the actual in-mine task.

For a given observer, the luminance levels were presented in either ascending or descending order for the first run. The odd number of observers made it impossible to perfectly counterbalance the order of luminance levels. A run consisted of a block of 42 trials at each of the six luminance levels. Each of the observers performed a second run with luminance levels presented in an order opposite to their first run, using the alternate board orientation, after an average interval of five days.

Geometric mean response times for the detection of wide cracks are shown in Figure 3-1. A 90 percent confidence interval for the mean is also shown graphically. As can be clearly seen, both the mean response time and its variance improve as background luminance increases. Table 3-1 lists the across observer means shown in Figure 3-1 and also lists the individual observer means. Figure 3-2 displays the individual observer means graphically.

Geometric mean response times are listed in Table F-1 of Appendix F, for each wide crack, for each observer, on run one and run two.

Test-retest reliability of the across observer means (run 1 vs. run 2) for detection of wide cracks was $r = 0.9557$, $p < 0.01$. Reliability data for the individual observers are shown in Appendix G. The relatively low values for individuals (ranging from $r = 0.5160$, N.S. to $r = 0.9375$, $p < 0.01$) appear to be a consequence of significant changes in target visibility due to rotation of the board at each change of luminance level. Those differences in some cases appear to overwhelm the effect of increased or decreased luminance, as can be seen in Table F-1 of Appendix F.

Geometric mean response times for the detection of narrow cracks are shown in Figure 3-3. A 90 percent confidence interval for the mean is also indicated. Here the effect of increasing background luminance is even more striking -- note the change of scale from the figures showing the wide crack results. Table 3-2 lists the across observer means shown in Figure 3-3 and also lists the individual observer means. Figure 3-4 shows the individual observer means.

Geometric mean response times for each narrow crack for each observer on each run are listed in Table F-2 of Appendix F.

Test-retest reliability of the across observer means (run 1 vs. run 2) for detection of narrow cracks was $r = 0.9923$, $p < 0.01$. Reliability data for the individual observers are listed in Appendix G. These reliabilities are higher compared to those obtained for wide cracks (ranging from $r = 0.8939$, $p < 0.05$ to $r = 0.9816$, $p < 0.01$). While rotation of the target board between luminance levels changed the target difficulty, the effect of increased or decreased luminance on response time appears to be much stronger for the more difficult, narrow cracks.

Recommended minimum luminance values for crack detection are reported in Section 4.

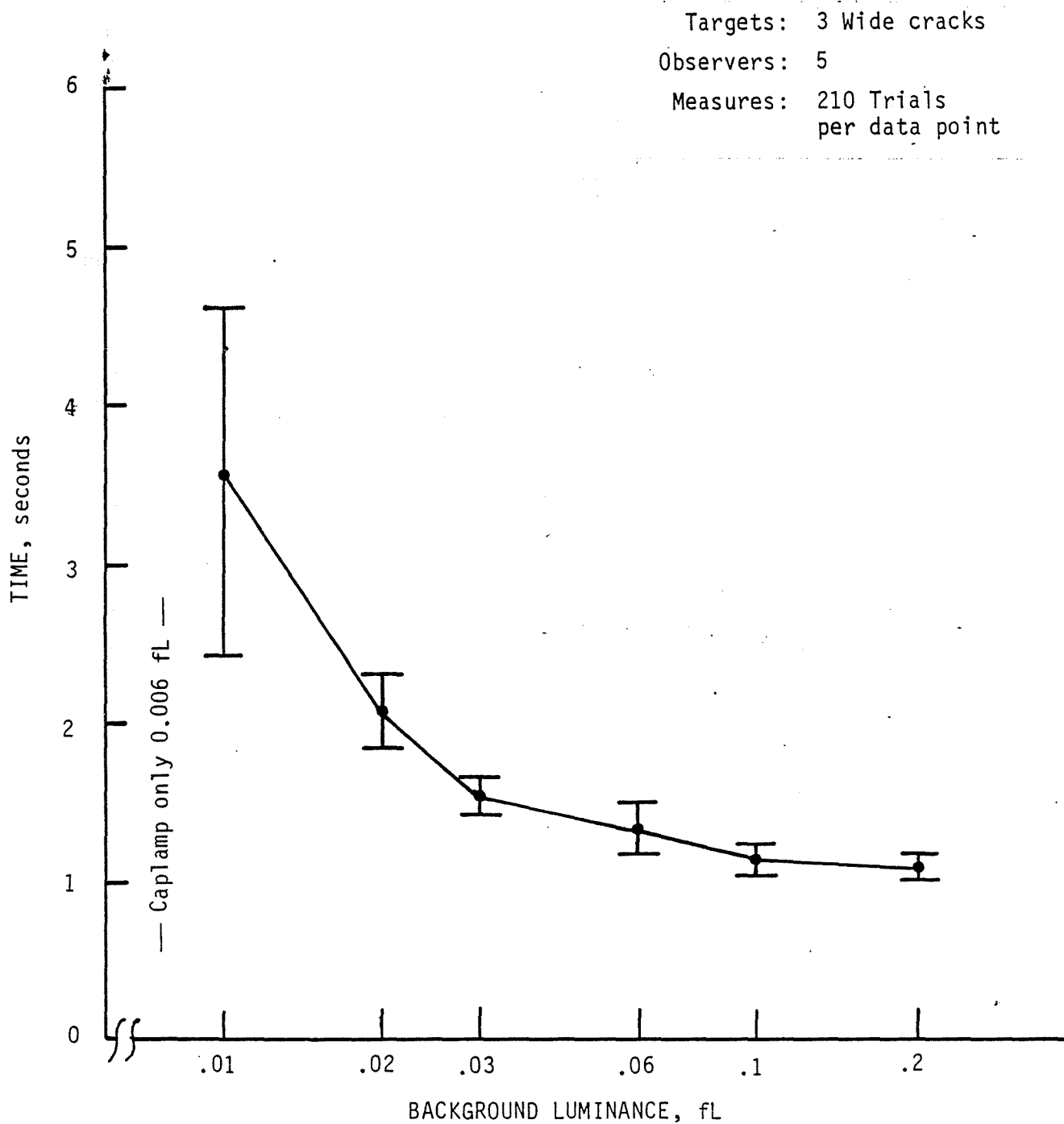


FIGURE 3-1. - Geometric mean response time (90 percent confidence interval) for detection of wide cracks.

TABLE 3-1. - Geometric mean response time (seconds)
for detection of wide cracks

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.01 fL ^c						
Geo. mean	3.5893	5.4992	3.2969	2.2160	2.8640	3.3358
Log mean	0.5550	0.7403	0.5181	0.3456	0.4570	0.5232
Log SD ^d	0.3057	0.3286	0.3455	0.1950	0.2307	0.1450
0.02 fL	2.5031 0.3985 0.2722	2.0468 0.3111 0.3060	2.0101 0.3032 0.3417	1.8503 0.2672 0.2777	1.8589 0.2693 0.1937	2.0411 0.3099 0.0533
0.03 fL	1.6806 0.2255 0.1941	1.5554 0.1919 0.1759	1.6062 0.2058 0.2319	1.4666 0.1663 0.1929	1.3853 0.1416 0.1462	1.5354 0.1862 0.0330
0.06 fL	1.4665 0.1663 0.1250	1.0652 0.0274 0.1479	1.3108 0.1175 0.1848	1.2526 0.0978 0.1477	1.4545 0.1627 0.2396	1.3012 0.1143 0.0567
0.10 fL	1.0904 0.0376 0.1066	1.0241 0.0103 0.1253	1.0126 0.0054 0.1345	1.2574 0.0995 0.1513	1.1535 0.0620 0.1040	1.1040 0.0430 0.0389
0.20 fL	1.1055 0.0436 0.1357	1.0171 0.0074 0.1344	0.9631 -0.0163 0.1310	1.0366 0.0156 0.1364	1.1619 0.0652 0.1036	1.0546 0.0231 0.0318

^aN=42 trials per cell.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra plus supplementary luminaire (caplamp penumbra only 0.006 fL at average distance of 8 feet).

^dSD Standard deviation of time in log seconds.

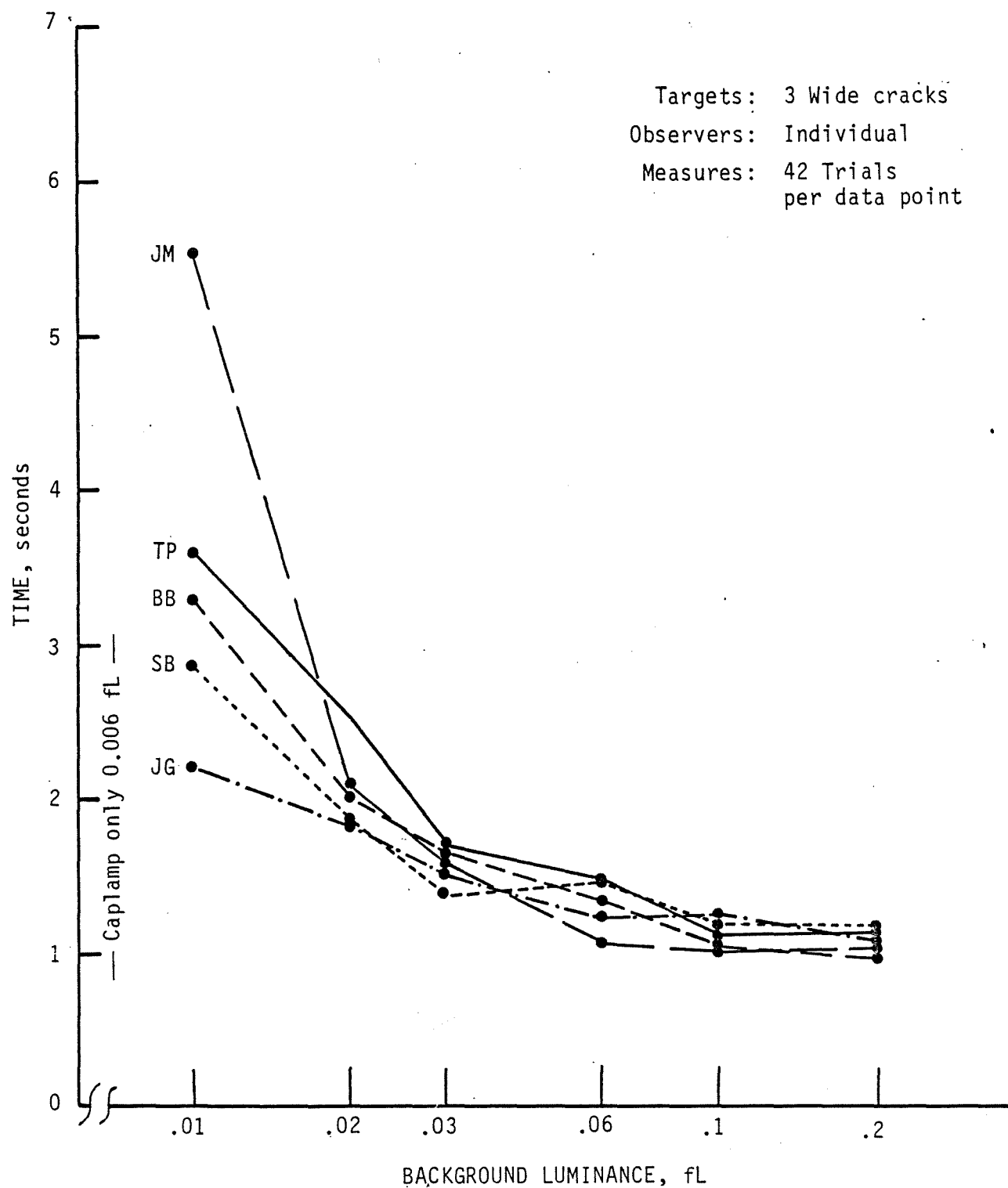


FIGURE 3-2. - Geometric mean response time for detection of wide cracks by individual observers.

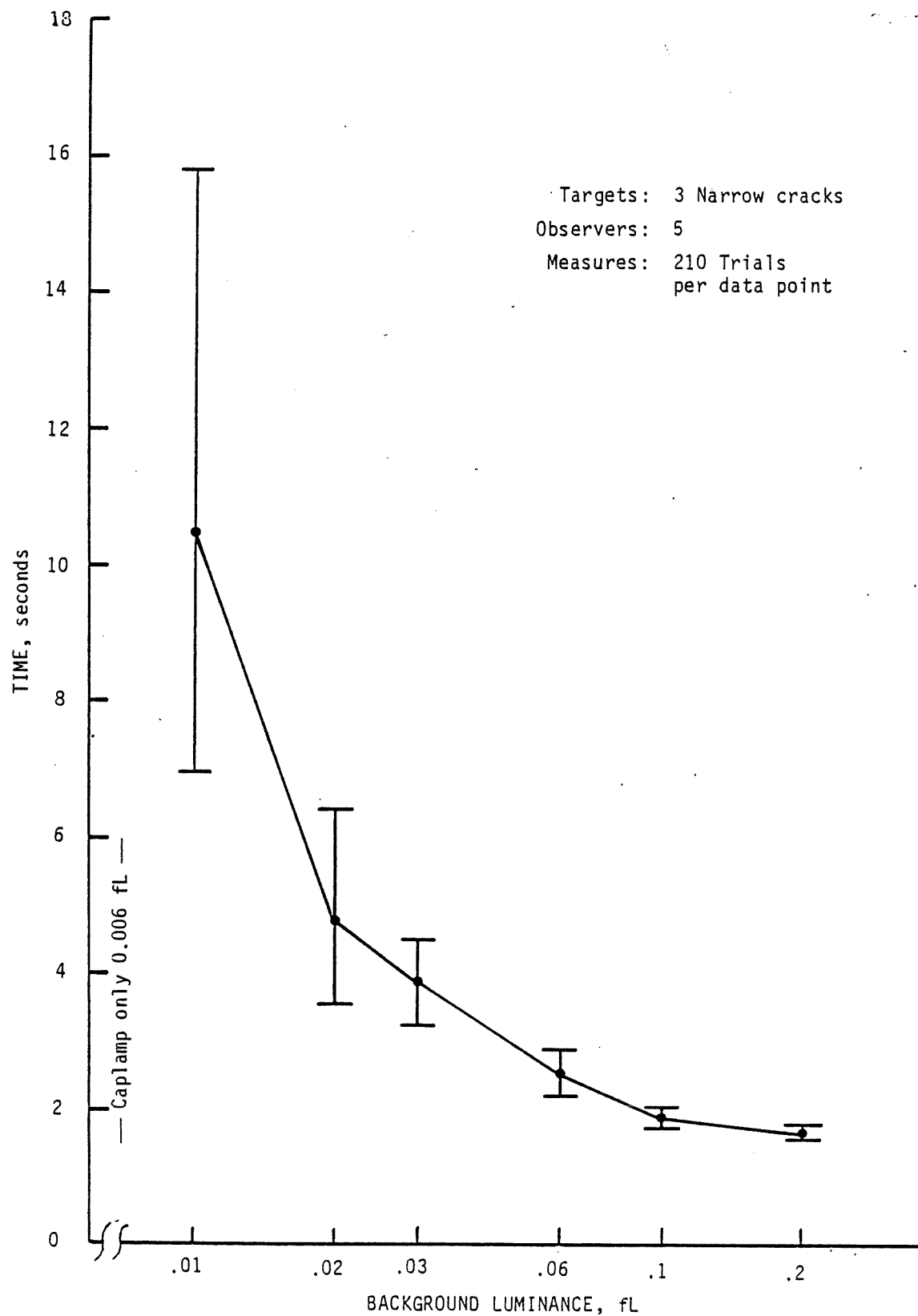


FIGURE 3-3. - Geometric mean response time (90 percent confidence interval) for detection of narrow cracks.

TABLE 3-2. - Geometric mean response time (seconds)
for detection of narrow cracks

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.01 fL ^c						
Geo. mean	9.2422	17.5159	14.8735	8.2856	6.1931	10.4318
Log mean	0.9658	1.2434	1.1724	0.9183	0.7919	1.0184
Log SD ^d	0.2351	0.2907	0.3510	0.3149	0.2778	0.1860
0.02 fL	4.1673 0.6199 0.2098	8.0736 0.9071 0.3779	4.5561 0.6586 0.2583	4.1874 0.6219 0.2748	3.7559 0.5747 0.2470	4.7472 0.6764 0.1323
0.03 fL	3.7888 0.5785 0.2021	4.5966 0.6624 0.2417	4.4050 0.6439 0.2646	3.3752 0.5283 0.2166	3.1485 0.4981 0.2794	3.8216 0.5822 0.0711
0.06 fL	2.6429 0.4221 0.2174	2.2538 0.3529 0.1937	3.1233 0.4946 0.2506	2.3815 0.3769 0.1471	2.4941 0.3969 0.2272	2.5626 0.4087 0.0544
0.10 fL	1.8924 0.2770 0.1566	1.9077 0.2805 0.1578	1.9601 0.2923 0.1823	2.0642 0.3147 0.1840	1.9074 0.2804 0.2008	1.9453 0.2890 0.0155
0.20 fL	1.6485 0.2171 0.1357	1.6235 0.2105 0.1755	1.7536 0.2439 0.2043	1.5407 0.1877 0.1487	1.7686 0.2476 0.1528	1.6648 0.2214 0.0248

^aN=42 trials per cell.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra plus supplementary luminaire (caplamp penumbra only 0.006 fL at average distance of 8 feet).

^dSD Standard deviation of time in log seconds.

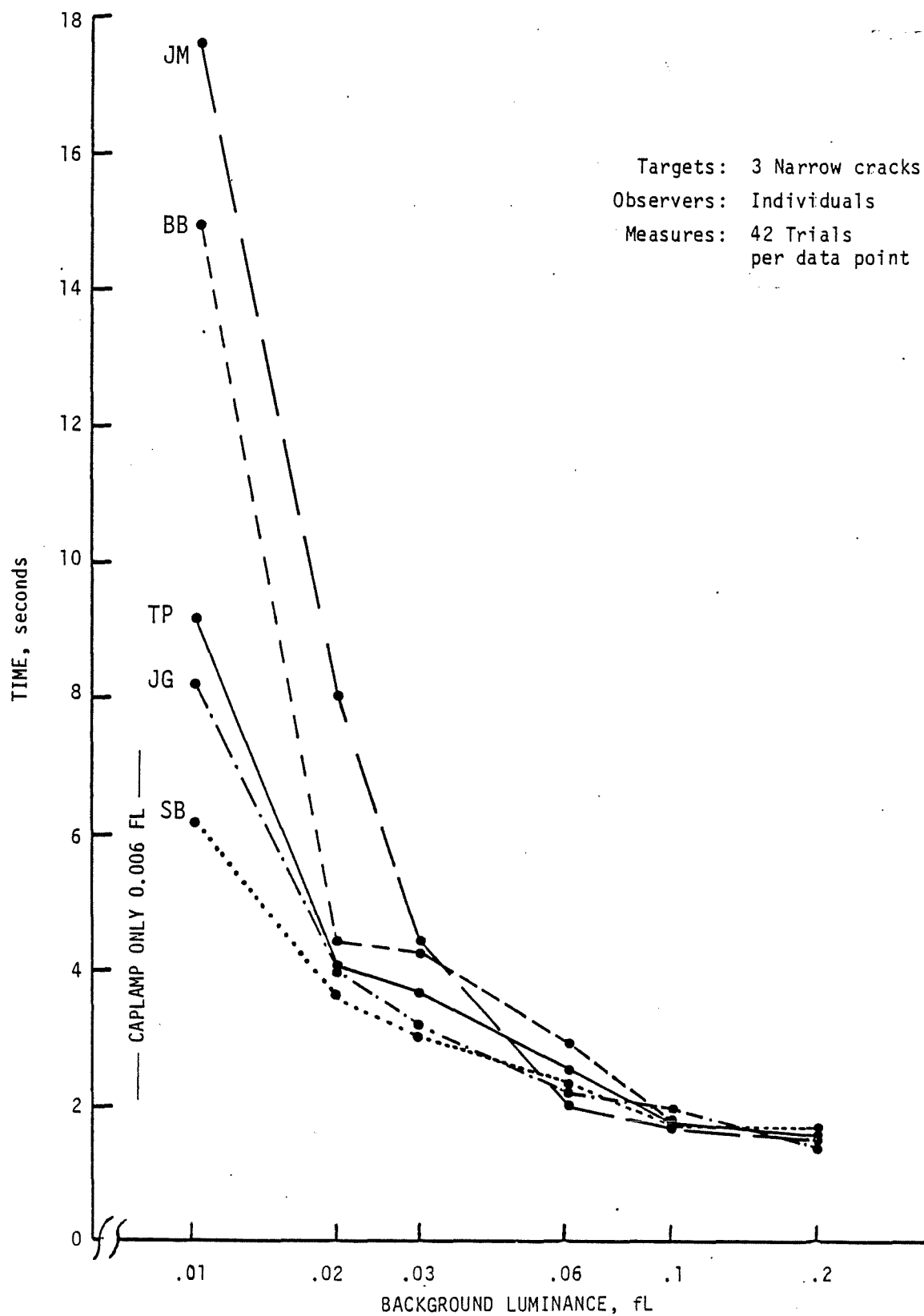


FIGURE 3-4. - Geometric mean response time for detection of narrow cracks by individual observers.

3.1.2 Rock Motion Detection. Response times and error data were obtained for five levels of luminance ranging from caplamp penumbra only (0.016 fL) to 0.4 fL at an average viewing distance of eight feet. The targets were six moveable simulated rocks arranged in a hexagonal array in a square box filled with a layer of similar fixed rocks. The observer sat facing the opening of the box. The observer's caplamp spot was aimed at a fixed rock in the center of the hexagonal array of moveable target rocks. Motion of the rocks was initiated by the experimenter. When its solenoid was triggered, a target rock moved approximately two inches toward the observer, and translated a smaller distance laterally. A timer started when the rock motion was initiated. Headphones (with continuous loud music) were worn to mask the sound of the solenoids, thus creating total reliance on the visual elements of the task.

When the observer detected motion of one of the six rocks, he pressed the timer-stop button on the response box. Observers were trained to respond as quickly as possible. Depression of the stop button froze the timer and released the solenoid, allowing the rock to return to its resting position. The return motion of the rock provided feedback to the observer on each trial. A point-source variable luminaire was again used to provide supplementary penumbra illuminance for luminance levels above caplamp only (0.016 fL).

The luminance levels were presented in either ascending or descending order during a given run. A run consisted of 14 random presentations of each rock during each block of 84 trials, one block per luminance level. Each observer performed a second run, after an average interval of ten days, with luminance levels presented in an order opposite to that used for the first run.

During most trials, the observers responded quickly to movement of a rock. Occasionally, especially at the lower light levels, the observers reported missing the actual motion of the rock while noticing that the appearance of the target array had changed. After being triggered, a target rock would remain in its forward position until released. The observers were allowed ten seconds in which to respond on each trial before the experimenter terminated the trial. The return motion of the rock would usually make the observer aware that he had failed to detect the original outward motion on that trial.

Geometric mean response times for detection of rock motion are shown in Figure 3-5. A 90 percent confidence interval for the mean is also shown graphically. Response times ≥ 1.00 second were defined as errors (failures to detect any motion, rather than calling out the wrong rock position) and were deleted in computation of the geometric

means. Table 3-3 lists the across observer means shown in Figure 3-5 and the individual observer means shown in Figure 3-6.

Geometric mean response times for each target rock for each observer on runs one and two are listed in Table F-3 of Appendix F.

Test-retest reliability of the across observer means (run 1 vs. run 2) for detection of rock motion was $r = 0.9872$, $p < 0.01$. Reliabilities for the individual observers ranged from $r = 0.9003$, $p < 0.05$ to $r = 0.9822$, $p < 0.01$, and are listed in Appendix G.

The rock motion response time data indicate that increasing the luminance by a factor of 25 within the range tested produced a relatively small improvement (0.115 seconds or 25 percent faster) in performance.

Increased luminance had a much more profound effect on errors (failures to respond within a specified time limit). Figure 3-7 presents data for two error criteria. The lower curve shows the percent of trials with response times ≥ 1.00 seconds. The upper curve presents a more rigorous criterion of response times ≥ 0.60 seconds. Table 3-4 lists the percent and number of errors for each observer and across observers. Figure 3-8 shows graphically the individual observer error data for response times ≥ 1.00 seconds. Figure 3-9 presents the corresponding individual curves for the more stringent criterion of response times ≥ 0.60 seconds.

Test-retest reliability of the across observer percent errors (run 1 vs. run 2) for detection of rock motion was $r = 0.8535$, $p < 0.05$ for errors defined as response times ≥ 1.00 seconds. The corresponding reliabilities for the individual observers ranged from $r = 0.6124$, n.s. to $r = 0.8855$, $p < 0.05$. Test-retest reliability for errors defined as response times ≥ 0.60 seconds was $r = 0.9605$, $p < 0.01$. Individual observer's reliabilities ranged from $r = 0.7344$, n.s. to $r = 0.9852$, $p < 0.01$. Complete reliability data for both error criteria are listed in Appendix G. Reliabilities derived using the more stringent 0.60 error criterion may be higher due to the larger number of responses in that category as compared with the number of responses meeting the 1.00 second criterion.

Recommended minimum luminance values for rock motion detection are reported in Section 4.

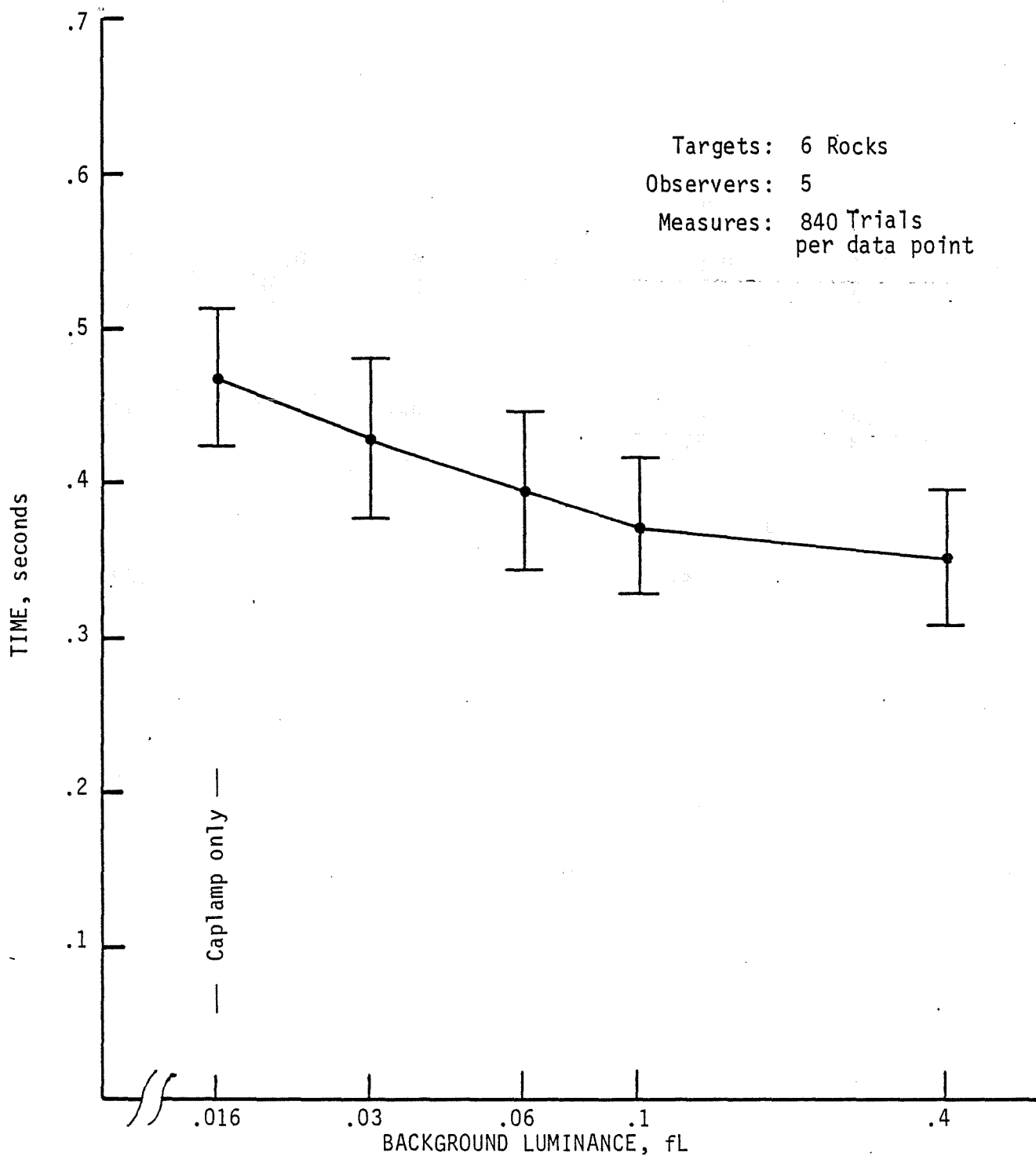


FIGURE 3-5. - Geometric mean response time (90 percent confidence interval) for detection of rock motion.

TABLE 3-3 . - Geometric mean response time (seconds)
for detection of rock motion

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.016 fL ^c						
Geo. mean	0.4937	0.5191	0.4192	0.4648	0.4158	0.4607
Log mean	-0.3065	-0.2847	-0.3776	-0.3328	-0.3811	-0.3365
Log SD ^d	0.0921	0.0738	0.0901	0.1006	0.0800	0.0426
Errors ^e	7	36	19	14	4	80
0.03 fL						
	0.4328	0.4867	0.3779	0.4433	0.3733	0.4206
	-0.3637	-0.3127	-0.4227	-0.3533	-0.4280	-0.3761
	0.0684	0.0835	0.0773	0.0827	0.0717	0.0489
	2	11	3	6	2	24
0.06 fL						
	0.3929	0.4562	0.3567	0.4249	0.3344	0.3905
	-0.4057	-0.3409	-0.4477	-0.3717	-0.4758	-0.4084
	0.0541	0.0763	0.0813	0.0804	0.0610	0.0548
	2	7	7	3	0	19
0.10 fL						
	0.3713	0.4290	0.3371	0.4011	0.3225	0.3701
	-0.4303	-0.3676	-0.4722	-0.3967	-0.4914	-0.4316
	0.0492	0.0729	0.0764	0.0936	0.0646	0.0513
	1	10	3	2	0	16
0.40 fL						
	0.3457	0.3890	0.3100	0.3970	0.2998	0.3460
	-0.4613	-0.4100	-0.5087	-0.4012	-0.5232	-0.4609
	0.0545	0.0601	0.0699	0.0945	0.0474	0.0555
	0	2	2	1	0	5

^aN=168 trials per cell minus errors.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time ≥ 1.0 seconds.

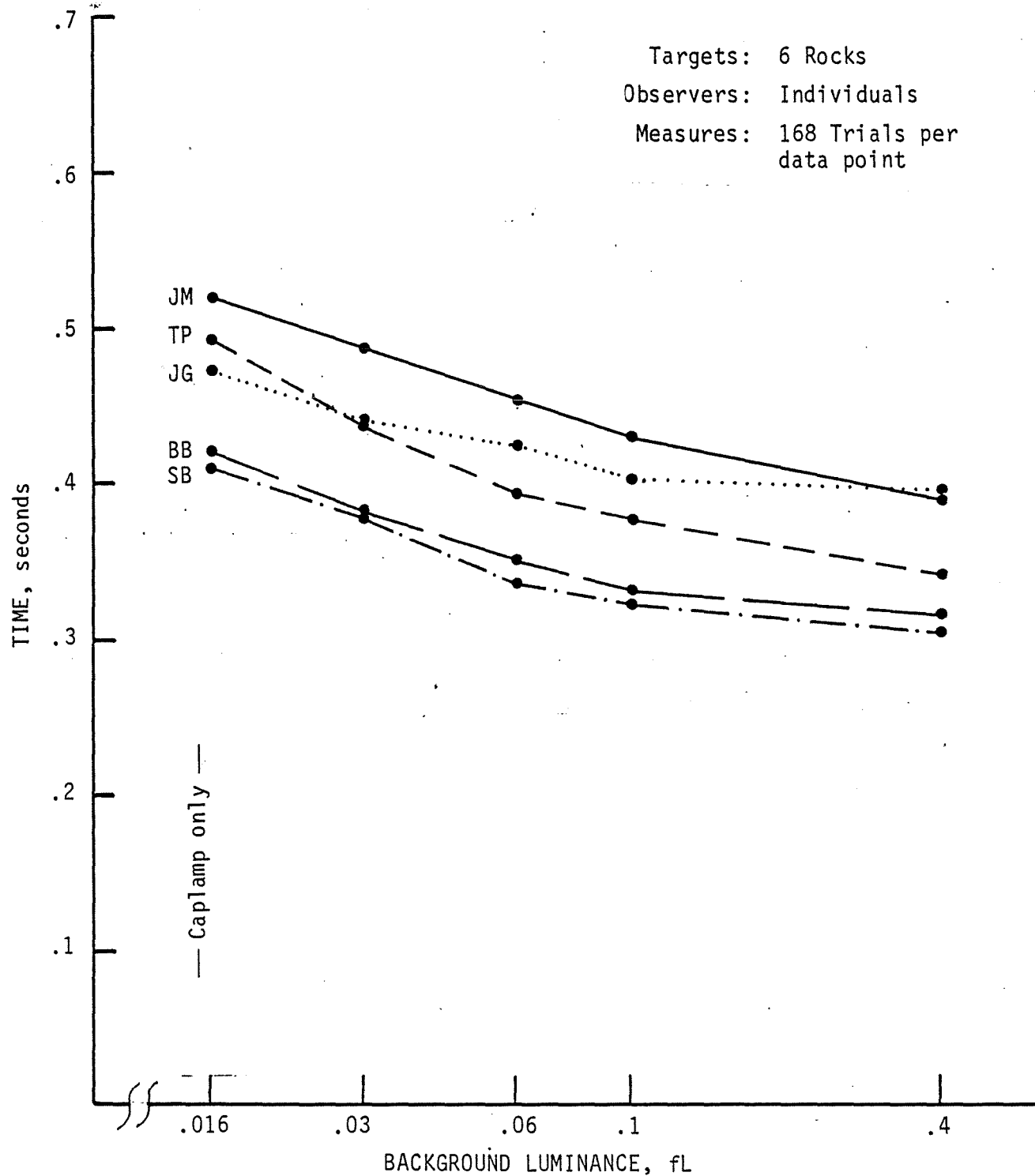


FIGURE 3-6. - Geometric mean response time for detection of rock motion by individual observers.

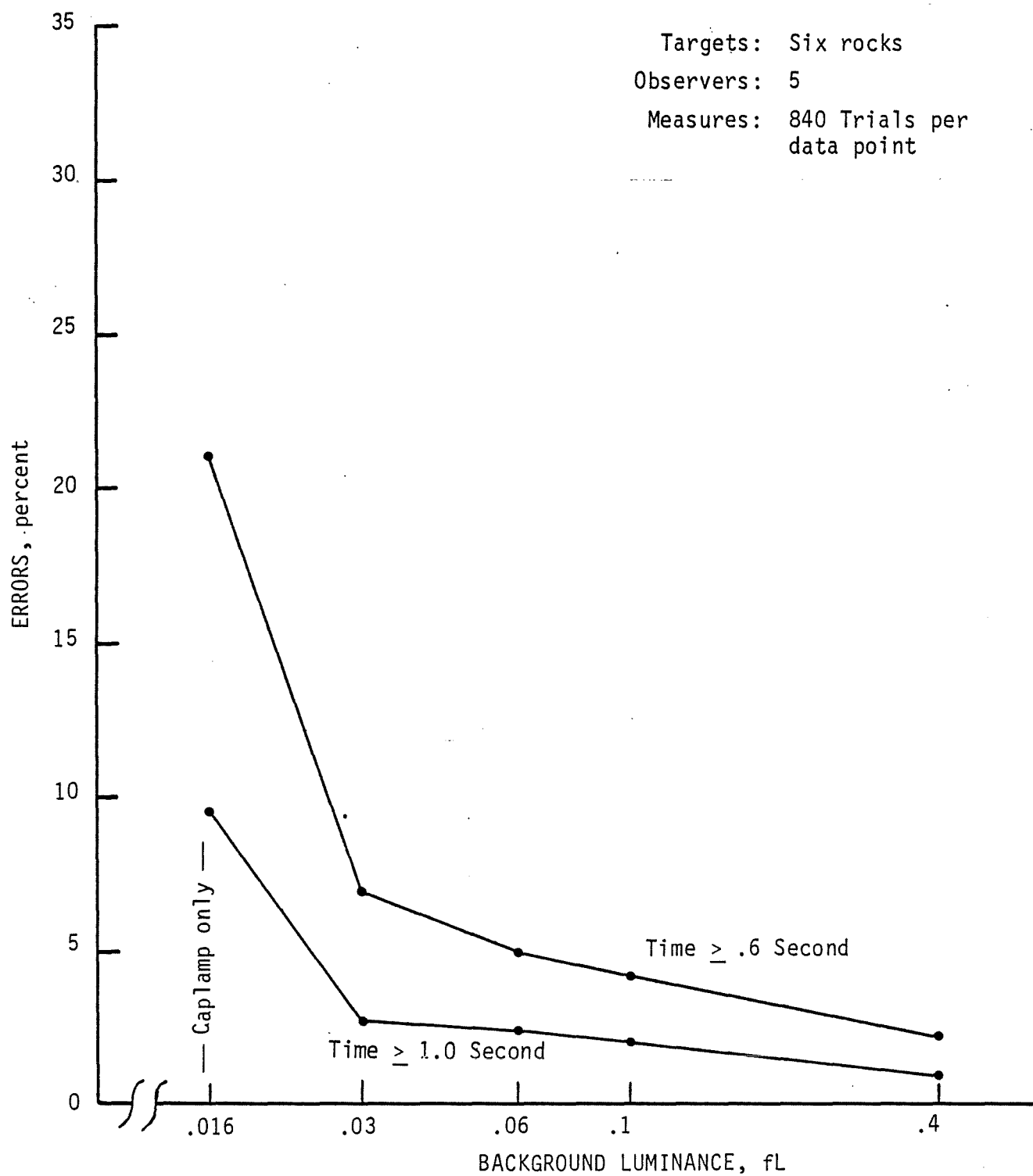


FIGURE 3-7. - Percent errors for detection of rock motion.

TABLE 3-4. - Percent and number of errors
for detection of rock motion

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.016 fL ^c						
t _≥ 1.0 ^d	4.2(7)	21.4(36)	11.3(19)	8.3(14)	2.4(4)	9.5(80)
t _≥ 0.6 ^e	26.2(44)	32.7(55)	17.9(30)	22.6(38)	6.5(11)	21.2(178)
0.03 fL						
t _≥ 1.0 ^d	1.2(2)	6.5(11)	1.8(3)	3.6(6)	1.2(2)	2.9(24)
t _≥ 0.6 ^e	5.4(9)	15.5(26)	4.8(8)	9.5(16)	1.8(3)	7.4 (62)
0.06 fL						
t _≥ 1.0 ^d	1.2(2)	4.2(7)	4.2(7)	1.8(3)	0 (0)	2.3(19)
t _≥ 0.6 ^e	1.8(3)	12.5(21)	6.0(10)	6.5(11)	0 (0)	5.4(45)
0.10 fL						
t _≥ 1.0 ^d	0.6(1)	7.0(10)	1.8(3)	1.2(2)	0 (0)	1.9(16)
t _≥ 0.6 ^e	0.6(1)	8.3(14)	3.6(6)	6.0(10)	0.6(1)	3.8(32)
0.40 fL						
t _≥ 1.0 ^d	0 (0)	1.2(2)	1.2(2)	0.6(1)	0 (0)	0.6(5)
t _≥ 0.6 ^e	0 (0)	1.2(2)	2.4(4)	6.0(10)	0 (0)	1.9(16)

^aN=168 trials per cell.

^bN=840 trials per cell.

^cCaplamp penumbra only at average distance of eight feet.

^dObserver's response time _≥1.0 seconds.

^eObserver's response time _≥0.6 seconds.

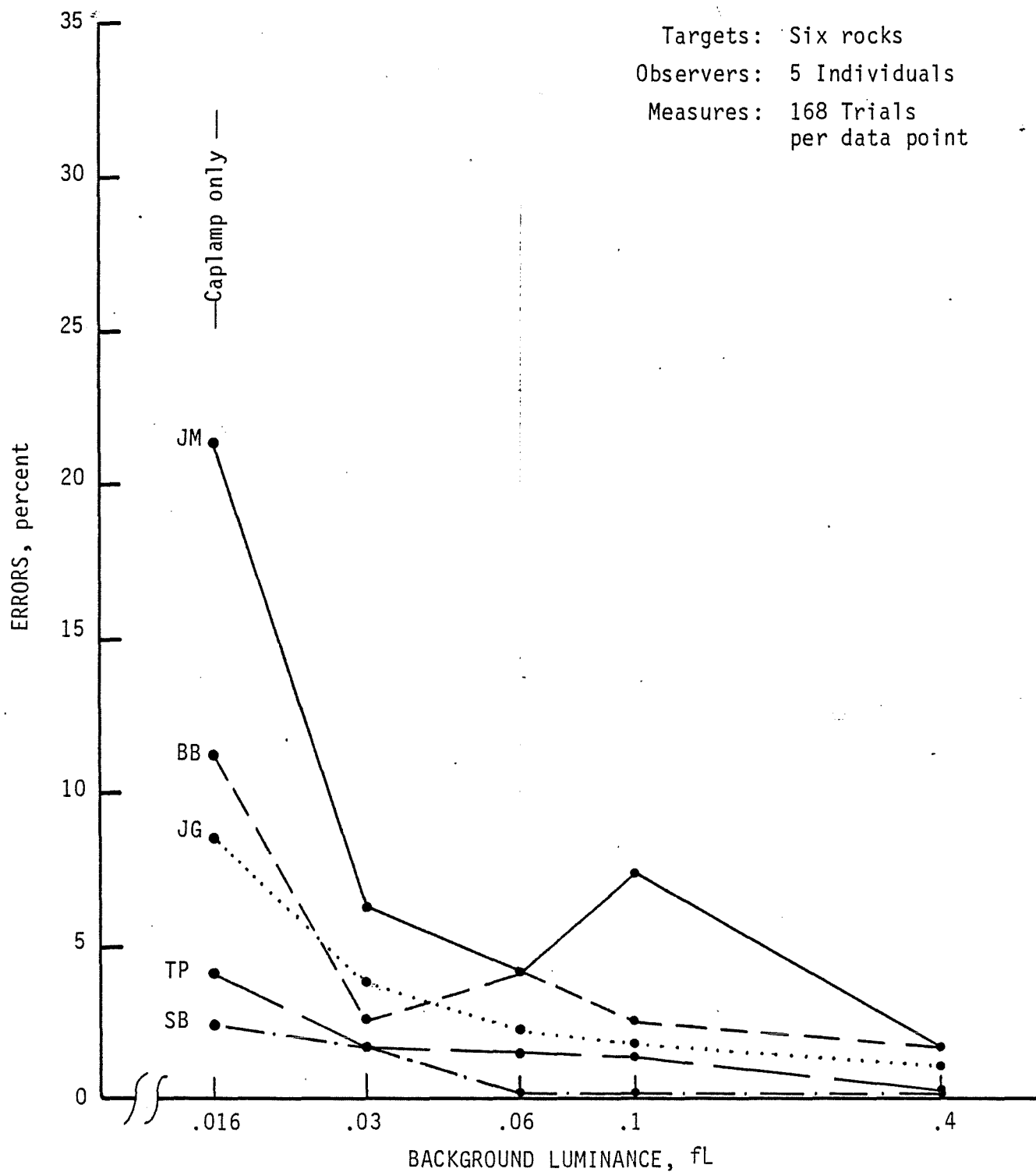


FIGURE 3-8. - Percent errors for detection of rock motion within 1.0 seconds by individual observers.

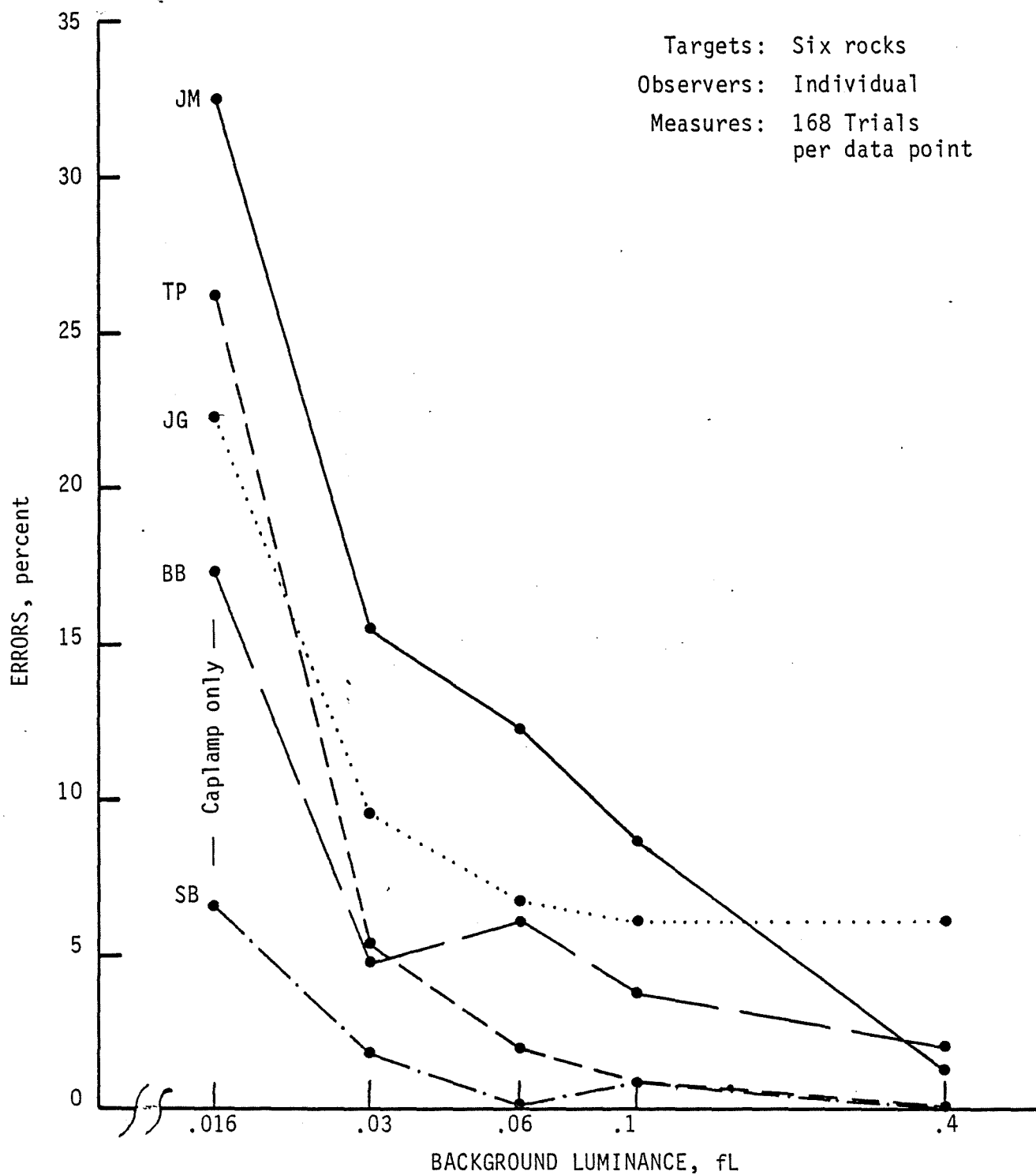


FIGURE 3-9. - Percent errors for detection of rock motion within 0.6 seconds by individual observers.

3.1.3 Floor Hole Detection. Response times were obtained for near and far floor holes at six levels of background luminance. The target was a ten-inch diameter, ten-inch deep depression located approximately 18 inches from the edge of a seven-foot diameter disk. The surface of the disk was covered with latex rubber castings of actual cave walls so as to simulate the irregular surface of a mine floor. The location of the hole was varied by rotating the disk left or right to any of six positions.

The three positions closer to the observer were designated the near targets. These targets were at a mean distance of six feet from the observer's eyes. The three more distant targets were designated as the far targets. They were at a mean distance of ten feet from the observer's eyes.

The observer was seated in an elevated chair that fixed his eye height at approximately 66 inches above the simulated floor surface (approximately equal to both standing eye height and machine operator eye height). The observer's caplamp was aimed at a point on the floor approximately 15 feet in front of the observer. The point-source supplementary luminaire was mounted as close as possible to the observer's caplamp to preserve the usual caplamp illumination geometry. Between trials the observer fixated an adaptation caplamp spot (6.5 fL) on the adjacent rib (sidewall) for a minimum of ten seconds. Headphones were worn to mask the noise of the motor-driven rotating disk.

In a manner similar to the crack detection task, a trial began when a relay switched the adaptation spot off and the observer's caplamp on while simultaneously starting the digital timer. The observer then shifted his gaze to the floor simulation and searched for the hole. When he located it, he pressed the stop button on his response box. This action stopped the timer and switched back from the observer's caplamp to the adaptation caplamp. The observer then pressed one of six hexagonally arrayed buttons to report the location of the hole. Feedback was provided by the experimenter in the event of an error. Only four errors were made during 420 trials at the lowest luminance level, while no errors were made at the higher luminances. Errors were therefore neglected in the subsequent data analysis.

The background luminance provided by the penumbra of a standard miner's caplamp was used as the lowest level for this visual task. The five higher levels were nominally set using the luminance of a test point on the disk eight feet from the observer's eye. The nominal luminances were caplamp only (0.006 fL), 0.01 fL, 0.02 fL, 0.03 fL, 0.06 fL, and 0.10 fL. The corresponding luminances of the

near and far target positions differed significantly as a function of the illumination distance and caplamp beam distribution.

The luminance levels were presented in either ascending or descending order during a run. A run consisted of seven random occurrences of each target position in a block of 42 trials (7 occurrences x 6 target positions) at each luminance level. After an average interval of 22 days, each observer performed a second run with the luminance levels presented in an order opposite that in his first run.

Geometric mean response times for the detection of near holes are shown in Figure 3-10. A 90 percent confidence interval for the mean is also shown. As can be seen, both the mean and its variance decrease as luminance increases. Table 3-5 lists the across observer means and the individual observer means. Figure 3-11 shows the individual observer means. Individual data for each near position on each run are listed in Table F-4 of Appendix F.

Test-retest reliability of the across observer means (run 1 vs. run 2) for detection of near floor holes was $r = 0.9868$, $p < 0.01$. Reliabilities of the individual observers ranged from $r = 0.9392$, $p < 0.01$ to $r = 0.9987$, $p < 0.01$ and are listed in Appendix G.

Geometric mean response times for the detection of far holes are shown in Figure 3-12. A 90 percent confidence interval for the mean is also shown. When in the far positions, the hole appears to have been much more difficult to see at the lower luminance levels. Note the change in scale from that used to plot the near hole means. Table 3-6 lists the across observer means and the individual observer means shown in Figure 3-13. Individual data for each far position on each run are listed in Table F-5 of Appendix F.

Test-retest reliability of the across observer means (run 1 vs. run 2) for detection of far holes was $r = 0.9982$, $p < 0.01$. Reliabilities of the individual observers ranged from $r = 0.9723$, $p < 0.01$ to $r = 0.9981$, $p < 0.01$ and are listed in Appendix G.

Recommended minimum luminance values for detection of floor holes are reported in Section 4.

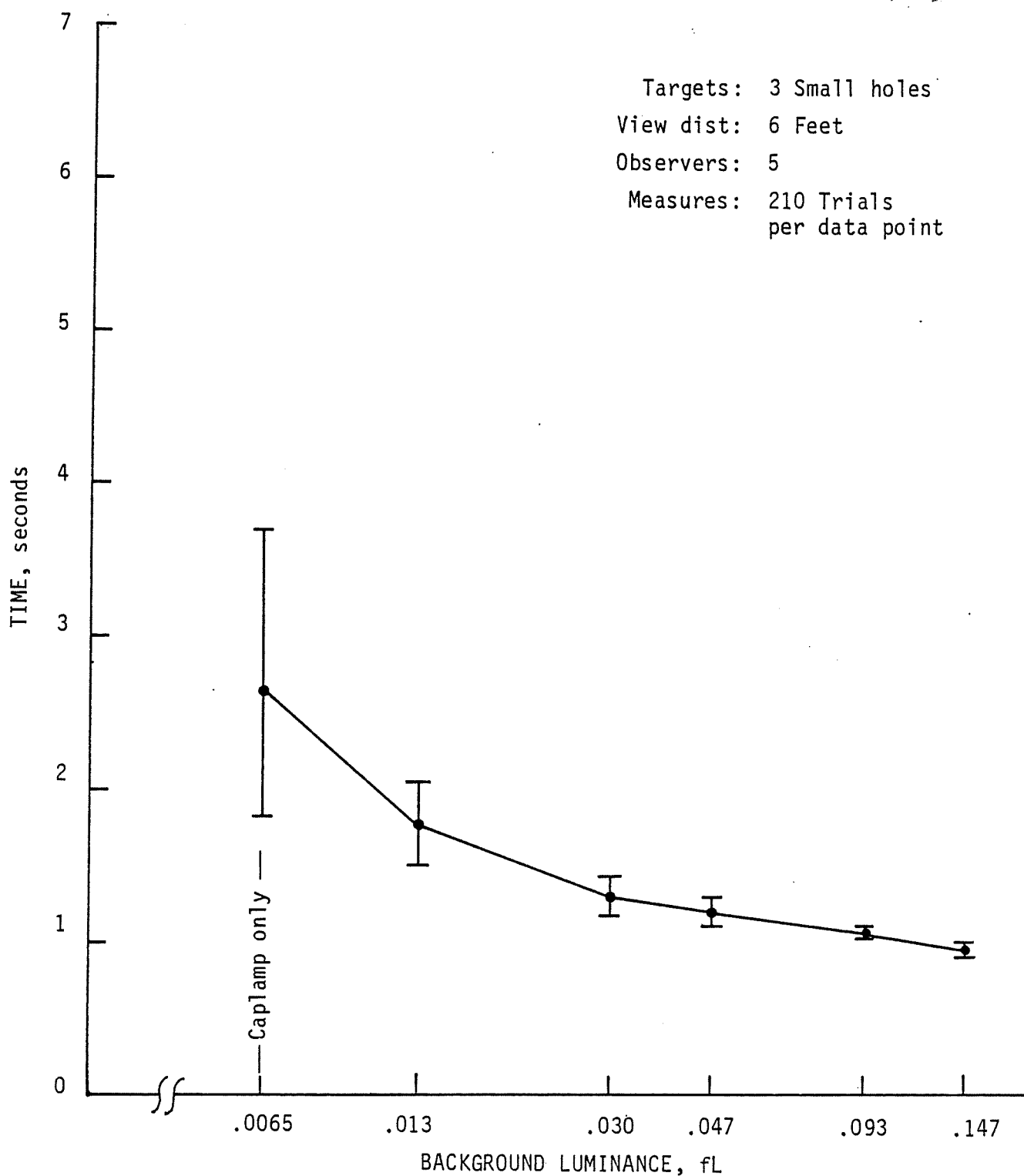


FIGURE 3-10. - Geometric mean response time (90 percent confidence interval) for detection of near holes.

TABLE 3-5. - Geometric mean response time (seconds)
for detection of near holes

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.0065 fL ^c						
Geo. mean	4.5950	2.4086	2.1755	2.9824	1.8829	2.6682
Log mean	0.6623	0.3818	0.3376	0.4746	0.2748	0.4262
Log SD ^d	0.2535	0.2006	0.2243	0.2879	0.1964	0.1507
0.013 fL						
	2.1026	1.8723	1.6352	1.8955	1.3874	1.7609
	0.3228	0.2724	0.2136	0.2777	0.1422	0.2457
	0.1735	0.2305	0.1569	0.1825	0.1239	0.0697
0.030 fL						
	1.3014	1.3191	1.2696	1.5009	1.1245	1.2977
	0.1144	0.1203	0.1037	0.1764	0.0510	0.1132
	0.1623	0.1035	0.1222	0.1042	0.0791	0.0447
0.047 fL						
	1.1758	1.2868	1.1680	1.2904	1.0555	1.1920
	0.0703	0.1095	0.0674	0.1107	0.0234	0.0763
	0.0742	0.1177	0.1011	0.0405	0.0815	0.0361
0.093 fL						
	1.0579	1.0879	1.0085	1.0572	1.0970	1.0613
	0.0245	0.0366	0.0037	0.0242	0.0402	0.0258
	0.1412	0.0803	0.0702	0.0896	0.0843	0.0143
0.147 fL						
	0.8888	0.9406	1.0157	1.0205	0.9118	0.9540
	-0.0512	-0.0266	0.0068	0.0088	-0.0401	-0.0205
	0.0672	0.0952	0.0897	0.1004	0.0834	0.0272

^aN=42 trials per cell.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra only at average distance of six feet.

^dSD Standard deviation of time in log seconds.

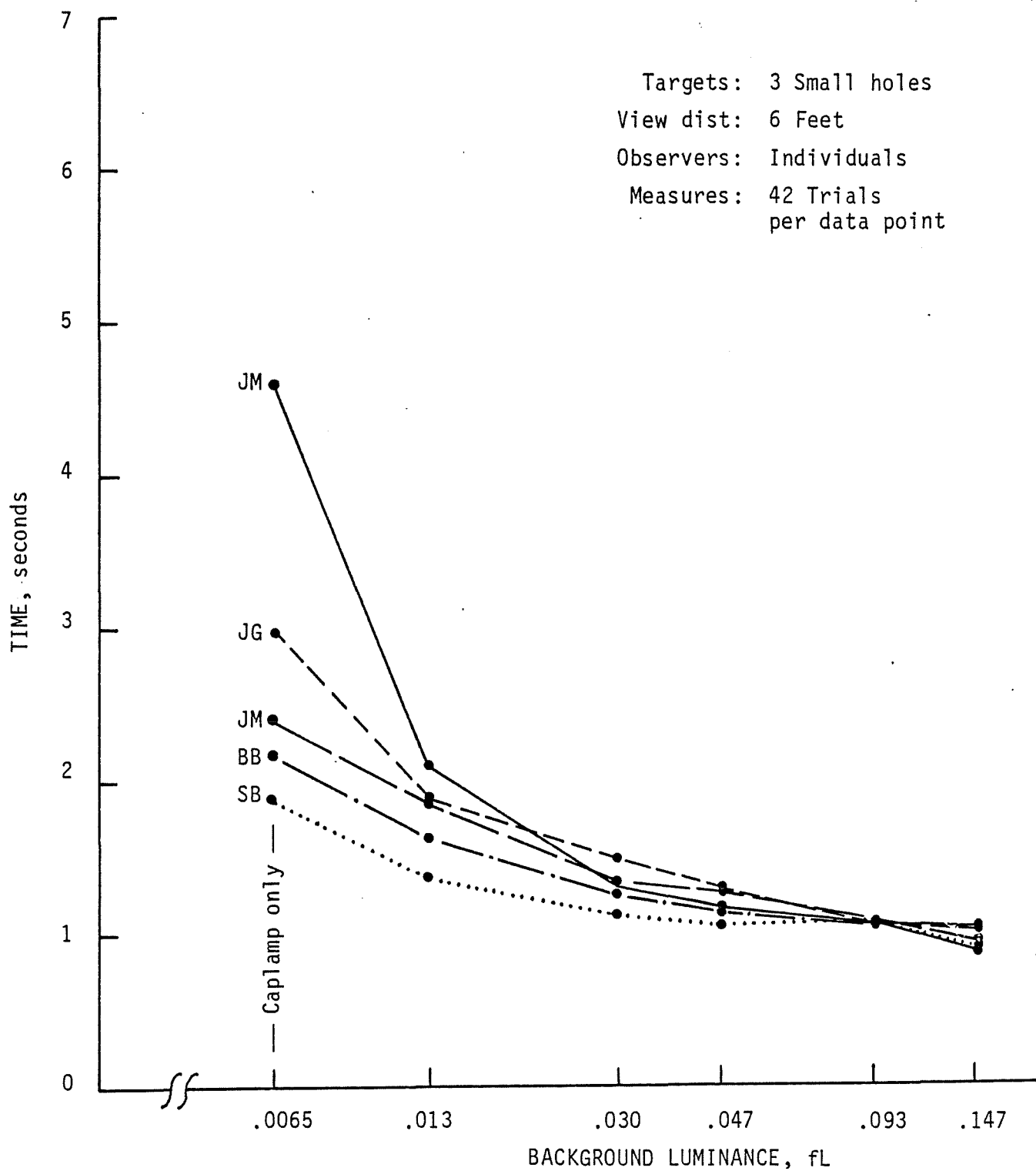


FIGURE 3-11. - Geometric mean response time for detection of near holes by individual observers.

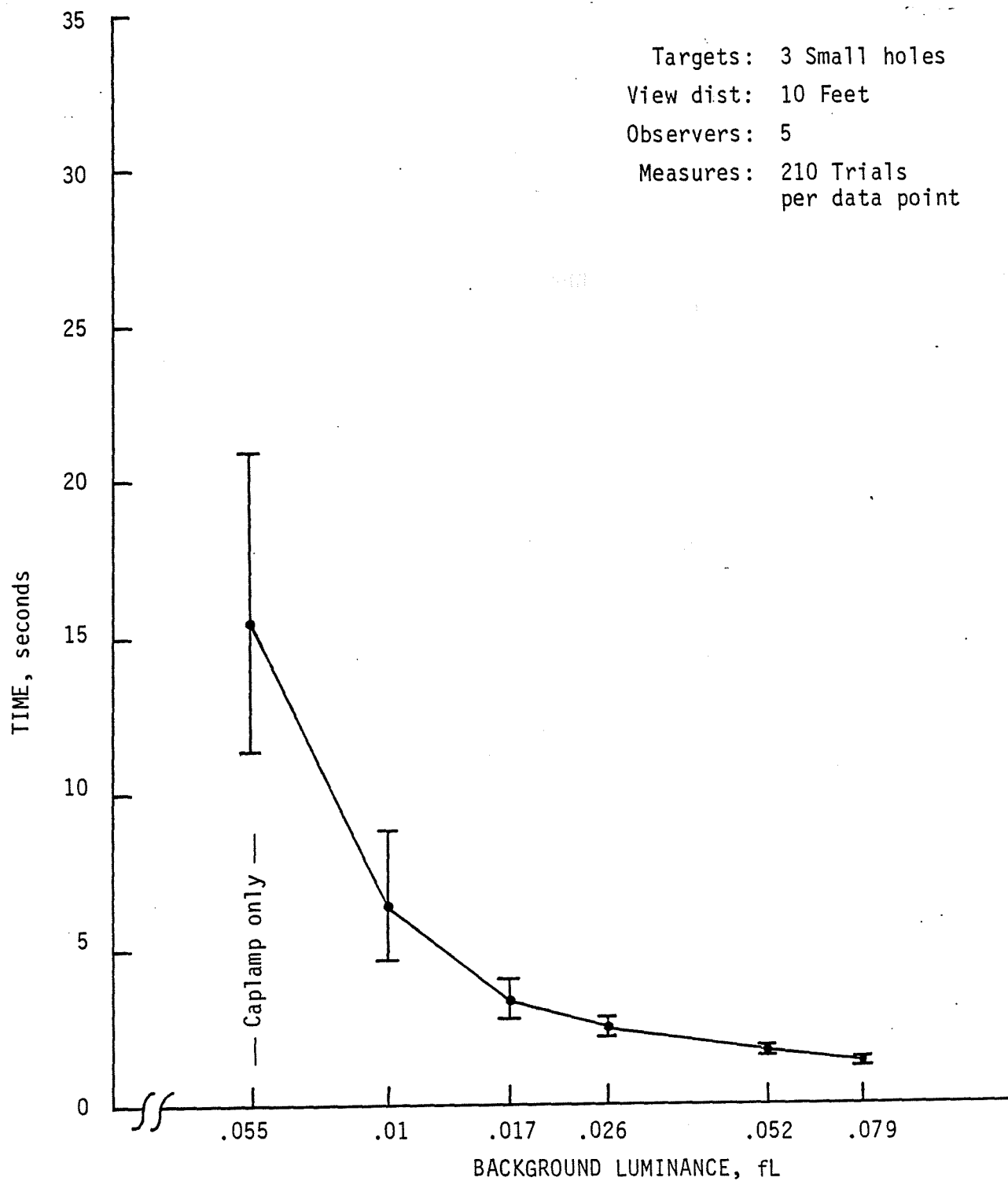


FIGURE 3-12. - Geometric mean response time (90 percent confidence interval) for detection of far holes.

TABLE 3- 6. - Geometric mean response time (seconds)
for detection of far holes

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.0055 fL ^c						
Geo. mean	24.6630	16.8592	15.7657	13.0441	10.5579	15.5282
Log mean	1.3921	1.2268	1.1977	1.1154	1.0236	1.1911
Log SD ^d	0.1776	0.3026	0.2161	0.1884	0.2456	0.1374
0.010 fL						
	10.5513	6.9514	6.6222	5.0745	4.4661	6.4319
	1.0233	0.8421	0.8210	0.7054	0.6499	0.8083
	0.1585	0.2475	0.2036	0.1808	0.1596	0.1442
0.017 fL						
	4.6701	3.2278	3.3395	3.1557	2.6969	3.3603
	0.6693	0.5089	0.5237	0.4991	0.4309	0.5264
	0.1827	0.1979	0.1335	0.1576	0.1596	0.0875
0.026 fL						
	2.8160	2.7607	2.4158	2.2859	2.1508	2.4722
	0.4496	0.4410	0.3831	0.3591	0.3326	0.3931
	0.1561	0.2118	0.1595	0.0929	0.1638	0.0510
0.052 fL						
	1.8539	1.7395	1.8112	1.6504	1.6211	1.7329
	0.2681	0.2404	0.2580	0.2176	0.2098	0.2388
	0.1161	0.1263	0.1282	0.1205	0.1036	0.0251
0.079 fL						
	1.3832	1.4581	1.4651	1.4761	1.3125	1.4176
	0.1409	0.1638	0.1659	0.1691	0.1181	0.1516
	0.0993	0.1053	0.1223	0.1720	0.0906	0.0218

^aN=42 trials per cell.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra only at average distance of ten feet.

^dSD Standard deviation of time in log seconds.

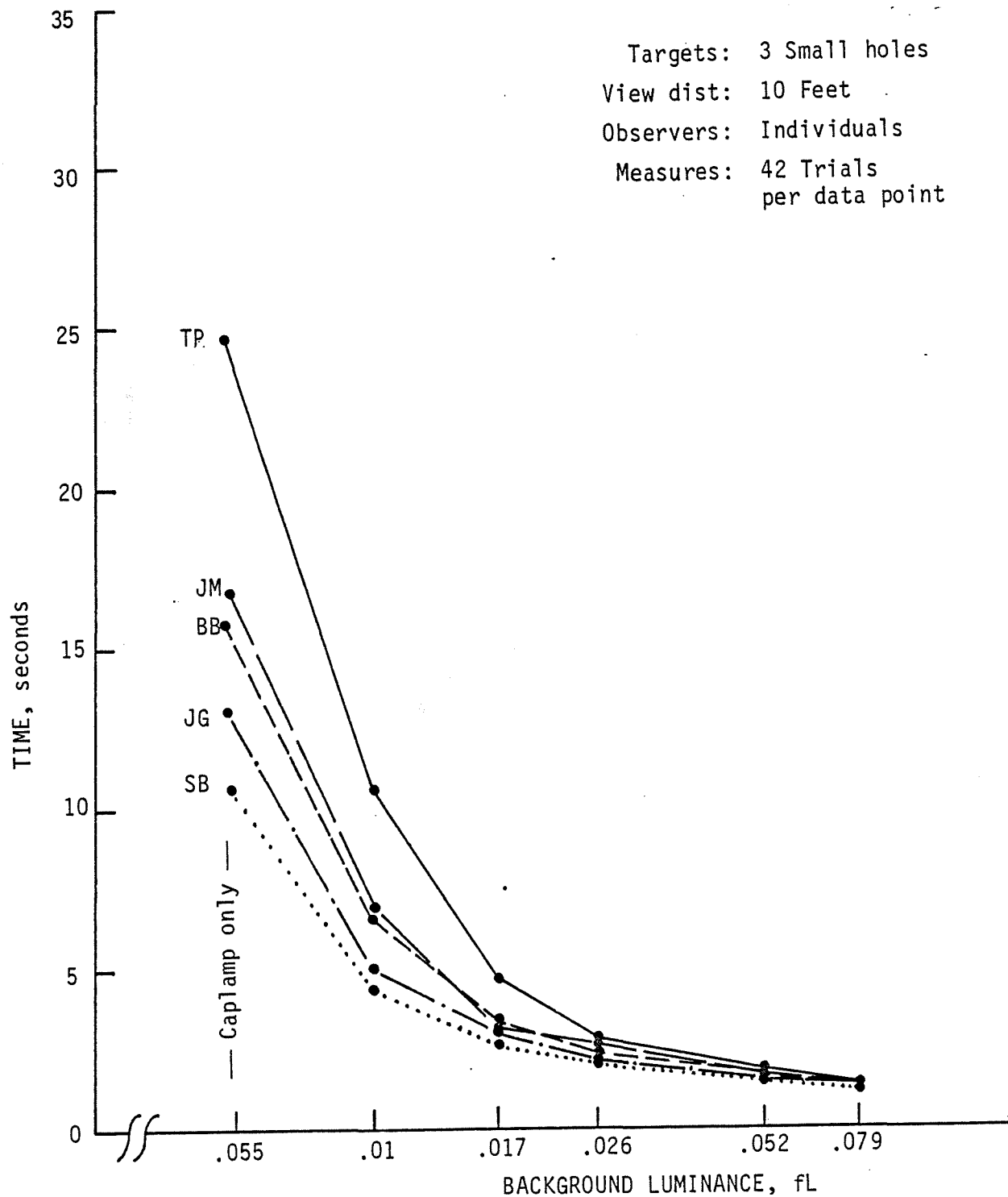


FIGURE 3-13. - Geometric mean response time for detection of far holes by individual observers.

3.1.4. Floor Rubble Detection. The apparatus and procedure for floor rubble detection was identical to that used for floor hole detection with only the visual target changed. The hole was eliminated and a rubble tripping hazard (a small rock the size of a grapefruit) was substituted. The simulated rock target approximated a 6x6x6 inch cube and gave the appearance of being embedded in the floor. No errors were made in target location identification. The mean interval between run one and run two was four days.

Geometric mean response times for the detection of near rubble are shown in Figure 3-14. A 90 percent confidence interval for the mean is indicated. Table 3-7 lists the across observer means and the individual observer means. The individual means are plotted in Figure 3-15. Individual data for each near position on each run are listed in Table F-6 of Appendix F.

Test-retest reliability of the across observer means (run 1 vs. run 2) for detection of near rubble was $r = 0.9939$, $p < 0.01$. Reliabilities of individual observers ranged from $r = 0.9079$, $p < 0.05$ to $r = 0.9921$, $p < 0.01$ and are listed in Appendix G.

Geometric mean response times for the detection of far rubble are shown in Figure 3-16. A 90 percent confidence interval for the mean is also shown. In sharp contrast with the effect of near and far distance in the hole data, the far rubble appears to have been slightly easier to detect than the near rubble. For example, the geometric mean response time at 0.01 fL for far rubble was 1.52 seconds vs. 1.82 for near rubble (linear interpolation of log-second means). This result is at least partially a consequence of observer visual search patterns.

Table 3-8 lists the across observer means, and the individual observer means are shown in Figure 3-17. Individual data for each far position on each run are listed in Table F-7 of Appendix F.

Test-retest reliability of the across observer means (run 1 vs. run 2) for detection of far rubble was $r = 0.9958$, $p < 0.01$. Individual observer reliabilities ranged from $r = 0.7770$, n.s. to $r = 0.9897$, $p < 0.01$, and are listed in Appendix G.

Recommended minimum luminance values for floor rubble detection are reported in Section 4.

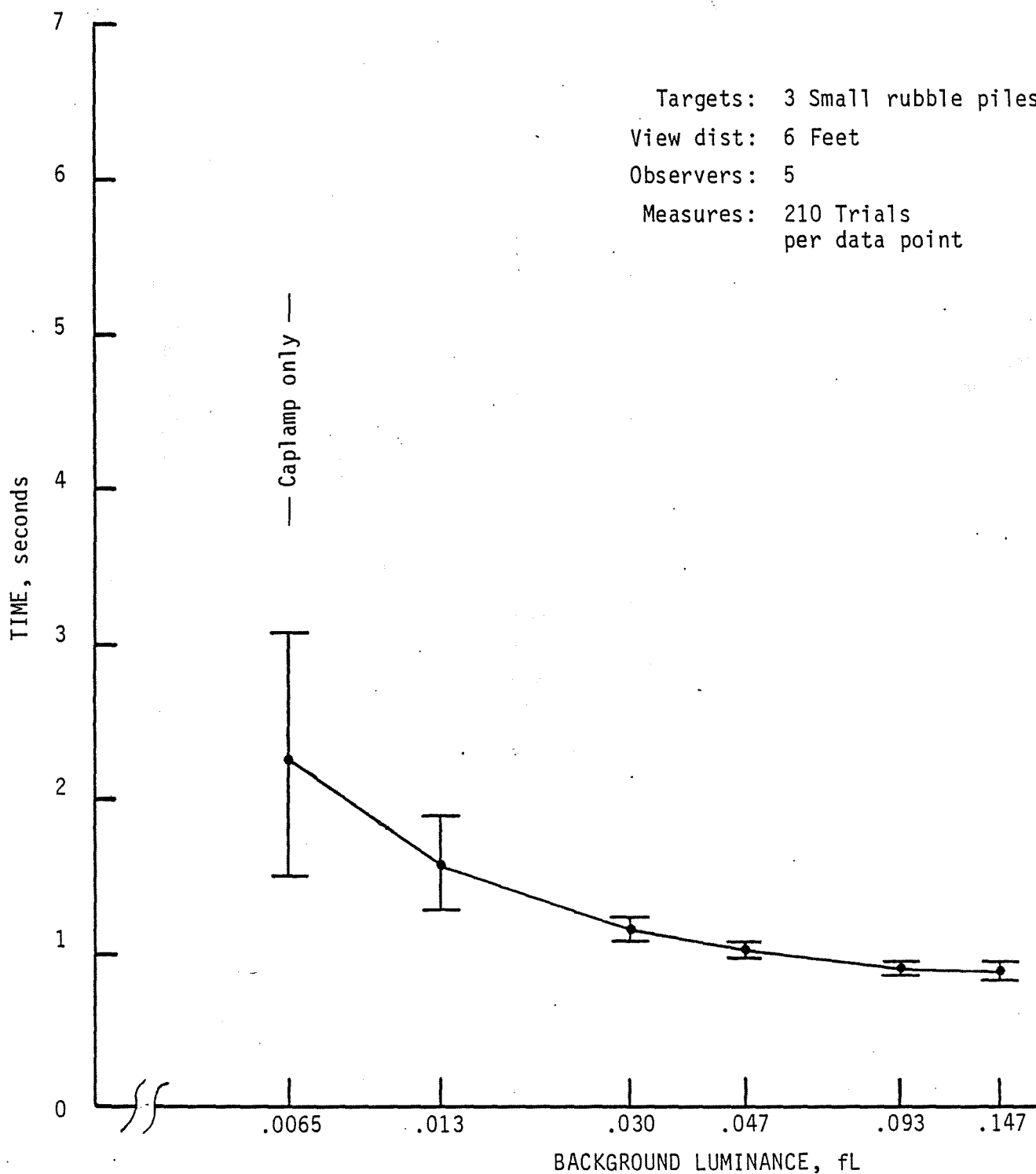


FIGURE 3-14. - Geometric mean response time (90 percent confidence interval) for detection of near rubble.

TABLE 3-7 . - Geometric mean response time (seconds)
for detection of near rubble

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.0065 fL ^c						
Geo. mean	3.5788	2.1082	1.4876	2.6133	1.6978	2.1849
Log mean	0.5537	0.3239	0.1725	0.4172	0.2299	0.3394
Log SD ^d	0.2467	0.2137	0.1561	0.3039	0.1395	0.1517
0.013 fL						
	2.0347	1.3293	1.3941	1.7387	1.3654	1.5502
	0.3085	0.1236	0.1443	0.2402	0.1353	0.1904
	0.2657	0.1185	0.1683	0.1812	0.1417	0.0807
0.030 fL						
	1.1697	1.2035	1.1790	1.2961	1.1799	1.2048
	0.0681	0.0804	0.0715	0.1126	0.0719	0.0809
	0.1179	0.1232	0.1694	0.1281	0.0780	0.0183
0.047 fL						
	1.0988	1.0459	1.0636	1.1695	1.0497	1.0846
	0.0409	0.0195	0.0268	0.0680	0.0211	0.0353
	0.1109	0.1019	0.1296	0.1007	0.0706	0.0202
0.093 fL						
	1.0221	0.9405	0.9380	1.0279	0.9548	0.9759
	0.0095	-0.0266	-0.0278	0.0120	-0.0201	-0.0106
	0.0856	0.1026	0.1394	0.1127	0.0748	0.0197
0.147 fL						
	0.9597	0.8477	0.9780	0.9678	0.9913	0.9474
	-0.0179	-0.0718	-0.0097	-0.0142	-0.0038	-0.0235
	0.1245	0.1232	0.1419	0.0951	0.0670	0.0275

^aN=42 trials per cell.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra only at average distance of six feet.

^dSD Standard deviation of time in log seconds.

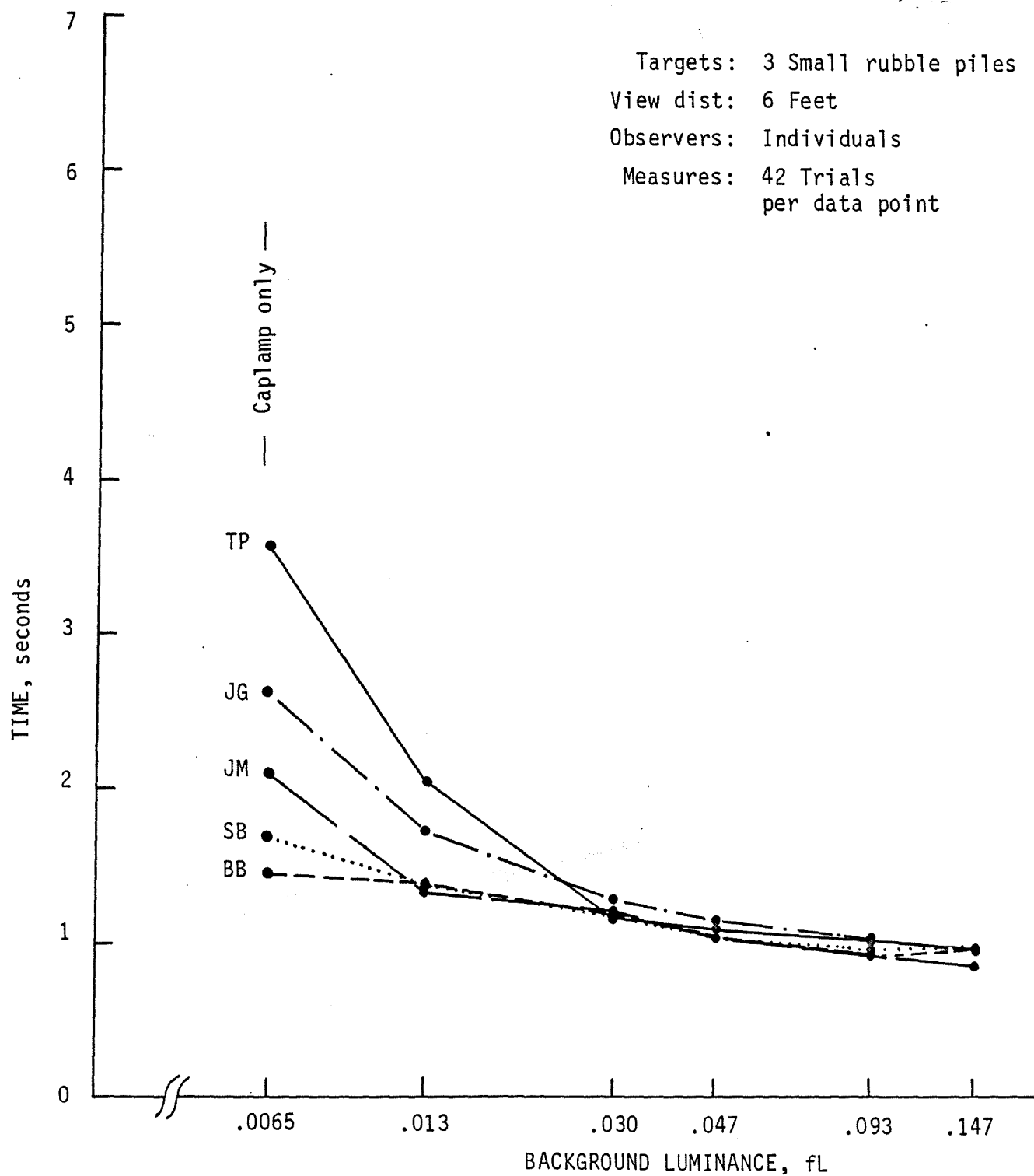


FIGURE 3-15. - Geometric mean response time for detection of near rubble by individual observers.

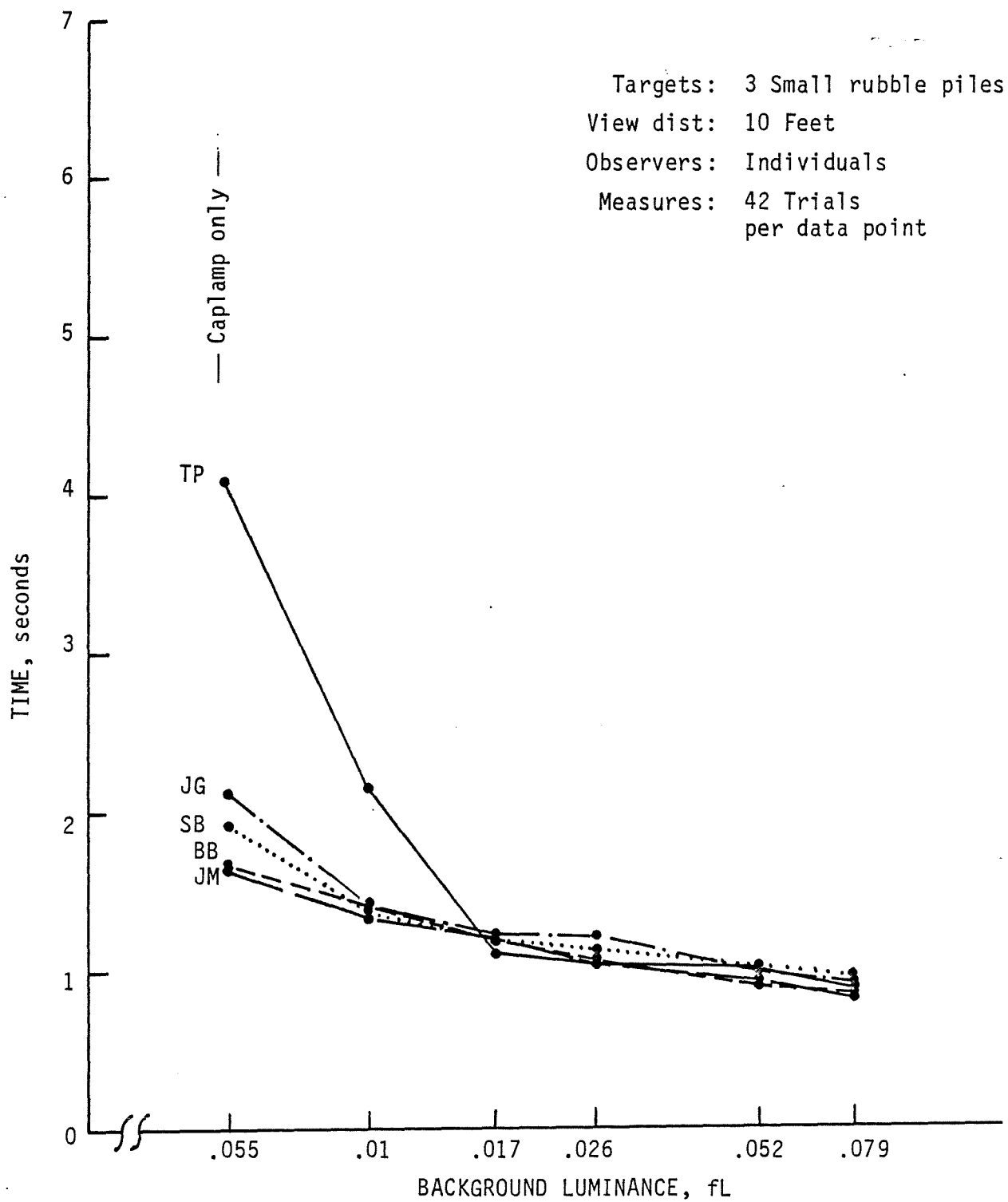


FIGURE 3-17. - Geometric mean response time for detection of far rubble by individual observers.

3.1.5 Protrusion Detection. The procedure used for this visual task was fundamentally the same as that used for the two preceding floor hazard tasks. The observer seated so that his eye-height above the simulated mine floor was approximately equal to that of a standing worker or equipment operator. The targets used were six simulated rock bolts. Each could be extended from a normal position flush against the rock surface so as to simulate the appearance of a bolt that had slipped, protruding into the work space. Three bolts were located at the back (ceiling) immediately in front of the observer and three were located on the left rib (wall). Their mean distance from the observer was six feet.

The observer's caplamp was aimed at the face approximately 15 feet from the observer. Background luminance was measured on a convex portion of the back near one of the back bolts. The point-source supplementary luminaire was mounted directly over the observer's caplamp to maintain caplamp illumination geometry. Headphones were worn to mask any sound cues created by extending and retracting the bolts. Between trials the observer fixated an adaptation caplamp beam (6.5 fL) on the right rib (wall) for a minimum of ten seconds. The observer also held a flat-black foam board screen up to block his peripheral view of the rock bolts. This was found to be necessary to prevent pre-trial detection of the target location.

A trial began when a relay switched power from the adaptation caplamp to the observer's caplamp, starting the digital timer. The observer then simultaneously shifted his gaze and moved the blocking screen away. When the observer saw which of the six bolts was extended, he pressed the stop button on the response box. The observer then pressed the position-report button corresponding to the target location.

Pilot testing of the visual task indicated that the rock bolts were highly visible in the caplamp only condition. Therefore, in the interest of economy, only two luminance levels were tested fully: caplamp only (0.0068 fL) and 0.06 fL (a luminance approximately ten times greater than that produced by the caplamp alone).

These two luminance levels were presented in either ascending or descending order. A run consisted of seven random presentations of each target position during a block of 42 trials at each luminance level. A second run was performed immediately after the first run, with the opposite order of luminance level presentation.

Geometric mean response times for the detection of slipped bolts at the back and the rib are shown in Figures 3-18 and 3-19, respectively. Ninety percent confidence intervals for the means are shown. Table 3-9 lists the across observer means and the individual

observer means. The nearly ten-fold increase in background luminance was found to decrease the geometric mean response time by only 0.0273 seconds for the back locations and 0.093 seconds for the rib locations. This relatively small effect of a large (ten-fold) increase in luminance is evidence that the presently used caplamp now provides adequate illumination for the detection of protrusion hazards.

Figures 3-20 and 3-21 show the individual observer means for back and rib protrusions, respectively. Individual response times for each target location on each run are listed in Table F-8 of Appendix F.

Test-retest reliabilities comparable to those reported for the previous results cannot be computed because only two luminance levels were tested. However, an estimate of the reliability was obtained by comparing the individual observer means for runs 1 and 2 at each luminance level. For back protrusions, the reliability of the ten data pairs was $r = 0.8837$, $p < 0.01$ and, for rib protrusions, $r = 0.9286$, $p < 0.01$.

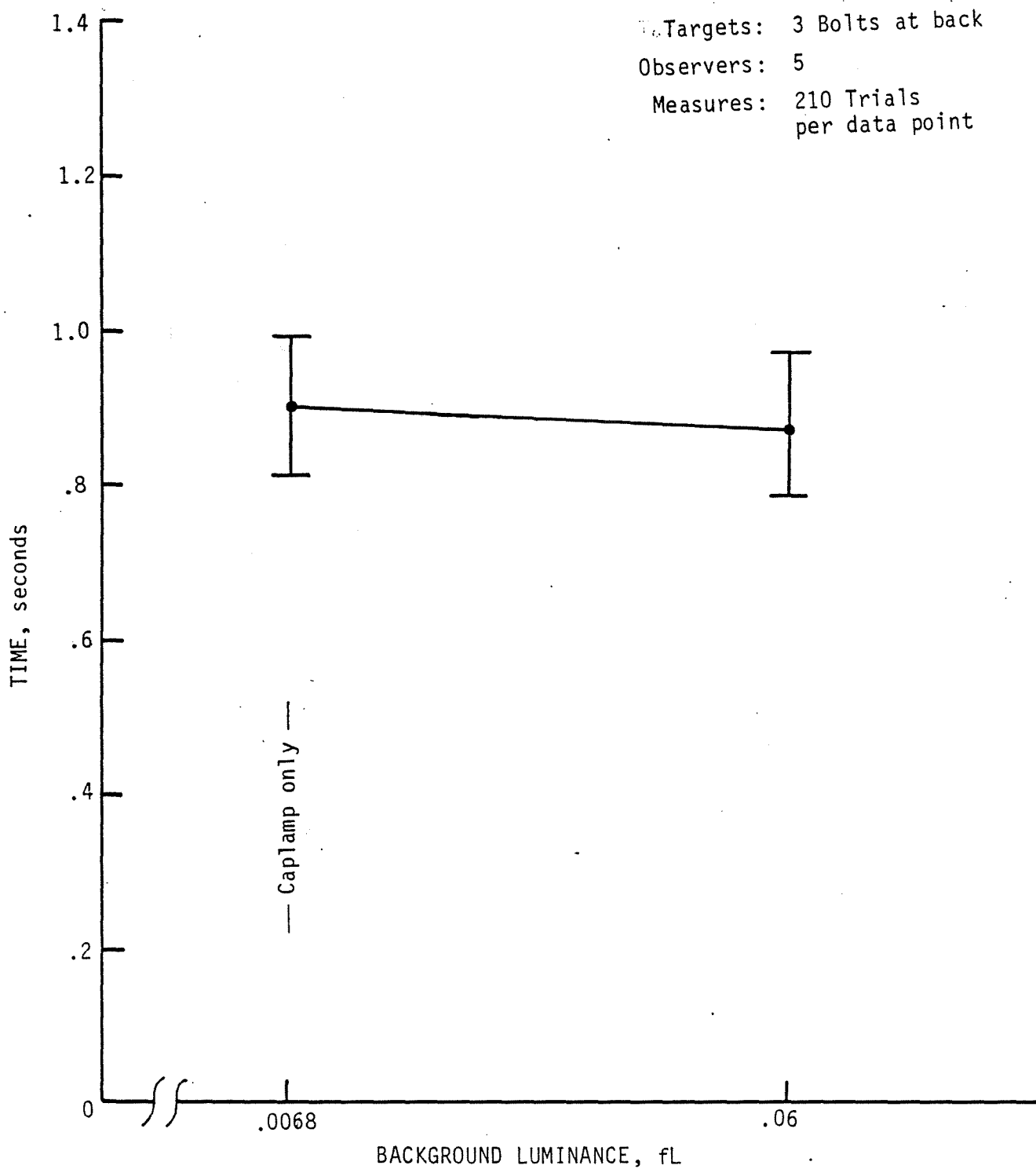


FIGURE 3-18. - Geometric mean response time (90 percent confidence interval) for detection of back protrusions.

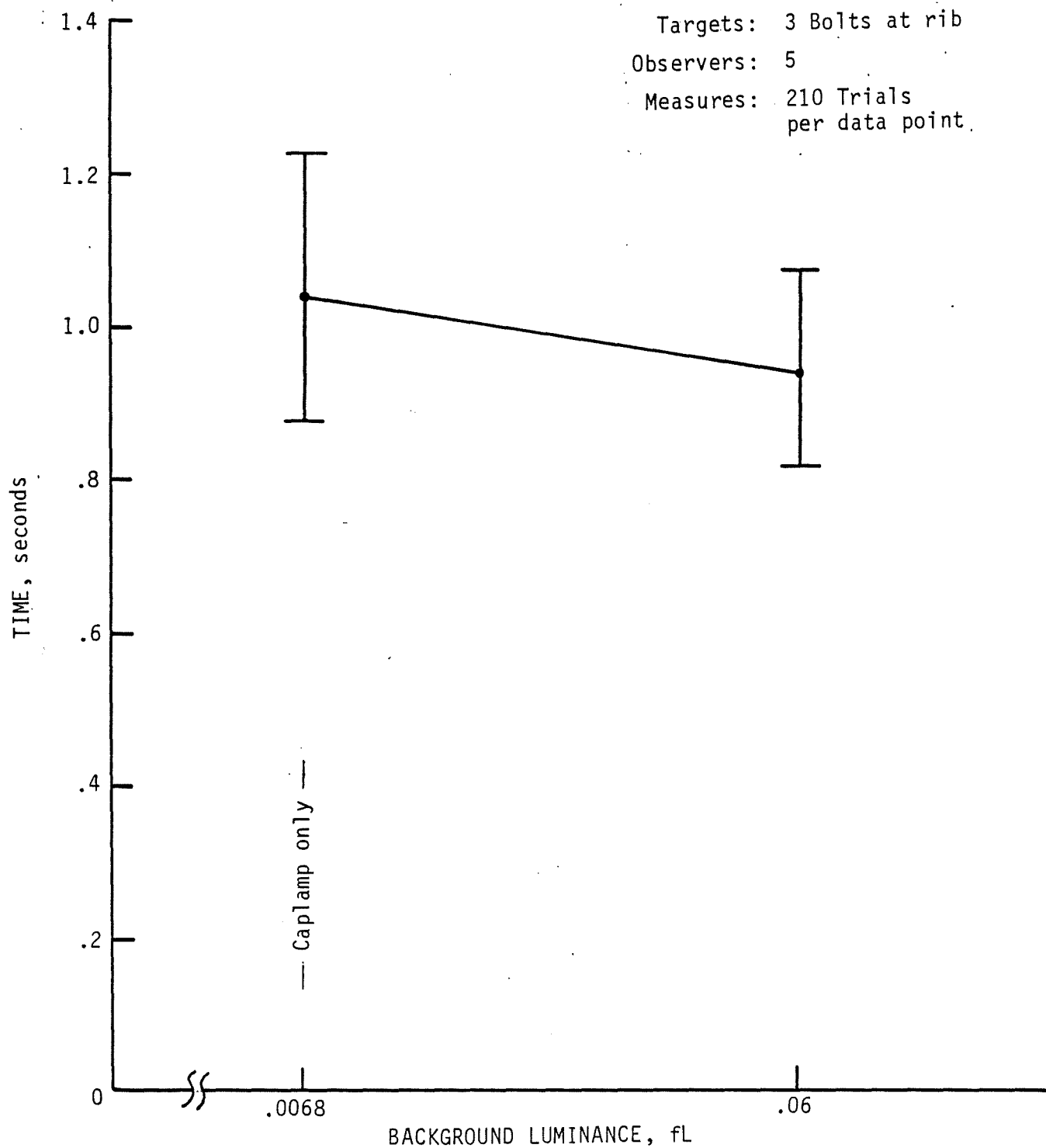


FIGURE 3-19. - Geometric mean response time (90 percent confidence interval) for detection of rib protrusions.

TABLE 3-9. - Geometric mean response time (seconds)
for detection of back and rib protrusions

Targets: Slipped rock bolts at the back

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.0068 fL ^c						
Geo. mean	0.8458	0.8553	0.8774	1.0666	0.8243	0.8899
Log mean	-0.0727	-0.0679	-0.0568	0.0280	-0.0839	-0.0507
Log SD ^d	0.0364	0.0366	0.0805	0.0895	0.0329	0.0450
0.06 fL						
Geo. mean	0.8063	0.8485	0.8128	1.0439	0.8229	0.8626
Log mean	-0.0935	-0.0713	-0.0900	0.0186	-0.0847	-0.0642
Log SD	0.0327	0.0508	0.0665	0.0891	0.0363	0.0470

Targets: Slipped rock bolts at the rib

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.0068 fL ^c						
Geo. mean	0.9639	0.9610	1.0627	1.3659	0.8812	1.0345
Log mean	-0.0160	-0.0173	0.0264	0.1354	-0.0549	0.0147
Log SD ^d	0.0597	0.0599	0.0788	0.1019	0.0648	0.0733
0.06 fL						
Geo. mean	0.9030	0.8726	0.9391	1.1761	0.8501	0.9415
Log mean	-0.0443	-0.0592	-0.0273	0.0704	-0.0705	-0.0262
Log SD	0.0471	0.0585	0.1140	0.0862	0.0438	0.0564

^aN=42 trials per cell.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra only at average distance of six feet.

^dSD Standard deviation of time in log seconds.

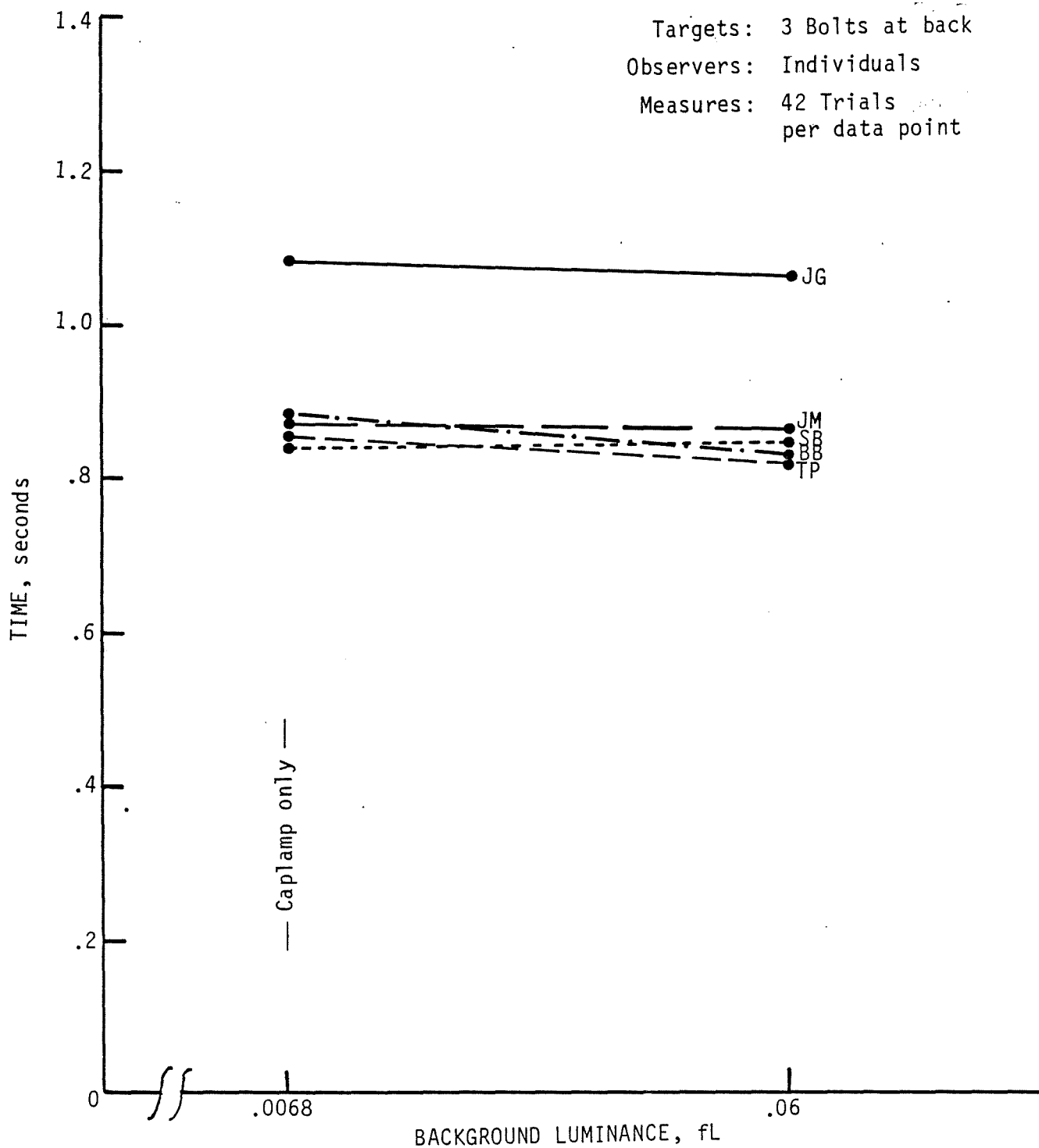


FIGURE 3-20. - Geometric mean response time for detection of back protrusions by individual observers.

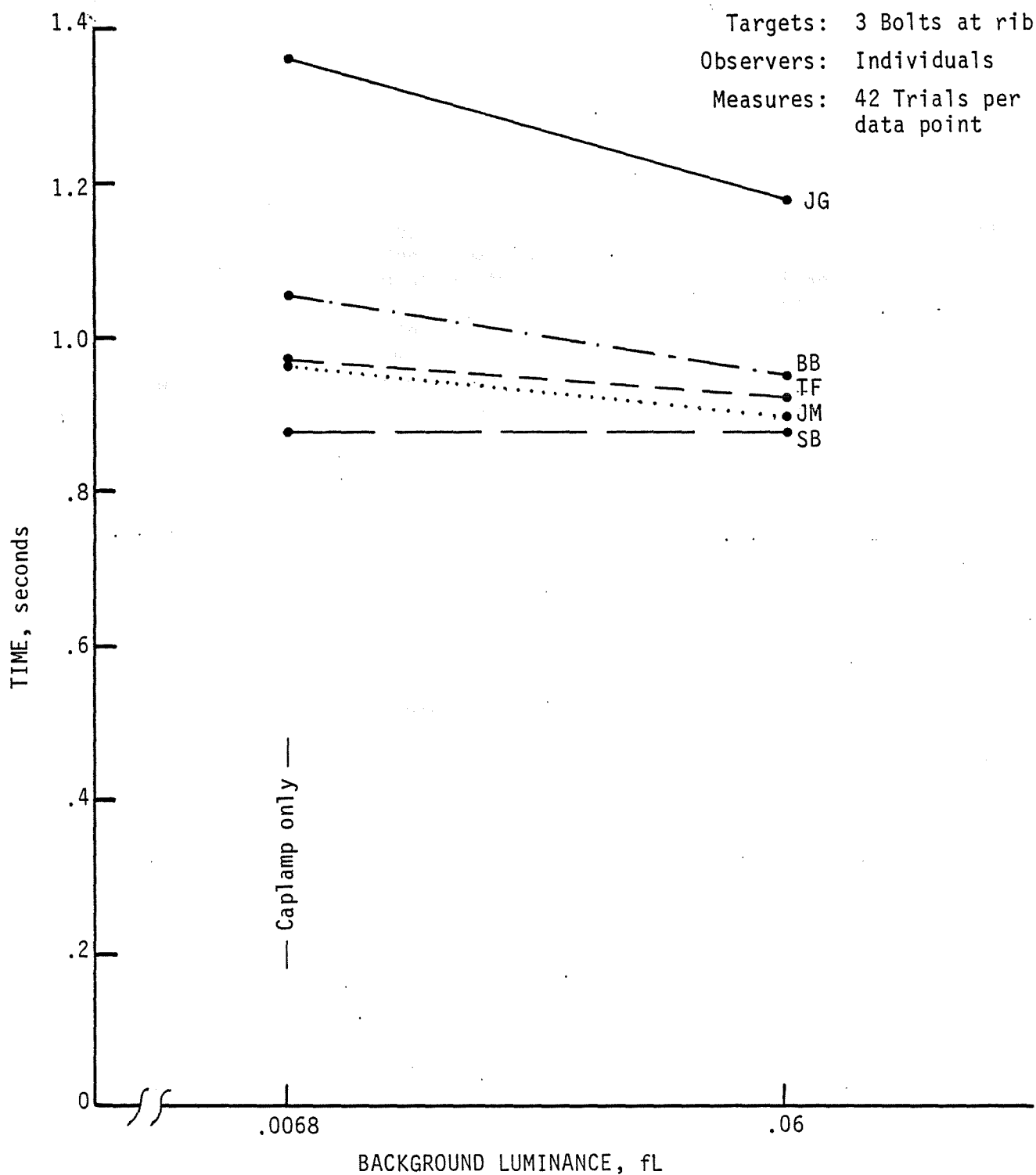


FIGURE 3-21. - Geometric mean response time for detection of rib protrusions by individual observers.

3.1.6 Peripheral Motion Detection. Response times were obtained for six levels of target luminance ranging from caplamp penumbra only (0.0018 fL) to 0.16 fL at an average distance of 12 feet. The targets were two 12-inch diameter, four-foot tall cylinders vertically mounted on revolving bases.

The observer was seated approximately nine feet from the wall. His attention was fixed by a secondary task requiring frequent responses. The observer's caplamp spot was centered on the secondary target. The peripheral detection targets were positioned 60° to either side of the secondary target. Multiple secondary task trials (typically 2 to 6) preceded each peripheral detection task. Headphones were worn to mask the sound of the motors driving the peripheral targets. The point-source, supplementary luminaire was mounted directly above the observer's caplamp to provide the usual caplamp illumination geometry.

The experimenter randomly selected one of the two peripheral targets for presentation in each experimental trial. A count-down timer would trigger the motor drive of the selected target and start the digital timer. The target would then move in a circular path. The observer reported detection of the target by pressing the stop button on his response box. The target would continue around its circular path and stop in its "parked" position.

The luminance levels were presented in either ascending or descending order. A run consisted of 21 random presentations of each target during a block of 42 trials at each luminance level. A second run was not possible due to the unavailability of the younger observers.

Geometric mean response times for detection of peripheral motion are shown in Figure 3-22. A 90 percent confidence interval for the mean is also shown. Table 3-10 lists the across observer means and the individual observer means. The individual data are plotted in Figure 3-23. Response times for each target for each observer are listed in Table F-9 of Appendix F.

Test-retest reliability data are unavailable due to the absence of a second run.

Recommended minimum luminance values for peripheral motion are reported in Section 4.

Targets: 2 Cylinders
Observers: 5
Measures: 210 Trials
per data point

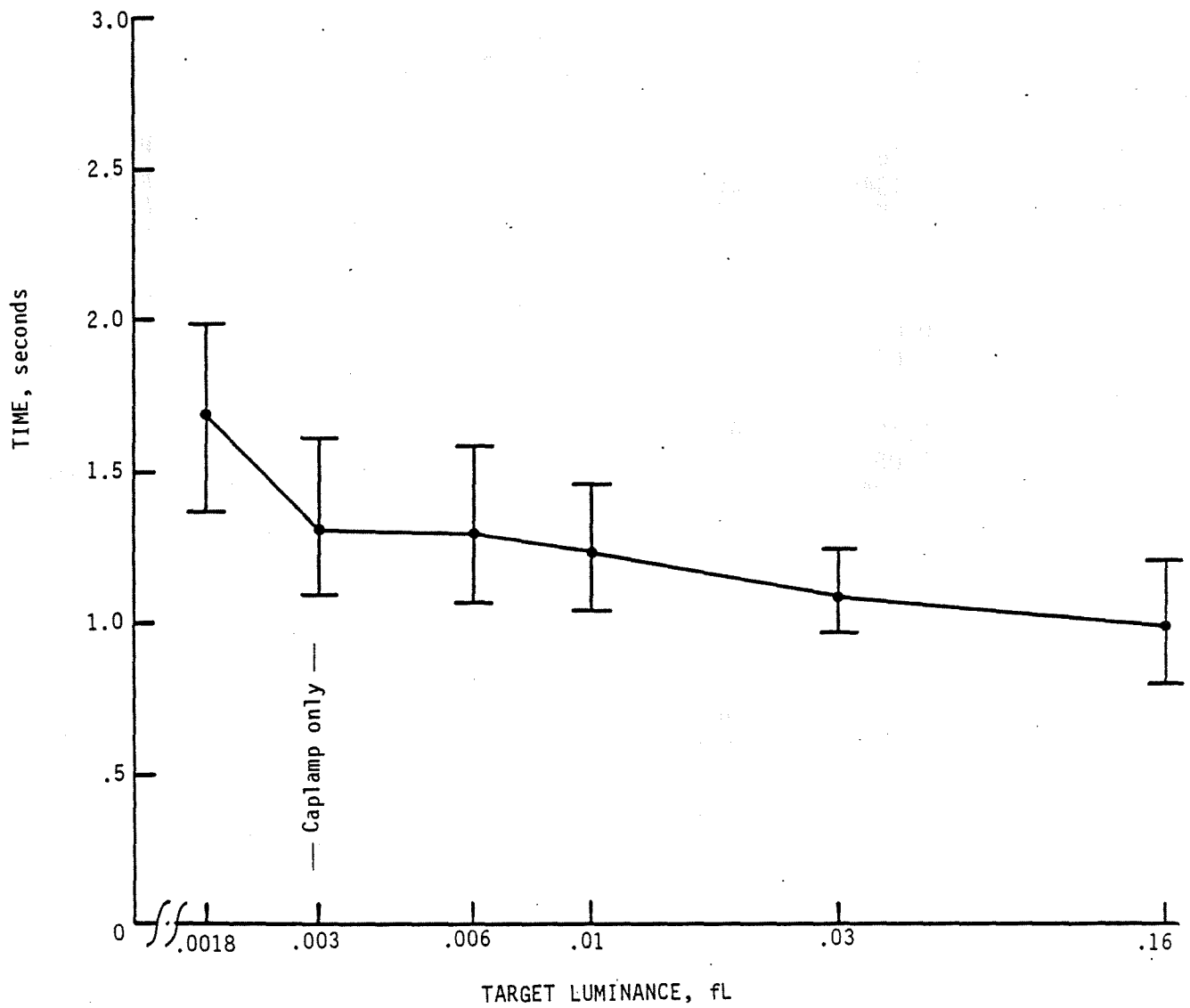


FIGURE 3-22. - Geometric mean response time (90 percent confidence interval) for detection of peripheral motion.

TABLE 3-10. - Geometric mean response time (seconds)
for detection of peripheral motion

Luminance Level	Observer ^a					Across Observers ^b
	TP	JM	BB	JG	SB	
0.0018 fL ^c						
Geo. mean	1.3640	1.7832	1.6868	2.1333	1.3591	1.6409
Log mean	0.1348	0.2512	0.2271	0.3290	0.1333	0.2151
Log SD ^d	0.1596	0.1909	0.1919	0.1788	0.0573	0.0830
0.003 fL						
	1.1767	1.3254	1.2340	1.8382	1.0795	1.3073
	0.0707	0.1223	0.0913	0.2644	0.0332	0.1164
	0.0777	0.1130	0.1417	0.1503	0.0500	0.0889
0.006 fL						
	1.1382	1.4602	1.1224	1.7439	1.0865	1.2872
	0.0562	0.1644	0.0501	0.2415	0.0360	0.1096
	0.1040	0.1677	0.1010	0.1635	0.0644	0.0897
0.01 fL						
	1.0913	1.2839	1.0645	1.6253	1.0587	1.2075
	0.0380	0.1085	0.0272	0.2109	0.0248	0.0819
	0.0822	0.1297	0.1690	0.1357	0.0566	0.0799
0.03 fL						
	1.0310	1.1257	0.9087	1.3093	0.9816	1.0627
	0.0133	0.0514	-0.0416	0.1170	-0.0081	0.0264
	0.1027	0.0998	0.1406	0.1245	0.0687	0.0609
0.16 fL						
	0.9665	1.1609	0.7007	1.1772	0.8367	0.9501
	-0.0148	0.0648	-0.1545	0.0708	-0.0775	-0.0222
	0.0889	0.1010	0.0889	0.1426	0.0583	0.0960

^aN=42 trials per cell.

^bArithmetic mean of individual observer's log means (N=5).

^cCaplamp penumbra only at average distance of 12 feet.

^dSD Standard deviation of time in log seconds.

Targets: 2 Cylinders
 Observers: Individual
 Measures: 42 Trials
 per data point

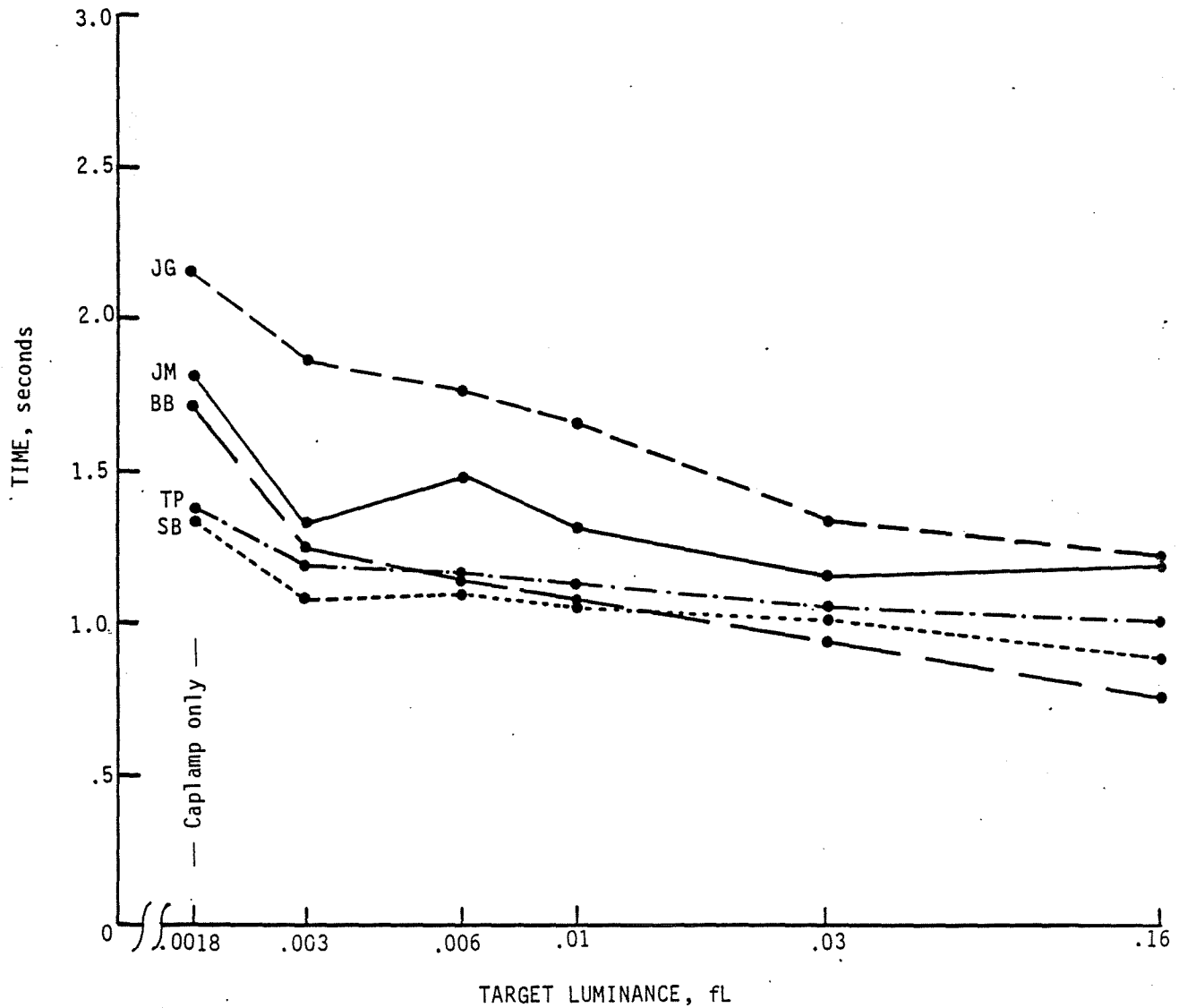


FIGURE 3-23. - Geometric mean response time for detection of peripheral motion by individual observers.

3.2 CONTRAST THRESHOLD MEASURES OF VISIBILITY

In addition to direct measures of visual task performance as a function of target luminance, as described in the previous section, it was possible to obtain relative measures of mining task visibilities using a portable Visual Task Evaluator (VTE Model 5) designed by Dr. H. R. Blackwell. The theory of operation, the specifics of the equipment and procedures, and the task visibility data are fully described in Appendix A.

During September, 1982, two members of the research team visited two large underground metal mines to obtain in-mine VTE measures of task visibility to compare our full-scale simulations of mining tasks with their counterparts in actual underground mines.

In total, 30 visual task items were measured with the VTE in our laboratory's simulated underground workspace, while 35 visual task items were measured in a large copper mine and a large zinc mine. Comparable VTE data were obtained both in our laboratory and in underground mines for rock cracks, slipped rock bolts, holes and rubble on the floor, rib and back protrusion hazards, muck pile hazards, and so on. It was not possible to obtain VTE data for certain tasks, such as rock motion and shaft inspection, due to practical considerations discussed in Appendix A.

Relative visibility levels (VL, the ratio by which an object is above its visual threshold) for our simulated rock cracks ranged from 2.2 to 4.0, while actual rock cracks in the two underground mines ranged from 3.0 to 7.1. The general correspondence between VL measures in the mines and in the laboratory confirms that our simulated rock cracks represent the slightly more difficult end of the spectrum of actual rock cracks as found in underground mines. This slightly conservative bias in the simulations ensures that our recommendations for minimum task luminance will be adequate to handle the commonly occurring more difficult task items found underground.

In general, the VTE readings obtained in our simulated mine workspace ranged from 2.2 to 23.3, whereas the VTE readings obtained in the mines ranged from 1.6 to 23.3, with most of the readings less than 10. This overlap in the VTE data for relative task visibility confirms that the laboratory simulations adequately represent the visual aspects of the underground mining environment.

4. RECOMMENDATIONS FOR MINIMUM LUMINANCE AND IMPROVED LIGHTING PRACTICES

In this section, we recommend performance criteria for the critical visual tasks and specify minimum luminance levels necessary to meet those criteria. An adjustment for age, eyewear, and atmospheric attenuation is suggested and minimum luminance requirements for each of the 43 mining jobs are recommended. Finally, we discuss lighting practices that will enhance task visibility and visual performance in the underground environment.

4.1 CRITERIA FOR MINIMUM LUMINANCE

The performance data show very clearly how increased luminance can shorten response times (and virtually eliminate errors for rock motion detection), down to an asymptote beyond which there is little if any further performance gain, no matter how high the additional luminance. Certain illumination-engineering considerations specific to the underground mining environment, such as energy requirements, cost factors, and potential glare problems, make it impractical to provide high levels of overall luminance for most mining tasks. Located on the continuum between the lowest luminance (caplamp penumbra) and the high asymptotic luminance (supplementary lighting) is the level to be selected as the minimum for safe task performance. That level represents a point where further increases in luminance will not yield meaningful performance gains.

Ideally, one would know precisely how much time is available for safe detection in each type of task. This maximum can be estimated for some visual tasks. For example, if rock motion in a chute is not detected quickly enough, the worker would not have enough time to take evasive action. On the other hand, it is far less clear what the maximum safe time for detection of rock cracks would be. The goal of the crack detection task is to locate any cracks, remove or secure the dangerous rock, and rule out the presence of any additional cracks. The time available for the task is limited by pressures for productivity and the worker's standard of adequate search.

The approach we have taken is to select reasonable performance criteria, based on our data for visual search and visual motion detection, for both the underground worker on foot and the mobile equipment operator. The various performance criteria for the determination of minimum luminance levels are:

- (1) Visual search (worker on foot): 150 percent of estimated asymptote.

- (2) Motion detection (worker on foot): 150 percent of estimated asymptote or a 5 percent error rate, whichever is more stringent.
- (3) Visual search (mobile equipment operator): 125 percent of estimated asymptote.
- (4) Motion detection (mobile equipment operator): 125 percent of estimated asymptote or a 5 percent error rate, whichever is more stringent.

We are suggesting that the worker on foot be allowed up to 50 percent longer to detect a target than would be required for detecting the same target under high levels of luminance. For the visual tasks in the present study, the 50 percent additional time represents a mean increase of only 0.54 seconds (range 0.35 to 0.83 seconds). To put this extra 0.54 seconds in perspective, a worker walking at two miles per hour would move 1.6 feet closer to a hazard in that interval.

While minimum luminance levels based on the 150 percent criterion imply a relatively small performance penalty compared with high luminance levels, the gains over caplamp-penumbra-only lighting are striking: the suggested minimum luminance levels improve detection time by a mean of 3.73 seconds (range 0.22 to 13.4 seconds). For the more difficult tasks, performance gains (over caplamp-penumbra-only) are impressive and should greatly improve the safety of the underground worker.

Visual search and motion detection by the mobile equipment operator require a more rigorous performance criterion (125 percent of the asymptotic response time at high luminance levels) because of the more severe consequences of performing these tasks too slowly. For the visual tasks associated with mobile equipment operation, the 25 percent additional detection time represents a mean increase 0.27 seconds (range = 0.22 to 0.35 seconds). During an interval of 0.27 seconds, a vehicle traveling at 10 miles per hour would move approximately 4 feet closer to a hazard.

Our extensive experience in measuring visual task performance at relatively low luminance levels in the mine illumination laboratory, combined with our broad knowledge of the visual demands of underground work, suggests that minimum luminance levels based on the criteria listed above would ensure that the underground worker's safety is not compromised by inadequate lighting.

An example of the procedure used to determine minimum luminance levels required for safety (assuming the above criteria) is shown in Figure 4-1. The visual task is detection of narrow cracks. The performance criterion is 150 percent of the response time at the estimated

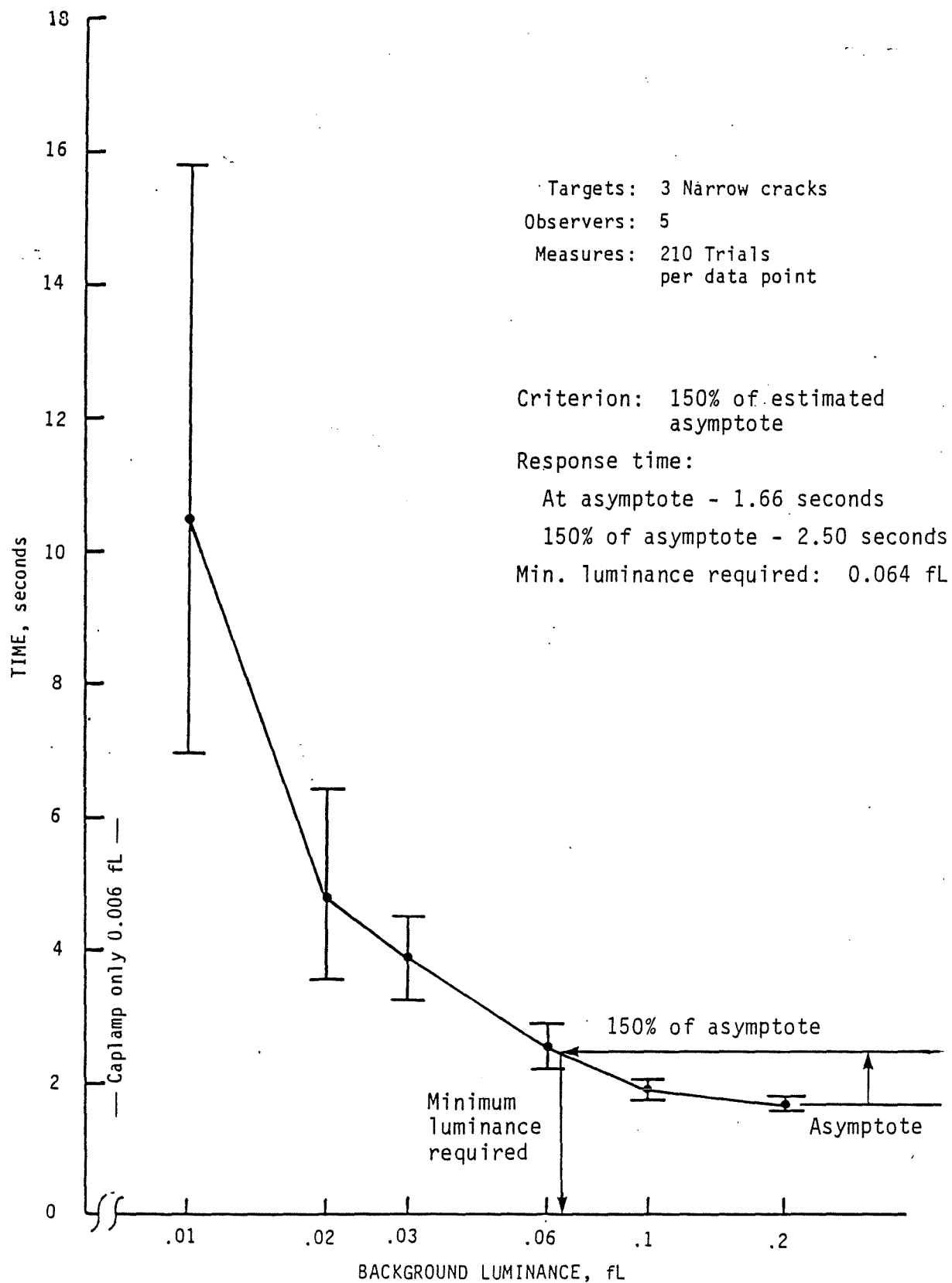


FIGURE 4-1. - Example of method used to identify minimum luminance recommendations from performance data.

asymptote. The response time at the highest luminance level tested (in this case, 0.2 fL) is taken as the best estimate of maximum performance. We then multiply the estimated asymptote response time (in this example, 1.66 seconds) by the criterion (1.5 or 150%) to obtain the minimum acceptable level of performance (2.50 seconds). The minimum luminance (0.064 fL) for that response time is then obtained from the performance data by linear interpolation.

Luminance requirements, obtained by application of these criteria, are listed in Table 4-1. The "target area" for the required luminance is described by taking the worker's caplamp (or machine operator's position) as a reference point for specifying the viewing distance and the angle off the central beam (or off the machine operator's central line of sight). The luminances specified are the minimum values for young workers (those under 40 years of age).

4.2 ADJUSTMENTS FOR AGE AND EYEWEAR

This section briefly reviews several approaches taken by other researchers to compensate for age and other factors that can affect minimum luminance requirements.

Hitchcock (1973) used a multiplier of about 4 to provide an additional safety margin beyond that already provided already by the criterion level of VL8. It was suggested that this combined criterion level of VL32.4 approximates a level of VL8 for 95 percent of a population with an average age of 60 years. Hitchcock notes that there is some "evidence that even this value may be too low" and that "there is some preliminary evidence that this assumption [that age corrections can be made simply by a single multiplying factor] may not be completely true; rather, a different reference function may be generated in each age group." Hopkinson and Collins (1970, p.77) suggest that it is "therefore probably meaningless to indicate in a code of lighting a factor by which the illumination should be multiplied in relation to the age of those working under it. Such a factor will vary according to the levels of visual performance to be expected from the older workers." Bodmann (1962) and CIE (1981) note that older subjects often do not match the performance of younger subjects even when illumination levels are increased by a factor of 20 or more. The authors of CIE (1981) note, however, that these results are obtained in experiments that may not realistically represent the way many older workers compensate for failing visual abilities through self-pacing on the task; they recommend "that no use be made of ... additional multiplier to help compensate for age under dynamic conditions] at the present time."

CIE Report 19/2, Volume I (1981) presents a set of equations for calculating the effects of age on various parameters in the mathematical

TABLE 4-1. - Minimum luminance recommendations derived from direct measurement of performance

Visual task	Geometric mean time			Luminance fL	Description of area to be illuminated to specified luminance
	Asymptote	1.5 x Asymptote	1.25 x Asymptote		
Cracks					
Wide	1.0546	1.5819	N.A.	0.029	Mid penumbra (12° off axis); 8 feet out.
Narrow	1.6648	2.4972		0.064	
Rock motion	0.3460	0.5/90	N.A.	---	Mid-penumbra (12° off axis); 8 feet out.
Time	N.A.	N.A.	N.A.	0.066	
Errors ^a					
Floor hazard ^b					
Near holes	0.9540	1.4310	N.A.	0.025	Far penumbra (22.5° off axis); 6 feet out
Far holes	1.4176	2.1264	N.A.	0.038	Near penumbra (9° off axis); 10 feet out
Near rubble	0.9474	1.4211	N.A.	0.019	Far penumbra (22.5° off axis); 6 feet out
Far rubble	0.8851	1.3277	N.A.	0.014	Near penumbra (9° off axis), 10 feet out
Floor hazard ^c					
Far holes	1.4176	N.A.	1.7720	0.050	Horizontal plane of floor 20 feet ahead of operator.
Far rubble	0.8851	N.A.	1.1064	0.024	
Peripheral Motion					
On foot	0.9501	1.4252	N.A.	0.0026	Very far penumbra (60° off axis); 12 feet out.
Mach. op.	0.9501	N.A.	1.1876	0.013	Vertical plane 60° to either side of operator, 20 feet out.

^a 5 percent error rate, errors are response times ≥ 0.06 seconds.

^b Worker on foot.

^c Mobile equipment operator.

N.A. Not applicable.

function that relates contrast threshold to luminance level (pages 55-57, 98-99). For a typical person without unusual ocular pathology, age 50-55 brings a reduction of about 50 percent in the amount of light that gets through to the retina (in agreement with the findings of Weale (1961) and Verriest (1971) for age 60).

This well-established photometric fact affects the minimum luminance required for any kind of task: if the amount of light reaching an older person's retina is only half (0.50 transmittance) that reaching a younger person's retina, the amount of illumination must be doubled for the older person to compensate simply in terms of retinal illuminance. In addition, there is a loss of about 8 percent (equal to 0.92 transmittance) even with clean eyewear, due to losses at the air/glass interface.

In the absence of a suitable age-compensation database directly relevant to the unusual visual task components in underground mining, we have chosen to adjust for age over 55 years by doubling the minimum luminance, as shown in Table 4-2. This is the basic approach taken in IES (1981) and in McCormick and Sanders (1982, p. 384-385). Note that in Table 4-2 a maximum luminance ratio (central beam to task area) is specified for each visual task.

Luminance ratio is the ratio of the luminance in the caplamp's central beam to the luminance in the specified task area (assuming surfaces with the same reflectance, at the same distance). If this ratio is exceeded (e.g., with a brighter central beam, as would result from simply increasing the overall output of a conventional caplamp in order to meet the target area requirements), visual performance will not meet the minimum performance criterion, due to increased glare and transient adaptation. Maximum luminance ratios have not been specified for machine-mounted luminaires. The broad beam pattern typical of those luminaires gives luminance ratios that are within the range recommended by the IES (1981) for industrial applications.

4.3 MINIMUM LUMINANCE RECOMMENDATIONS FOR MINING JOBS

Table 4-3 lists our recommendations of minimum luminance for 10 of the 19 critical visual task. These recommendations were derived from the performance data by application of criteria of adequate visual performance. Where more than one value was found for each performance measure (e.g., for narrow and wide cracks), the greater luminance is cited. Maximum luminance ratios are specified for the visual tasks performed under caplamp illumination. For example, if the ratio is 12:1, the luminance of the caplamp central beam falling on a surface of equivalent reflectance and distance should be no more than 12 times the luminance of the specified task area.

TABLE 4-2. - Age-adjusted minimum luminance recommendations

Visual task	Luminance, fL		Description of area to be illuminated to specified luminance	Maximum luminance ratio
	Age <40	Age >55		
Cracks Wide Narrow	0.029 0.064	0.058 0.13	Mid-penumbra (12° off axis); 8 feet out.	27:1 12:1
Rock Motion Time Errors ^a	--- 0.066	--- 0.13	Mid-penumbra (12° off axis); 8 feet out. Mid-penumbra (12° off axis); 8 feet out.	--- 12:1
Floor hazard ^b Near holes Far holes	0.025 0.038	0.050 0.076	Far penumbra (22.5° off axis); 6 feet out. Near penumbra (9° off axis); 10 feet out.	55:1 13:1
Near Rubble Far Rubble	0.019 0.014	0.038 0.028	Far penumbra (22.5° off axis); 6 feet out. Near penumbra (9° off axis); 10 feet out.	72:1 36:1
Floor hazard ^c Far holes Far rubble	0.050 0.024	0.10 0.048	Horizontal plane of floor 20 feet ahead of operator.	N.A. N.A.
Peripheral Motion on foot Mach. op.	0.0026 0.013	0.0052 0.025	Very far penumbra (60° off axis); 12 feet out. Vertical plane 60° to either side of operator, 20 feet out.	85:1 N.A.

^a5 percent error rate, errors are response times $\geq$ 0.6 seconds.

^bWorker on foot.

^cMobile equipment operations.

N.A. Not applicable for broad beam machine-mounted luminaires.

TABLE 4-3. - Minimum luminance recommendations for critical visual tasks

Rank	Visual task	Performance measures				
		Rock cracks	Rock motion	Floor hazards	Protrusions	Peripheral motion
1	Keystone effect	a	b			
2	Unsupported ground					
3	Slabs/protrusions					
4	Rock motion (chute)		b			
5	Cracks in rock	a				
6	Rib/back (tramming)					g
7	Condition of back	a				
8.5	Haulage way hazards			f		g
8.5	Pattern slips					
10	Rib/back (walking)	a			*	e
11	Oversize slabs					
12	Falling loose		b			e
13	Floor hazards			c,d		
14	Bootholes					
15	Vehicle clearance					
16	Escape path			c,d	*	e
17	Muck pile hazards					
28.5	Shaft guides					
28.5	Shaft timbers					

Caplamp only

^a0.13 fL; 12° off axis at 8 ft. Lum. ratio 12:1.

^b0.13 fL; 12° off axis at 8 ft. Lum. ratio 12:1.

^c0.076 fL; 9° off axis at 10 ft. Lum. ratio 13:1.

^d0.050 fL; 22.5° off axis at 6 ft. Lum. ratio 55:1.

^e0.0052 fL; 60° off axis at 12 ft. Lum. ratio 85:1.

*Caplamp penumbra adequate.

Tramming of mobile equipment

^f0.10 fL; floor 20 ft ahead of operator.

^g0.025 fL; vertical plane 60° to each side of operator, 20 ft out.

For reasons discussed in Appendix A, we were unable to derive specific minimum luminance requirements from the VTE measures of the remaining mine critical visual tasks. However, our research indicated that the associated visual targets are all more visible than cracks in rocks, which were measured extensively.

Table 4-4 shows the critical visual tasks and associated luminance requirements of each mining job, expressed in footlamberts (fL). As can be seen, requirements "a", "c", and "e" are common to 37 of the 43 mining jobs. These encompass all of the common caplamp-only jobs with the exception of shaft maintenance. Requirement "b" (rock motion detection) is also specified for two of the 37 jobs, but, since the luminance required for "b" is essentially equal to that required for crack detection ("a"), the difference is assumed to be insignificant.

The remaining caplamp-only mining job is shaft maintenance. The principal visual task is detection of defects (cracks, rot, wear, etc.) on the shaft guides, girders, and timbers. The job is performed at regularly scheduled intervals by a small number of underground workers. During the shaft inspection, the workers are secured to the top of the cage. As the cage slowly descends or ascends, the workers perform the inspection, typically by caplamp only.

The specialized nature of this visual task precluded development of a realistic simulation and extensive performance testing. We were also unable to obtain VTE measures of the visual targets involved. However, observations during mine visits under this project and previous work leads us to believe that the visual tasks associated with shaft maintenance are no more difficult than those associated with the other 37 caplamp only jobs. We suggest that those requirements be extended to cover shaft maintenance.

Thus, the minimum luminance requirements for the vast majority of mining jobs can be reduced to a single four-part recommendation:

- (a) 0.13 fL at 8 ft viewing distance, 12 degrees off-axis, maximum luminance ratio 12:1 (82 candlepower)
- (c) 0.076 fL at 10 ft viewing distance, 9 degrees off-axis, maximum luminance ratio 13:1 (76 candlepower)
- (d) 0.050 fL at 6 ft viewing distance, 22.5 degrees off-axis, maximum luminance ratio 55:1 (18 candlepower)
- (e) 0.0052 fL at 12 ft viewing distance, 60 degrees off-axis, maximum luminance ratio 85:1 (7.5 candlepower)

TABLE 4-4. - Minimum luminance recommendations for mining jobs

Rank	Visual task	Mining jobs																																																		
		Feedleg drilling	Raise boring	Jumbo drilling	Stoper drilling	Ring drilling	Rotary drilling	Rock bolting	Timber post erection	Gunite/shotcreting	Timberset assembly	Cribbing	Sandfilling	Prepare work area	LHD operation	Slusher operation	Overshot loader operation	Manual shoveling	Chute pulling/clearing raises	Train operation	Truck operation	Conveyor operation/maintenance	Tugger operation	Shaft maintenance	Machine maintenance	Roadway maintenance	Track maintenance	Pipe installation/repair	Ventilation installation/repair	Electrical installation/repair	Concrete construction	Steel construction	Timber construction	ANFO loading/blasting	Stick powder loading/blasting	Diamond drilling	Surveying	Sampling	Continuous miner operation	Manacge operation	Ore skip operation	Supervising/coordinating workforce	Safety inspection	Ore crusher operation								
1	Keystone effect													ab																																						
2	Unsupported ground																																																			
3	Slabs/protrusions																																																			
4	Rock motion (chute)																		b																																	
5	Cracks in rock													a																																						
6	Rib/back (tramming)														g					g	g						g																g									
7	Condition of back																																																			
8.5	Haulageway hazards														fg					fg	fg							fg																								
8.5	Pattern slips																																																			
10	Rib/back (walking)	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae		ae	ae	ae	ae		ae	ae		ae		ae	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae	ae													
11	Oversize slabs																																																			
12	Falling loose																																																			
13	Floor hazards	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd		cd	cd	cd	cd		cd	cd	cd	cd		cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd	cd
14	Bootholes																																																			
15	Vehicle clearance																																																			
16	Escape path	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde		cde	cde	cde	cde		cde	cde		cde		cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	cde	
17	Muck pile hazards																																																			
28.5	Shaft guides																																																			
28.5	Shaft timbers																																																			

Caplamp only

^a0.13 fL; 12° off axis at 8 ft. Lum. ratio 12:1.^d0.050 fL; 22.5° off axis at 6 ft. Lum. ratio 55:1.^b0.13 fL; 12° off axis at 8 ft. Lum. ratio 12:1.^e0.0052 fL; 60° off axis at 12 ft. Lum. ratio 85:1.^c0.076 fL; 9° off axis at 10 ft. Lum. ratio 13:1.

Tramming of mobile equipment

^f0.10 fL; floor 20 ft ahead of operator.^g0.025 fL; vertical plane 60° to each side of operator, 20 ft out.

These luminance values are relatively low; in most metal and nonmetal mines, they could be provided by an improved caplamp. Note: these values are for an end-of-shift caplamp. A freshly charged lamp could significantly exceed these values. Assuming a minimum reflectance of ten percent, required luminance (fL) can be converted into required illumination (footlamberts multiplied by 10 = footcandles). Required illumination can, in turn, be transformed to required candlepower by assuming a point-source relationship of distance and intensity (footcandles x distance squared = candlepower, as indicated in a, c, d, and e, listed above). Our study of the beam distributions of current caplamps indicates that this is a reasonable assumption for the unfocused penumbra.

Figure 4-2 shows an example of a possible beam distribution pattern for an improved caplamp incorporating these candlepower and luminance ratio recommendations. A program of further research to develop an optimal caplamp is discussed in Section 5. Note that the candlepower in the center of the beam is equal to that in the presently used caplamps, but the intensity in the penumbra (surround) does not fall off as sharply. In this pattern, the specified minimum luminances are provided without exceeding the maximum luminance ratios or reducing the central beam intensity.

The improved caplamp candlepower distribution shown represents end-of-shift minimum values (3.2 volts at the bulb). The distribution pattern of a typical existing caplamp is shown for comparison.

Referring again to Table 4-4, we see that the five remaining mining jobs entail operation of mobile equipment. These all share luminance requirements "f" and "g." The basic luminance recommendations for the seven mobile equipment jobs are:

- (f) 0.10 fL at a distance of 20 ft, in a horizontal plane on floor in front of operator (405 candlepower)
- (g) 0.025 fL at a distance of 20 ft, in a vertical plane 60 degrees to either side of the operator (102 candlepower)

Continuous miner operation requires the following additional recommendation:

- (a) 0.13 fL at a distance of 8 ft above and in front of the operator (82 candlepower)

The IES recognizes the importance of looking for ways to improve task visibility by enhancements in the task itself, rather than just specifying minimum illumination requirements for the task as it exists (IES, 1981, p. 3-21). It should be emphasized that the minimum luminance recommendations provided above are for the tasks and typical lighting

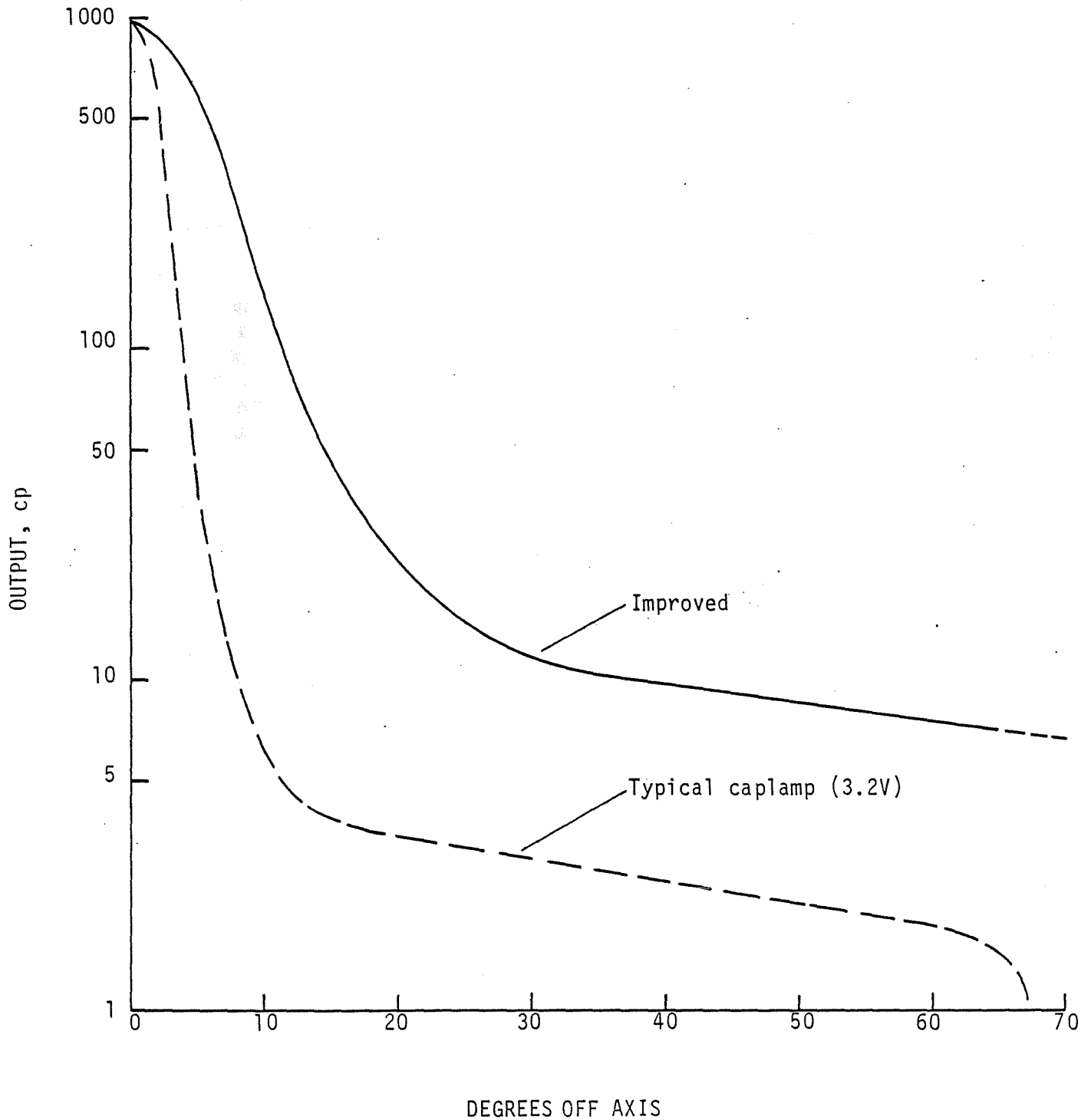


FIGURE 4-2. - Example of possible improved caplamp beam distribution (end-of-shift minimum).

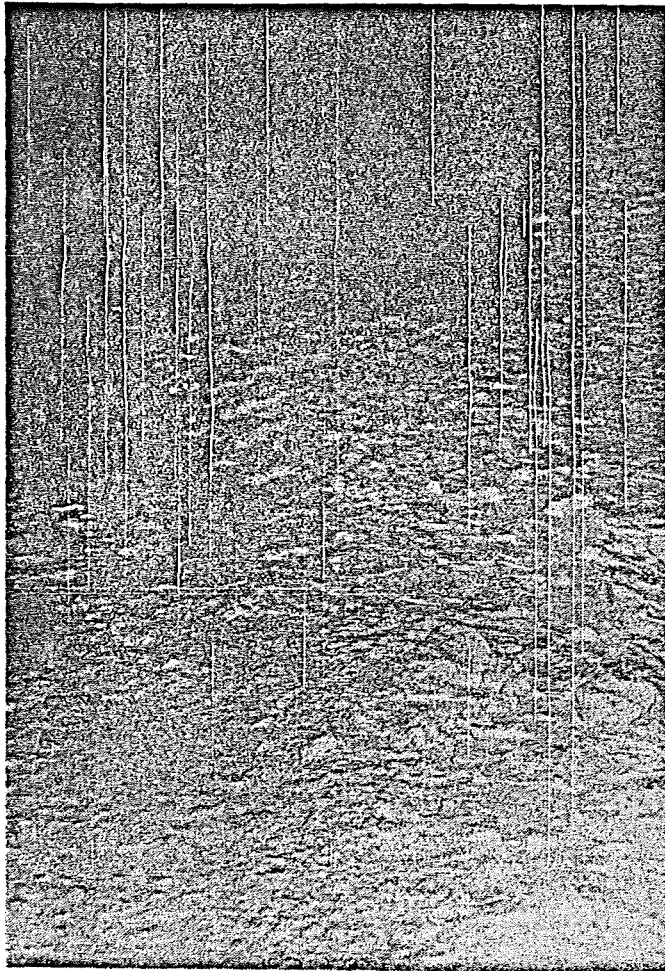
methods now in effect. It may be possible to greatly improve task visibility, and thus somewhat reduce the recommended minimum luminance values given above, through improved methods of lighting. These considerations are discussed below, and in our recommendations for further research (Section 5.0).

4.4 RECOMMENDED LIGHTING PRACTICES

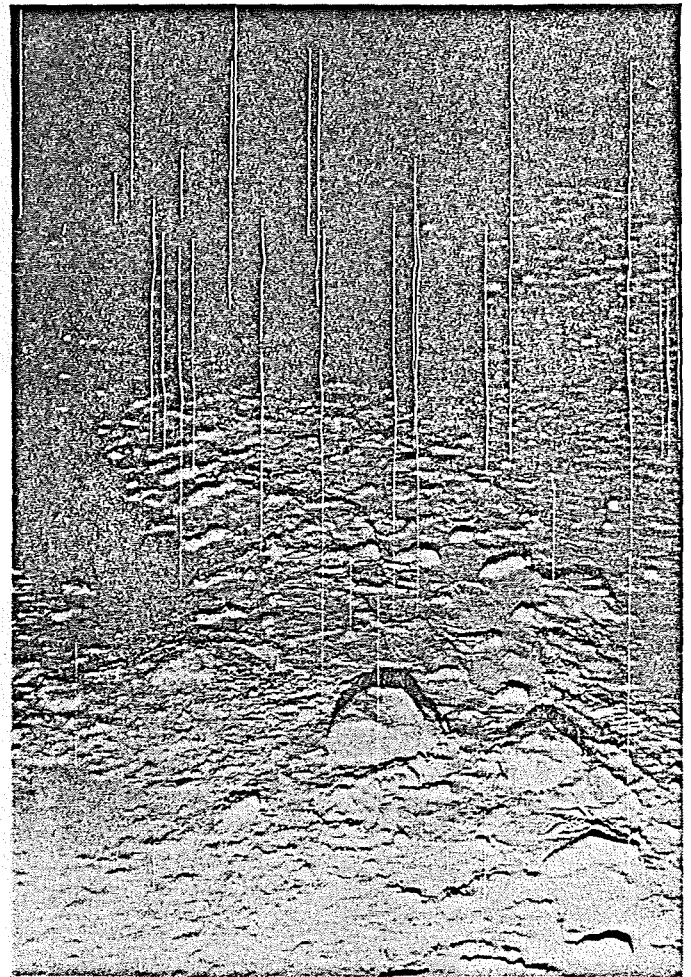
It is common knowledge that large improvements in visual performance can often be obtained by increasing the size or contrast of task details, as well as by increasing task illumination (Boyce, 1981, p. 107). In the mining environment, although task objects are typically quite large, contrast is often extremely low (as compared with features of the normal above-ground environment) due to uniform coatings of mud or rock dust. One way of significantly improving the visibility of low-contrast objects is with directional illumination that creates dark shadow outlines around objects (this is often called "shadow modeling"). The miner's caplamp, however, is usually located just over the eyes, and this source-target-eye lighting geometry can destroy the visibility of shadow cues for the wearer. By taking the caplamp off the cap and holding it below the eyes, the user can often greatly improve the visibility of hazards on the mine floor, especially when walking.

The effect of shadow modeling on the conspicuity of stumbling hazards in a haulageway can be seen in Figures 4-3a and 4-3b (see also Figures 2-13 and 2-14 illustrating the effect of shadow modeling in our laboratory simulation of floor hazards). In one photograph, the flash was held just over the camera lens to duplicate the lighting geometry of a caplamp mounted on the hardhat. In the corresponding photograph, the flash was held near waist level to duplicate the effect of holding the caplamp below the eyes, creating shadows that help outline hazards on the floor. In addition to improving the visibility of floor hazards through shadow modeling, holding the caplamp lower also significantly increases penumbra illumination on the nearby floor, due to the inverse square law. The shadow-modeling effect also applies to the caplamp's central spot, permitting easy visibility of the floor area 20 or 30 ft ahead; this look-ahead distance makes avoidance of stumbling hazards easy and natural, as in the above-ground environment. With the caplamp mounted on the hardhat, however, large rocks or other floor hazards can remain virtually invisible, even in the central spot, until the worker is just about to step on them. This tends to force the worker to look down at the nearby floor area when walking, potentially decreasing awareness of other hazards such as rib protrusions or low headings.

There is an additional, age-related problem to consider with respect to floor hazards, but this is one easily remedied by wearing appropriate eyeglasses. One of the older mine workers commented that it was difficult

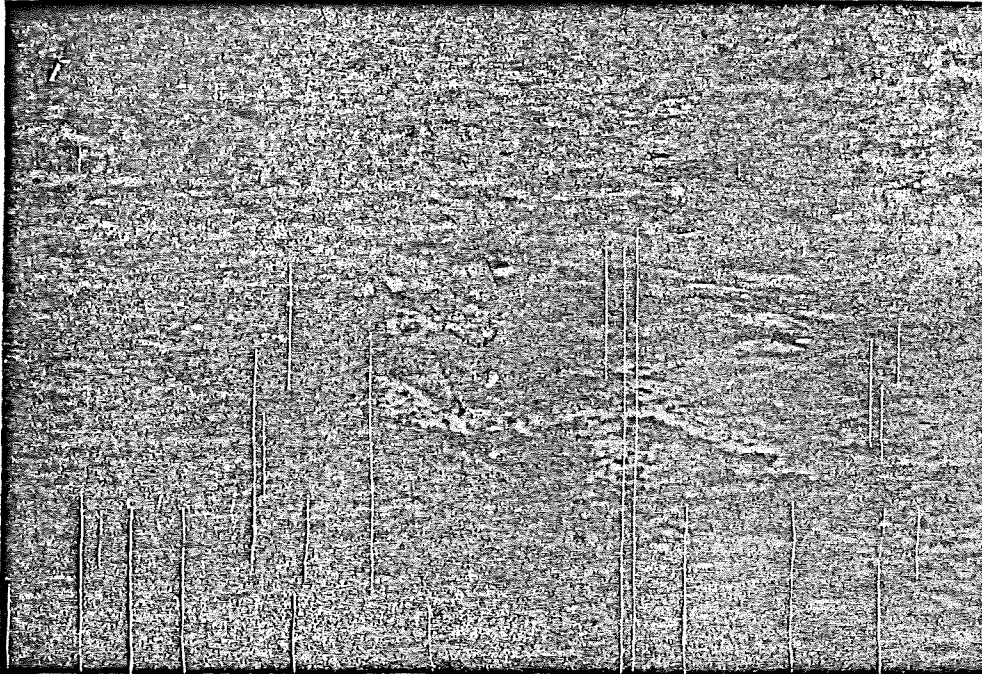


Ordinary caplamp geometry
(flash above eyes)

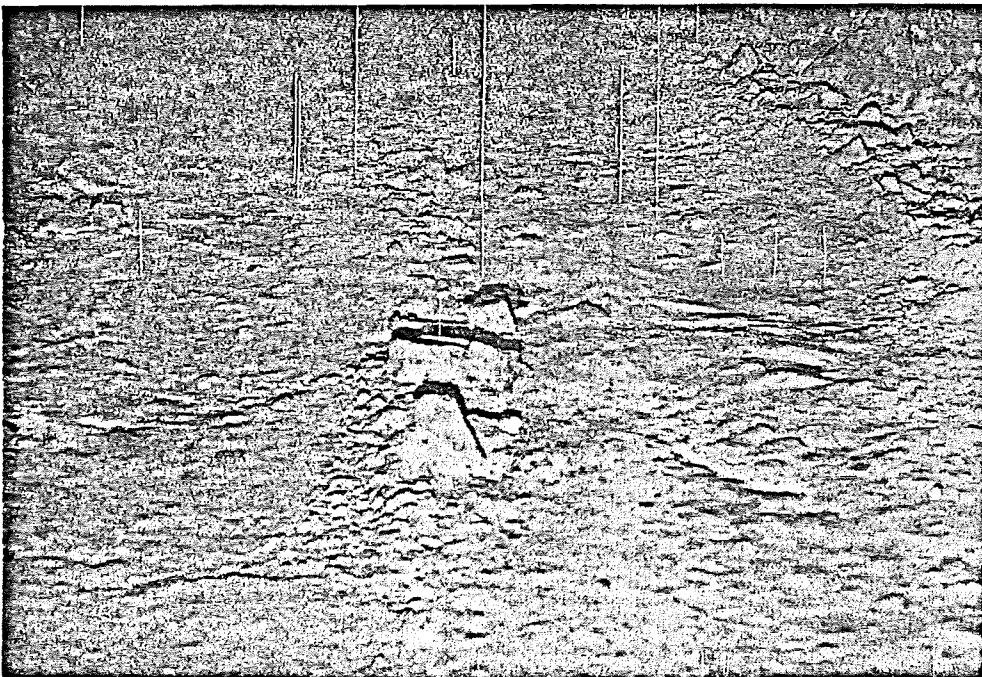


Flash hand-held at waist

FIGURE 4-3a. - Flash photographs showing the effects of lighting geometry on visibility of stumbling hazards.



Ordinary caplamp geometry (flash above eyes)



Flash hand-held at waist

FIGURE 4-3b. - Flash photographs showing the effects of lighting geometry on visibility of stumbling hazards

to see downward when walking because bifocals (or trifocals) throw the lower half of the visual field out of focus. In low luminance surroundings, with larger pupil size, the eye's depth of field (range of focus) is severely reduced. Given the very low contrast typical of most floor hazards (rubble, holes, hoses, etc., with caplamp mounted over the eyes), defocus blur created by bifocal correction for near vision can easily make objects invisible below the dividing line in the eyeglass lenses. What is particularly insidious in this situation is the impression that the mine worker can see well enough and that there are no hazards on what appears to be a smooth floor surface (again, refer to Figures 4-3a and 4-3b for examples of the way large stumbling hazards can be virtually invisible with normal caplamp lighting geometry). One way to alleviate this problem would be for older mine workers to wear single-vision glasses rather than bifocals, except when performing certain near-vision tasks (such as machine maintenance, reading meters, etc.). Most mining jobs do not require near acuity (Crooks et al., 1980), so for many workers this may be a simple solution to a difficult problem.

4.4.1 Use of Caplamp. When walking or inspecting in the case where one hand is free to hold the caplamp, the visibility of certain types of task objects or hazards can be greatly enhanced by shadow modeling. In addition, the speed and ease of scanning with the caplamp spot improves when it is hand-held, since the hand is quicker than the head, better matching the speed of the eyes in glancing about.

Many of the hazards that must be visually detected in the underground mining environment are relatively large, but of very low luminance contrast due to uniform coatings of mud and dust; it is as if everything has been painted with the same flat gray paint. Compounding the problem of low contrast is the decreased contrast sensitivity of the human visual system at low luminance levels, and the optical contrast reduction that can occur with dirty eyewear or backscatter from dust or fog. As previously noted, there are relatively large objects (such as rocks on the surface of a haulageway in Figures 4-3a and 4-3b) that would be virtually invisible with the caplamp mounted on the hardhat; with the caplamp held below the eyes, however, hazards can often be made easily visible even in the dim penumbra with peripheral vision.

In first inspecting an area before beginning work, the shadow modeling created by hand-holding the caplamp may make it easier to locate any floor hazards that may exist; scanning with a hand-held caplamp may help in detecting loose rock and other hazards that should be removed or avoided. In our site visits to measure the visibility of rock cracks in underground mines, both authors often observed that a rock crack would be highly visible when illuminated by a co-worker's caplamp or by equipment lights, but would nearly disappear when his own caplamp spot fell on the target. This is because the rock crack was no longer clearly defined by

shadow when the light source was right next to the observer's eyes. This would suggest that the "worksite preparation" task may in many cases be better done with a hand-held caplamp (whenever one hand is free, of course).

4.4.2 Machine-Mounted Luminaires. Machine-mounted lighting systems are much less restricted in weight, size, and electrical power, compared with the caplamp. This makes it possible to take advantage of several principles of good lighting in providing ample light to supplement the mine worker's individual caplamp. Because the machine lights are not located along the line of sight, beneficial shadow modeling is a natural consequence of the lighting geometry (floor contours and hazards are rendered easily visible). Light sources should be shielded from direct view, unless they are low-luminance, large-area devices.

One inexpensive and very effective way of creating a large-area low-luminance source is with indirect lighting techniques. In this method, machine-mounted lights are directed upwards (fully shielded from side view and protected from damage by falling objects) to illuminate a broad area of the surface overhead; the lighted surface then becomes a low-glare source illuminating the work area.

One common type of accident involves floor hazards when stepping down from a piece of equipment. The machine operator often does not notice a large rock or other object on the mine floor next to the machine, and is injured when stepping or jumping down onto this unexpected object. As previously shown in Figures 4-3a and 4-3b, the lack of shadow modeling in caplamp lighting geometry can make even fairly large rocks invisible, especially in the dimmer illumination of the caplamp penumbra; further compounding this problem, the typical machine operator has lost some dark adaptation due to looking at the work area brightly illuminated by the machine lights. A related problem is the dark floor area beside and behind the machine (behind a jumbo drill, for example) where light-adapted workers may stumble over objects on the floor (hoses, cables, drill steel, rocks, etc.) when walking in the area next to the machine. Two relatively simple and inexpensive solutions could alleviate these problems:

- (1) Provide recessed lights around the skirt of the machine at the sides and rear, especially near step-down points.
- (2) Provide low-level ambient illumination of the area around the machine by indirect lighting of the back.

The use of recessed skirt-lighting (similar to that along the aisles of a theatre) at the sides and in the normally dark area behind the machine would create excellent shadow modeling of floor hazards, due to

the grazing angle of the illumination. Since the light sources should be deeply recessed to avoid creating glare for the workers, they would be inherently protected from damage and should require little maintenance. We recommend that skirt lighting be provided, at least at the step-down points of a machine, even when indirect overhead lighting is used, since a worker stepping down would tend to block overhead illumination on the floor area directly below.

In general, machine lighting should be designed so that workers can maintain adequate dark-adaptation for working with caplamp illumination away from the machine. In addition to the higher intensity illumination focused on the production task, thought should be given to providing wide-area low-level "ambient" illumination for continual "environmental awareness" of the workspace layout, including hazards in the area and the best escape routes.

4.4.3 Portable/Fixed Luminaires. In locations where supplementary illumination can be provided by permanently installed luminaires, the same principles discussed above can improve visibility without creating adverse glare and loss of dark adaptation. Even though indirect lighting methods can result in lower illumination falling on the target itself, the net effect can be better due to the absence of glare and maintenance of light levels that work with, rather than against, caplamp illumination. For example, fixed lighting can be created by a number of shielded lights along the rib, below eye level, so as to eliminate glare and to create excellent shadow definition of the floor area. Similar lights along the rib can be mounted just above eye level, to provide glare-less illumination of the back, which then in turn indirectly illuminates the work area.

In most of the underground mines we visited, fixed luminaires were often directly visible to the eye, creating adverse glare and, in many instances, actually reducing visibility below that of a fully dark-adapted worker using only a caplamp. Well-shielded fixed illumination, designed to work in conjunction with the caplamp, is not only beneficial for safety, but also for visual comfort and acceptance by workers (who have sometimes been known to eliminate particularly adverse glare sources with a rap wrench).

Indirect lighting methods, as mentioned above in the discussion of machine lighting, can be very effective for converting a small-area high-intensity source (such as a mercury vapor lamp) into a large-area low-luminance secondary source. Further, the effective location of the source can be on a surface normally not practical for attaching light fixtures (in a low-back haulageway, for example), while the actual location is lower and out of the way (as well as convenient for maintenance). Indirect lighting for industrial or office work normally requires a high reflectance in the ceiling for acceptable efficiency,

since office illumination standards are relatively high due to the types of fine-acuity tasks involved. Even with the lower reflectance of surfaces in metal and nonmetal mines, however, indirect lighting methods can provide excellent illumination to supplement the dim caplamp penumbra for overall environmental awareness in the underground work area.

In our mine illumination laboratory, we used low-level indirect lighting in the large simulated underground workspace to maintain the dark-adaptation level of our experimental observers; this low, even "ambient illumination" made it much easier for the researchers to move around in the large simulated opening. The entire work area was adequately illuminated by a single 100 watt incandescent bulb in a bowl-reflector above eye-level, pointed up at the center of the simulated back. The surfaces in the simulated large opening had an average reflectance of only 10 and 15 percent (see Section 2.4.1), but for the low-acuity requirements of environmental awareness this was more than sufficient for maintaining good sense of orientation in the workspace and keeping us from walking into the many pieces of experimental apparatus throughout the 15 by 42 ft area. Our informal test of indirect lighting, by using it in our laboratory work area for about a year, suggests that it should be thoroughly tested for possible applications in many areas of underground mining.

Portable lighting systems are limited in weight, size, power, and installation location, but the same general considerations apply as for machine lighting and fixed lighting. In summary,

- (1) The source should not be visible, to eliminate glare and adaptation problems.
- (2) Our experience showed that indirect lighting methods (using reflected light) can be very effective for general environmental awareness, even with the low reflectances found in some mines.
- (3) Supplementary lighting should work with, rather than against, caplamp illumination (as discussed above).

4.4.4 Conspicuity Enhancement. If the underground worker's ability to detect and recognize hazards can be enhanced, it follows that the safety of the workers will be increased. This goal may be pursued in a variety of ways. The principal approach employed in our research program has been to identify improvements in the amount of illumination required. Another approach is to increase the luminance contrast of the hazard. Applying retroreflective surface treatments or affixing retroreflectors on or near the hazard offers a substantial increase in detectability, especially given the low levels of illumination available. This approach is feasible

for hazards that are relatively permanent and have a known location. For example, retroreflective materials may be applied to machinery, pinch points on machines, protrusions from the back, ribs, or floor, cables and pipes, low points at the back, etc. Retroreflective materials may also be affixed to apparel to increase the conspicuity of the underground worker (Beith, Sanders and Peay, 1982). Other hazards occurring at irregular intervals or at variable locations are not amenable to this approach.

Excessive or inappropriate use of retroreflective materials could cause confusion and actually interfere with the detection of hazards. Guidelines for their use should therefore be developed and evaluated in an operational test in one or more mines. A research plan to accomplish this is recommended in Perry, Schwalm, and Crooks (1981).

4.5 ANTICIPATED PROBLEMS IN IMPLEMENTING MINIMUM LUMINANCE RECOMMENDATIONS

We are fortunate to have had the benefit of several years experience of compliance with minimal luminance requirements in underground coal mining. This history allowed prior identification of two major potential problem areas for any underground lighting program.

The greatest problem in terms of safety and worker acceptance is glare. In some cases, as many as 12 luminaires per machine were required to meet the coal illumination regulation. Direct glare from the luminaires has been a problem, especially when the operator must leave his usual position. James Bell, in the Mining Congress Journal (October, 1979), reported that "many workers feel that the lights create a slight safety hazard in that they create a glare problem," and that most coal "operators do not agree with the federal government's contention that the illumination of face equipment will provide a safer working area."

The second problem is that the brightness of the luminaires causes a "temporary blindness" each time the worker turns away from the machine. This transient adaptation problem means that workers must wait for their eyes to adapt to the lower level of illumination provided by the caplamp after having looked at an area of high luminance.

Our approach to these potential problems was tripartite. First, because glare and "temporary blindness" are known to significantly reduce visual performance and characteristic of the illumination environment, we choose to include realistic lighting conditions in the visual task simulations. The luminance levels we have recommended are appropriate for the commonly occurring, more difficult conditions found in underground work.

The second approach is the use of lighting practices that enhance task visibility and reduce glare. Recommended lighting practices were discussed in Section 4.4. However, certain aspects of these problems will require a limited program of additional research to:

- (1) Identify systematically the factors of lamp design and utilization that affect task performance and safety of underground workers.
- (2) Use the data from these systematic studies to develop improved caplamps and supplementary lighting systems.
- (3) Demonstrate the advantages of these improved lighting systems in operating underground mines.

Our recommendations for such a research and development program are described in Section 5.

Drawing on our earlier work (Crooks, et al., 1980) in planning the study, we also anticipated other difficulties that are unique to the metal and nonmetal industry. These difficulties are, in most instances, a consequence of the variability of the industry. Aspects of the variability that we anticipated would cause the greatest problems included variance in:

- (1) Work performed in the industry.
- (2) Work performed at any work site.
- (3) Size and configuration of mine machinery.
- (4) Reflectance of mine surfaces.
- (5) Size of the work site.

The variability found in metal and nonmetal mining could suggest that a unique standard might be required for each case. This, of course, is not practical and, as we found empirically, not necessary. In fact, we found that the safety illumination requirements of the 38 unit operations typically performed by caplamp only can be met by improvements in the caplamp output and beam distribution. The remaining five unit operations all involve operation of mobile equipment and have equivalent luminance requirements. These two general luminance recommendations satisfy the safety illumination needs of underground work.

While the variance in reflectance of underground surfaces is considerable, it is, in fact, no greater than that found in the coal mining industry. [Hitchcock (1973) found reflectances ranging from 1 to 20 percent or a 20:1 ratio.] Crooks, et al. (1980) found three-fourths of underground work sites had reflectances of 10 to 30 percent. Thus, the assumption of a single, lower-bound reflectance, i.e., 10%, is a reasonable simplifying assumption. This assumption then allows specification of minimum luminaire outputs for the entire industry.

5. RECOMMENDATIONS FOR FURTHER RESEARCH

Minimum task luminance is only one aspect of lighting in underground mining. Additional lighting factors, such as the distribution of illumination and the relative positions of workers and light sources, also have significant impacts on workers' ability to perform tasks adequately and safely. These additional lighting factors have important implications for the design and use of caplamps and other illumination systems in the underground mining environment.

We strongly recommend a continued research program to determine quantitatively how variations in lamp design and lighting methods can affect the performance of mining tasks critical to safety.

Observations and informal studies conducted during the current study of minimum task luminance have demonstrated the importance of three additional major factors in lamp design and utilization, namely:

- (1) The pattern or distribution of illumination produced by the specific lamp design.
- (2) The geometry between workers, tasks, and light sources.
- (3) Glare and adaptation consequences that would result from a general implementation of recommended changes in current lighting methods.

Although some improvements in the design and utilization of underground lamps could most certainly be made on an ad hoc basis, initial observations and informal studies indicate that definitive improvements can be made only on the basis of systematically studying the full range of lamp design and utilization factors that affect worker performance. Such systematic studies will provide the data from which design optimizations and trade-off decisions can be made and justified.

A central focus of the recommended research program is to measure directly the effects of lamp design factors on task performance. The direct measurement of worker performance as a function of changes in illumination parameters represents a significant addition to the state-of-the-art in mine illumination engineering. This approach is made possible by performance measurement methods and equipment developed during the current research program to determine minimum task luminance.

These direct measurement methods are based on precise laboratory control of simulated mining tasks that are performed in a full-scale simulated underground mine workspace. Highly realistic simulations of mining tasks that are critical to safety allow precise quantification of task performance, while the simulated mine workspace allows precise control and variation of the illumination factors that are being studied. In the present study of minimum task luminance observers performed simulated mining tasks under different luminance levels. A database of over 13,000 performance measures, representing many repetitions at each luminance level, was obtained for existing caplamp design and commonly used underground lighting methods. Additional experimental work is essential for determining how variations in caplamp design and lighting methods would affect visual performance in safety-critical mining tasks.

We recommend that a three-phase program of research and development be undertaken, encompassing the following elements:

Phase I: Studies of Lighting Factors. Systematic studies should be conducted during this phase to determine the performance effects of (1) lamp beam pattern, (2) lighting geometry, and (3) glare and adaptation considerations. These studies should be parametric analyses designed to examine the full range of each variable. In addition to determining the direct performance effects of each of the three major variables, the studies should also determine the interactions among these variables and the overall levels of task luminance. The studies should be conducted using a full-scale simulated mine workspace and dynamic simulations of safety-critical mining tasks. A VTE device should be used to collect relative measures of task visibility (VL) in operating underground mines and in the laboratory, so as to produce a coordinated VL/performance data base specifically for mining tasks.

The product of these studies should be a comprehensive data base and an analysis of the entire range of task luminances, beam patterns, lighting geometries, and glare and adaptation considerations. These data should provide a solid basis for the subsequent development of improved caplamps and other supplementary underground lighting systems.

Phase II: Specification and Development of Improved Underground Lamps. Using the data obtained during Phase I, design specifications should be developed for an improved caplamp and for improved methods of secondary underground lighting. Then, working with the research and development staff of a caplamp manufacturer, prototype caplamps should be developed and tested in a mine simulation laboratory to obtain performance data on the critical visual tasks. This process of prototype development and subsequent performance analysis in a mine

illumination laboratory should be continued iteratively, leading to the final design of an improved caplamp and improved supplementary underground lighting methods.

Phase III: Technology Transfer. The final phase of the program should be devoted to evaluating and demonstrating the improved caplamp and supplementary lighting methods in operating underground mines. This field testing should ensure that any problems with the equipment or the lighting concepts can be fully corrected before final recommendations are reported to the mining industry. The field demonstration should also serve as the basis for cost/benefit analyses that should be performed to demonstrate the feasibility of using the improved lighting systems.

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APPENDIX A

USE OF TASK VISIBILITY DATA OBTAINED
WITH A CONTRAST-REDUCING VISIBILITY METER

A.1 BACKGROUND

It was pointed out in the main body of this report that Hitchcock's 1973 study of illumination requirements for coal mining involved measures of task visibility obtained with the Blackwell Model III Visual Task Evaluator (VTE). Correction or adjustment factors were used to increase visibility thresholds obtained in the laboratory to what were considered suitable "suprathreshold levels"; from these suprathreshold levels, luminance requirements were derived by reference to a basic visual science database that related luminance to visual sensitivity.

This procedure was widely used by lighting specialists in the USA from 1959 up until 1981. It was then considered to be the best available approach, in part because of the unavailability of task performance data necessary for a direct link between visibility measures and predicted task performance. CIE Report No. 19/2 (1981) has altered this picture considerably.

In any case, it must be recognized that the method was limited by the lack of a database that could be used to predict losses or gains in task performance as a function of luminance levels slightly higher or lower than the values derived from the criterion suprathreshold-level procedure. Whereas CIE Report No. 19 (1972) was based entirely on task visibility data, CIE Report No. 19/2 (1981) represents the combined use of task visibility data and task performance data. Task visibility measures, obtained with an VTE, represent the most practical and feasible methodology for establishing relative visibility, either for different tasks, different levels of luminance, differing lighting geometries and luminance ratios, or different individuals. However, the performance implications of a given level of task visibility can be shown only when corresponding task performance data are available for differing levels of task visibility. Then and only then can the data be used to define levels of luminance for different application areas. Report No. 19/2 demonstrates the use of combined task visibility and task performance data, with 18 of the sets of "visual work data" obtained for conditions of interior lighting and two data sets obtained under conditions of outdoor road lighting.

Significantly, no task performance data were available for mine lighting at the time the present project was initiated. It was primarily for this reason that the decision was made to concentrate on obtaining task performance data. However, it was also decided to investigate the value of coordinated measurements of task visibility and task performance, as has been done.

The results confirm the wisdom of the original decision to rely primarily on a methodology that directly measured task performance as a function of differing luminance levels. However, as will be shown, good use was made of the task visibility methodology in comparing task difficulty of simulated mining tasks in the laboratory with the difficulty of the corresponding tasks in actual underground mines. The following sections of this Appendix report details of the equipment and methods used to obtain task visibility measures, the results obtained; general conclusions regarding the future use of coordinated measures of task visibility and task performance are presented at the conclusion of this Appendix.

A.2 MEASUREMENT EQUIPMENT AND PROCEDURES

As compared with direct methods, where actual performance on a real or simulated visual task is measured as a function of lighting parameters such as luminance level or geometry of sources, indirect methods attempt to use well-established data about human visual response to simple targets in order to predict human visual performance in more complex real-world tasks. The advantage of this approach is that the visual difficulty of task elements can be assessed without the time and expense of direct performance measurement under varied lighting conditions. One disadvantage with indirect methods is that the transfer functions relating real-world tasks to the fundamental visual database (obtained by extensive direct performance testing with simple visual target elements) must first be established for targets of that general type.

In addition to direct measures of visual task performance as a function of target luminance, as described in Sections 2.4 and 3.1 of the main body of this report, it was possible to obtain relative measures of the visual difficulty of tasks with a portable Visual Task Evaluator (VTE Model 5) designed by Dr. H. R. Blackwell. Among the many references that provide detailed descriptions of various devices and methods using contrast reduction as a measure of visual difficulty are Blackwell (1959), Blackwell (1970), IES (1972), CIE (1972 and 1981), and Boyce (1981).

A.2.1 Theory of Operation of the VTE. The VTE is an optical device that permits an observer to vary the visual contrast of objects seen through the instrument. By fading out the luminance of a scene while reciprocally fading in a uniform veiling luminance, target details can be reduced to contrast threshold, as if just barely visible through an intervening fog or mist.

The proportion of original contrast that gets through the optics

of the VTE is the "contrast transmittance" (CT) of the instrument. This is continuously variable from nearly 100 percent to nearly zero percent, while keeping the general level of background luminance constant. This is achieved by two sets of filters arranged so that a reduction in the transmittance (t) of the target image channel is reciprocally matched by an increase in the transmittance (1-t) of the veiling luminance channel. A control knob on the side of the portable VTE provides smooth variation in contrast transmittance over a very large range, from clear visibility to near-zero visibility.

The visibility (visual ease or difficulty) of a given target object can be quantified in terms of how much optical fog it takes to make it fade away: a highly visible object will require more "fogging" to reduce it to contrast threshold, whereas a less visible object will disappear with only a moderate amount of contrast reduction.

If a given target object reaches threshold when the VTE's contrast transmittance is turned down to a level of 0.25, then the object must be inherently 4 times above its threshold (since it was reduced to being just barely visible when its contrast was cut to a quarter of its original value). An object that is 4 times above its threshold is said to have a "visibility level" (VL) of 4; an object that reaches the threshold of visibility at a VTE contrast transmittance of 0.10 has a VL of 10.

A measure of relative visibility for objects is thus obtained by mathematically inverting the contrast transmittance (VTE setting) that reduces an object to being just barely visible. If an object is just barely visible at a contrast transmittance (CT) of 0.5, then it must be inherently 2 times above its threshold ($1/0.5 = 2$), a "visibility level" (VL) of 2. Thus, VL is a measure of suprathreshold (above threshold) visibility. The further a visual target is above its threshold, the more resistant it is to being rendered invisible by fog, haze, low luminance levels, scratched or dirty eyeglasses, and other such image-degrading factors. In addition, suprathreshold visibility will, up to a point, improve performance for most tasks with significant visual components.

A visual target or object with a VL of 17, for example, could have its apparent contrast reduced (by intervening fog, defocus blur, off-axis viewing, dim illumination, or other such factors) to only 1/17th of its original value and still be visible, whereas an object with a VL of 13 would be reduced below visual threshold under the same conditions. While it is difficult to specify how visual task performance at VL 16 will compare with performance at VL 20, the advantage of providing higher VL's in the underground mining environment is the greater resistance of visual tasks to being reduced

below visual threshold.

A.2.2 Limitations of the VTE Method for Underground Mining. The presently available equipment and methods based on the VTE principle were developed primarily to assess illumination requirements for industrial and interior office tasks, not the relatively low-acuity, low-luminance tasks involved in underground mining. Blackwell (1970, p. 287) points out that "there are situations in which the cues received through binocular vision will have important effects on task difficulty. These situations may also involve moving tasks or tasks which are large in angular size. Such situations seem to demand a VTE of radically different properties."

The underground mining tasks studied in the present research program involve relatively large fields of view and binocular vision. The Visual Task Evaluator Model 5 used here was the best device available for the job, but it had, with respect to the target items, a fairly narrow field of view (about 6 inches at 6 feet) and was a monocular instrument with a light transmittance of only about 7 percent. As a result of experience with VTE Model 5 in the underground environment, specifications are being evolved for a VTE specifically designed to assess visual tasks in underground mining. Ideally, such an instrument would be light, portable, compact and have about a 30 degree binocular field of view with relatively high light transmittance. It will be extremely difficult to obtain both a compact, portable design along with a wide binocular field of view and good light transmittance due to certain engineering problems that will not be discussed here.

As noted in the main body of this report, Hitchcock (1973) describes the use of a VTE for assessing illumination requirements in underground coal mining. He notes that in "reviewing relevant literature, it becomes apparent that the Visual Task Evaluator was expressly designed to evaluate the visibility of small objects and that the repeatability and meaning of the measurements are adversely affected by large tasks that occupy a significant portion of the instrument field..." (page 28). He further suggests that another "confounding issue is...the difference in contrast sensitivity between objects subtending four minutes of arc and those 2 to 6 degrees. The increase in contrast required to detect these large targets at low light levels is proportionately less than the increase in contrast necessary to detect targets subtending 3 to 4 minutes of arc."

Although nearly all the targets measured in the present study occupied a significant portion of the instrument field, the trained VTE operator was able to select some portion of the border between a target object and its background to obtain a measure of visual contrast threshold for that section of the object. These measures

were repeatable and consistent, but did not fully assess the visibility of the whole object (such as a rock crack 3 or 4 times longer, or a rock several times larger, than the VTE's field of view) as it is normally seen. For example, a dust-covered rock the size of a football could pose a significant stumbling hazard on the mine floor (due to its very low contrast with the background, and the lack of shadow modeling produced by the caplamp's positioning just above the eyes); this rock, however, could not be seen as a whole object in the VTE's 6-inch field of view at a distance of 6 feet. In addition to problems with field of view, the 7 percent light transmittance presented a minor problem in that a special auxiliary light had to be provided for VTE operation in the underground workspaces. With the auxiliary source, a typical level of background luminance as seen through the VTE was about 0.375 fL at a distance of 8 feet. The luminance levels at which VTE readings were taken varied with target distance, from about 0.75 fL at 6 ft, to about 0.14 fL at 12 feet. The skilled operator's contrast threshold was calibrated using standard targets over this range of VTE eyepiece luminance.

A.2.3 VTE Measurements of Laboratory Tasks and In-Mine Tasks.

Relative visibility levels (VL is an index of how easy it is to see a given pattern or object) were obtained with the Blackwell VTE Model 5 in two large underground mines and in the Perceptronics Mine Illumination Laboratory. By measuring the relative visual difficulty (VTE readings of VL) of rock cracks both in our simulated mine task and in actual underground mines, it was possible to determine how well our lab tasks matched those found in operating mines.

In addition to determining the representativeness of our mine-lab task simulations, a second objective in the VTE field measurements was to obtain VL data for certain mining tasks that were not tested by direct performance measurement in our lab.

To provide a comparison between laboratory tasks and actual underground tasks, VTE readings were obtained for rock cracks, slipped rock bolts, holes and rubble on the floor, protruding hazards (pipe, drill steel), muck pile hazards, and so on. In the case of "rock motion", "pattern slips", and "boot holes" comparative lab and mine data were not obtained (see list below).

In-mine measures were obtained during a two-day site visit to a large underground copper mine and two-day site visit to a large underground zinc mine. The numbers of VTE readings obtained for each type of visual task were as follows: 12 rock crack measures in lab, 9 in mines; 6 rock motion measures in lab; 6 rib and back protrusions in lab, 2 in mines; 5 floor hazards in lab, 14 in mines; 1 muck pile hazard in lab, 4 in mines; 2 pattern-slip measures in mines; 4 boot hole measures in mines. In total, 30 visual task items were measured

with the VTE in the lab's simulated mine workspace, and readings of 35 visual task items were obtained at approximately the 2400 ft level in the two operating mines.

A.2.4 Equipment and Procedures for VTE Data Collection. Equipment for in-mine collection of VTE data included the VTE itself, a light-weight photographic tripod, a 12-volt diffused spotlight with small rechargeable lead-acid battery pack, a tape measure, 35-mm camera with wide-latitude black & white film, waterproof backpacks, data-recording forms, footcandle meter, and a reflectance grayscale.

Upon arriving at the mine headquarters, the two researchers discussed data-collection objectives with the mine superintendent and foreman to identify suitable underground sites where a number of targets could be obtained with each setup.

The equipment was transported underground in backpacks, the VTE wrapped in protective foam rubber. At a given target site underground, the VTE was unwrapped and placed on the tripod. Figure A-1 shows the equipment set up for measuring rock cracks in the rib (sidewall) at the 2400 ft level of the large underground mine, near a rotary drilling site. Specific targets were selected for measurement in consultation with the mine personnel accompanying our team. As an example, mine personnel assisted us in finding rock cracks that were typical or generic (in some cases, the cracks discovered in assisting us revealed possibly dangerous loose rock that was barred down after our measurements were completed).

On one occasion, the VTE's lenses and internal optical surfaces fogged up when it was first removed from the backpack for setup. (The VTE was initially colder due to overnight storage in the car's trunk, and the warm humid air at the underground worksite that morning penetrated the case of the VTE.) With the case opened up, the 12-volt auxiliary light was used as a heat-lamp to defog the optics; after that, care was taken to keep the VTE at room temperature overnight. It could be recommended that a VTE designed explicitly for studying underground mine illumination should be fully sealed (with a filtered pressure-relief port) to prevent the entry of dust and moisture.

The VTE was pointed at the target object and the tripod was locked in position for repeated measurements. The 12-volt diffused spotlight was hand-held resting on top of the VTE, at the front, to duplicate the lighting geometry typical of caplamp use (the light source right above the eye, or "camera"). Distance was measured from the VTE's input lenses to the target, and illuminance from the spotlight was measured at the target position using the illuminance meter. A simple sketch of the target layout was drawn in the

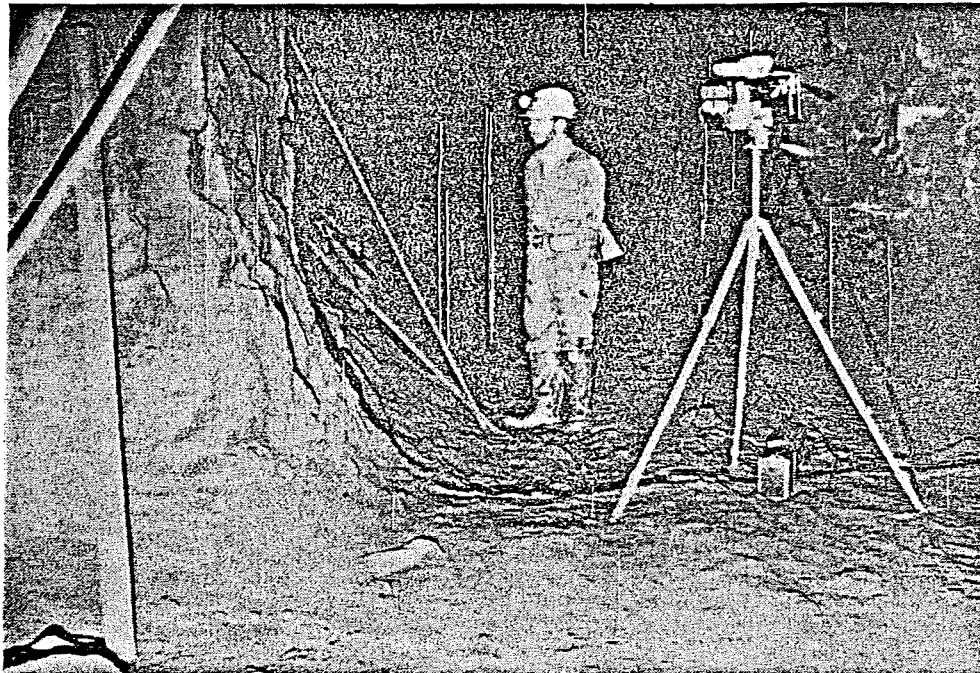


FIGURE A-1. - Setup of VTE in underground mine.

data-recording notebook forms, noting the distance, illuminance, and VTE readings. The 35-mm camera was used to document each of the targets on special wide-latitude B&W film. For certain targets, a gray-scale was included in the scene so that reflectances could be determined if necessary.

A.2.5 Details of Equipment. The VTE used in the present study was designed and constructed in 1982 by Professor H. R. Blackwell. It differs from previous VTE devices in that it obtains veiling light from the scene itself rather than from an illumination source inside the instrument. This has two advantages: first, the veiling luminance is more likely to be close in color to the scene background luminance; second, the instrument can be operated without electrical power. Of course, electrical lighting of some type is necessary for use in underground mines, but the VTE itself can be operated without power in a static mode (continuous viewing rather than 1/5 sec shuttering).

The VTE we used is a monocular instrument with nearly unity magnification (things seen through the instrument are slightly larger than when viewed directly at the same distance; this helps to compensate for monocular viewing). The operator sees a circular portion of the scene about 4.6 degrees in diameter, a field of view covering about 10 inches at a distance of 10 feet. The internal optical elements (e.g., beam-combining optics) inevitably result in reduced scene luminance when viewing through the VTE; the instrument's transmittance factor is approximately 7 percent. The VTE was used with a lightweight photographic tripod for portability in underground mines. A powerful quartz-halogen 12-volt automotive spotlight was fitted with a sheet of diffusing plastic film (1 layer of plastic document protector, Stock # MF-3, 20th Century Plastics, Los Angeles, CA) to create a smooth wide spot of illumination for the VTE target areas underground (the uniformity of the illumination on and around the target was extremely important, since this VTE derives its veiling luminance from the target scene itself). The 12-volt spotlight (#552 Hollywood Accessories) plugged into a small 12-volt lead-acid battery (Globe GEL/CELL Rechargeable Battery Pack PP1260-12v, 6 amp-hour capacity) that was recharged each night between underground data-collection trips. The 12-volt light produced illuminance ranging from 14 fc at a distance of 12 ft, to 75 fc at 6 feet. Wide-latitude black and white film (Ilford XP-1, ASA range 100 to 1600) was used to document VTE targets. This film is designed for development in the C-41 color print process, and thus proof prints could be obtained from a one-hour photo finishing shop before leaving the field sites. The unusually wide latitude of this B&W film is important for in-mine photography, since the ratio of luminances is often extremely high (e.g., 400:1, caplamp hotspot to surrounding penumbra); the ability to capture detail in both light and dark areas helps to duplicate what is seen by the human eye in the underground mining environment.

A.2.6 Procedures for Obtaining VL Measures. After the target type and distance, illuminance or luminance, and general layout were recorded on the data-collection form, the trained VTE operator repeatedly set the VTE's contrast transmittance control to a point where the target features (those critical to the mining task being assessed) were just barely visible. At least 3 settings of contrast threshold were made for each target item, testing continuing until a stable threshold value was evident. The VTE operator always approached from the lower side of the threshold, slowly turning the control knob until the target detail of interest suddenly broke through the VTE's optically produced "fog." This procedure effectively eliminated any spurious effects of backlash in the internal workings of the VTE, since the VTE was specifically calibrated (using a Pritchard 1980-A photometer) for this ascending direction of control rotation. VTE readings were remarkably repeatable, inspiring confidence in the equipment and methods. It should be noted that, strictly speaking, these measures were only relative indices of visual task difficulty, permitting rank-order comparisons of visual difficulty for various tasks both in the mines and in the mine simulation laboratory. As noted above, a data-base relating visual performance to visibility level (VL) for these types of mining tasks will be required before VL can be used to specify minimum luminance requirements.

When the VL measures for a number of targets (e.g., rock cracks, tripping hazards on the floor, protrusion hazards on the rib or back) had been recorded at a given underground worksite, the VTE was wrapped in its sheet of protective foam rubber, placed in a large backpack, and transported (along with its accessories in a second backpack) to the next target setup location.

The VTE was operated without internal power, in continuous viewing mode. The continuous viewing (as opposed to the 0.2 sec pulse-train method often used with smaller targets and less experienced VTE operators) has produced excellent results with skilled operators (Blackwell, 1982), and more closely matched the types of visual tasks studied in this project. In this case, any problem of visual fading near threshold was countered by blinking or changing eye position momentarily. Due to the typically uniform backgrounds found in underground work areas (rock dust or mud coats all surfaces with a matte reflectance), there was little problem with where the veiling light came from in the scene; it was thus possible to fix the position of the trimming filters in the S and V beam paths by covering them with duct tape (keeping dust and dirt out of the instrument in the process). The trimming filters remained fixed throughout the mine visits and the subsequent mine laboratory measurements, thus keeping constant the relationship between VTE control readouts and contrast transmittance through the instrument (assuming a uniform background

such that the veiling beam was equal to the background luminance: $L_v = L_b$). The contrast transmittance was carefully and repeatedly calibrated with a Pritchard 1980-A photometer in the lab.

A.2.7 Operator Calibration. The same VTE operator, equipment, and procedures were used for all VL measures both in the laboratory and in the mines to ensure comparability of readings. As a result of over 7 years of research work involving visual contrast thresholds, the VTE operator was thoroughly experienced in making consistent visual contrast threshold settings. The VTE operator's contrast thresholds for standard calibration targets were obtained in the Mine Laboratory, with the same equipment and procedures used for collecting data in underground mines. A circular target 20 arc-minutes in diameter was used, in addition to the standard 4 arc-minute circular target, to better represent typical mining visual tasks. Visual contrast thresholds for the 20' target and the 4' target were obtained with negative contrast (target darker than background) as well as with the usual positive contrast (target lighter than the background), in order to better match the typical mining visual tasks (e.g., rock cracks, boot holes, shadows defining objects). It was observed that VTE readings for the 20' target did not vary significantly over the range of eyepiece luminance (background luminance as seen through the VTE eyepiece) used for the data reported below, and thus the operator's contrast threshold for the 20' circular target seen through the VTE was 0.05 for a darker-than-background disc, and 0.08 for a lighter-than-background disc, for background illumination ranging from 14 footcandles to 75 footcandles (.14 fL to .75 fL as seen through the VTE, with 0.14 reflectance and 0.07 transmittance through the VTE). The contrast thresholds of 0.05 and 0.08 should nominally be linked to a background luminance of 5.5 fL, or 0.385 fL as seen through the VTE used in this study. Although the operator's contrast thresholds for a dark 4' disc (0.08) and a light 4' disc (0.16) were also obtained at a nominal background luminance (external) of 5.5 fL, it has been suggested that the 20' disc thresholds are better matched to the larger target details of mining visual tasks.

The standard visibility reference function that defines VL 1 for a 4' disc lighter than the background (CIE, 1981, p. 9; IES 1981, p. 3-15) shows how the minimum background luminance must be increased to compensate for lower contrast in the target disc (i.e., to compensate for targets that are harder to see), up to a point where increasing the luminance does not appreciably improve visual performance. It is important to note that the Visibility Reference Function was obtained with 0.2 sec pulses presented at the rate of one per second. Continuous viewing, as used for data collection in this project, produces different threshold values. Because continuous viewing, larger target detail size, and negative contrast more closely match typical mining visual tasks, the standard reference function for a 4' positive-

contrast disc with 0.2 sec pulse-train viewing should not be used to estimate equivalent contrast or minimum required luminance. Instead, a database could be obtained for visual reference tasks more closely related to generic classes of mining tasks and then linked to expected visual performance for generic classes of safety-critical mining tasks.

A.2.8 Equivalent contrast and minimum luminance. The concept of equivalent contrast is simple, although the actual values of "reference equivalent contrast" and "effective equivalent contrast" are more complex (as explained in CIE, 1981). The idea of equivalent contrast, often written as $\tilde{c}$ (read as "c-wave"), can be illustrated by using a rock crack as an example, with a 4' positive-contrast disc as a reference target. Looking through the VTE, the operator turns the contrast transmittance control until the rock crack is reduced to being just barely visible (assume the VTE reading at threshold for the rock crack is 0.10 contrast transmittance, a VL of 10, indicating that the rock crack is, at that background luminance, 10 times above its threshold). Then, without changing the contrast transmittance setting on the VTE, a 4' disc target with adjustable contrast is substituted for the rock crack target. The operator then adjusts the contrast of the 4' disc target, while looking through the VTE, until the 4' disc is just barely visible. It is assumed that at any VTE setting (in this example, the VTE is set to transmit 0.10 of the contrast of anything seen through the VTE) a 4' disc with a contrast level that makes it just barely visible will have the same degree of visual difficulty as the rock crack being measured. Since there is an extensive database showing the tradeoff between contrast and luminance for the reference 4' disc target, it is then possible to determine how much luminance is needed to see (just barely) the rock crack. In practice, there is no need to actually set a 4' disc to threshold for each real-world target in order to find the contrast of a reference target equivalent to the rock crack; there is an extensive reference target database showing the 4' disc contrast threshold that would be set by a reference observer for any VTE contrast transmittance value. Assuming this example is conducted at a background luminance level of 29 fL (100 cd/m²), using 0.2 sec pulse-train viewing, a typical young VTE operator would adjust the 4' disc contrast to 0.9230 while looking through a VTE set at 0.10 contrast transmittance, thus producing, in the image seen through the VTE, a standard contrast of 0.0923. The "equivalent contrast" of the rock crack would then be 0.9230, which is 10 times the usual threshold contrast for the 4' disc viewed directly at 29 fL. By moving along the Visibility Reference Function that shows the minimum luminance required to just barely see the 4' disc with a given contrast, it is possible to determine (in this simple example) how low the luminance could be without losing sight of a 4' disc of 0.9230 contrast, and thus how low the luminance could be without losing the ability to see the rock crack in question. The

mathematical function relating minimum luminance (fL_{min}) to the contrast of a 4' disc target for young observers (0.2 sec pulse-train presentation), is adapted from equation 3-15d on page 3-20 of the 1981 IES Lighting Handbook Reference Volume (IES, 1981):

$$fL_{min} = 0.4784 * ((1 / (16.846 * C)) ** -0.4 - 1) ** -2.5$$

where C is the contrast of a 4' disc (or, the "equivalent contrast" of a given real-world target feature), fL_{min} is the minimum luminance of the target background in footlamberts, / indicates division, * indicates multiplication, and ** indicates raising to a power.

Using this minimum luminance function (relating fL to 4' disc contrast in the example above), a minimum of 0.0849 fL would be required for an average young observer to see (just barely) a 4' disc target with a contrast of 0.9230 (10 times the threshold contrast of 0.0923 at 29 fL, because the VTE was set at a contrast transmittance of 0.10 when finding the threshold for the rock crack). The minimum luminance for reliably seeing the rock crack could be derived in a similar way, using the formula for fL_{min} above: since it was established that the rock crack was equal in visual difficulty to a 4' disc of 0.9230, then a minimum of 0.0849 fL would be required to be able to see (just barely) the rock crack (with 0.2 sec pulse viewing and previous knowledge of the crack location).

To allow for the many real-world factors (such as uncertainty of location and time of presentation) that in effect reduce the visibility of a given target, a complex series of mathematical adjustments must be made, as specified in CIE Report No. 19/2, Volume I (1981). In this simple example, however, it will be assumed that a safety margin or "field factor" of 8 should be applied to the "equivalent contrast" of the rock crack, before finding the minimum luminance required. By dividing the "equivalent contrast" of the rock crack by 8, it is in effect made harder to see, and thus the luminance requirement will be higher to provide a margin of safety in the estimated minimum value. Dividing 0.9230 by 8, the "equivalent contrast" is reduced to 0.1154, a contrast level associated with a higher minimum luminance requirement (according to the formula given above) of 9.3496 fL. A "field factor" of 15 would reduce the equivalent contrast from 0.9230 to 0.0615, for which a minimum background luminance of 18,964 fL would be required. It is interesting to note that, due to the diminishing effects of luminance increases at higher levels, a field factor of 16 would reduce equivalent contrast to a level (0.0577) where no amount of extra luminance could make the target visible, assuming the formula given above.

The VTE measures reported below are given in terms of relative visibility level (VL) rather than in terms of minimum luminance, due to the great disparity between the standard visual reference task (4' positive-contrast disc, equal to an eighth-inch dot seen from 9 ft away) and the visual characteristics of mining tasks. Relative visibility level is simply the inverse of the contrast transmittance ($VL = 1 / CT$). In the example above, a contrast transmittance of 0.10 implies a VL of 10, indicating that a target's inherent contrast (at the background luminance used for measurement) is 10 times greater than its threshold contrast.

Relative values of VL provide an excellent means for comparing the visual ease or difficulty of widely differing targets, as long as the measurements are obtained at similar levels of background luminance, with similar procedures for determining thresholds. In this project, one of the principal objectives in obtaining VTE readings in underground mines was to determine the representativeness of our mine laboratory task simulations. Although, strictly speaking, VL readings cannot be used to say how much easier one visual task is compared to another, VL readings can definitely be used to rank-order tasks in terms of visual difficulty. A rough idea of relative visual task difficulty can be derived from VL readings, however, and these comparative data can be used to extend the results of direct performance measurements (reported in section 3.1 of the main body of this report) to other mining tasks that share similar visual requirements for detail acuity, contrast sensitivity, motion perception, and depth perception.

A.3 RESULTS

A.3.1 Rock Crack Detection. In order to compare actual rock cracks in underground mines with the simulated rock cracks used for direct measurement of visual performance in the mine illumination laboratory, 9 measures of relative visibility level (VL) were obtained in two underground mines and 12 measures were obtained in the laboratory. Tables A-1 and A-2 reveal that the simulated rock cracks were somewhat more difficult visually than actual rock cracks measured in the mines. In Table A-1, the individual simulated rock cracks (identified by letters A through F) are ranked by average detection times at the lowest light level in the direct performance tests (described previously in Sections 2.4 and 3.1 of the main body of this report). It is to be expected that the visibility measures (VL) obtained with the VTE would fall generally in the same rank order, but the differences are not large and the ordering is not completely consistent with the performance measures. As noted previously, the relatively narrow field of view of the VTE (4.6 degrees in diameter) covered less than 6 inches at a distance of 6 ft, making it impossible

TABLE A-1. - VTE measures of rock cracks (in lab)^a

V _L ^b	Simulated Rock Crack	Target Position	Average Detection Time at 0.01 fL Background Lum.
2.3	D	9 o'clock	16.7 sec
2.9	B	1 o'clock	8.7 sec
2.2	A	3 o'clock	8.7 sec
2.9	C	11 o'clock	4.0 sec
2.8	E	7 o'clock	2.5 sec
3.2	F	5 o'clock	2.1 sec
2.5	B	4 o'clock	12.3 sec
2.6	D	12 o'clock	9.4 sec
2.7	A	6 o'clock	8.7 sec
2.3	C	2 o'clock	5.7 sec
3.3	E	10 o'clock	4.5 sec
4.0	F	8 o'clock	2.4 sec

^aSee Section 3.1.1 for experimental details.

^bVTE data collected using same equipment and procedures as for in-mine data shown in Table 3-12.

TABLE A-2. - VTE measures of rock cracks (in-mine)

VL	Viewing dist.	Background illum.	Target description
<u>Copper mine</u>			
3.0	11 ft	10 fc	Small, overhead rock
5.7	7 ft	12 fc	1/8 inch, fresh
5.1	7 ft	12 fc	3/16 inch, fresh
3.3	7 ft	12 fc	In muddy rib
<u>Zinc mine</u>			
5.1	8 ft	46 fc	1/8 inch, dust around
5.7	8 ft	46 fc	1/32-1/16 inch, light dust
4.0	8 ft	46 fc	1/16 inch, middle of crack
6.7	10 ft	23 fc	1/4 inch, up-angle viewing
7.1	9 ft	27 fc	3/8 inch, gap in rock

to see most rock cracks along their full length. This effectively changed the visual nature of the target, because perceptually speaking the whole is more easily seen than any one of its parts. The rock cracks varied in visual difficulty along their length; the easiest portion of the target was measured with the VTE, since that would typically determine the level of best visual performance in normal direct viewing.

Note that in Table A-2, the rock crack in a muddy rib, with a VL of 3.3, is only half as visible as the 3/8 inch wide gap in the rock, with a VL of 7.1; it was observed that rock dust around the rock cracks makes them more visible, probably due to its uniform, matte reflectance characteristics.

The general correspondence between VL measures in the mines and VL measures in the laboratory confirms that the simulated rock cracks represent the more difficult end of the spectrum of actual rock cracks that are found in underground mines, and that the luminance recommendations based on the laboratory performance measures (see Section 4.0 in the main body of this report) are valid and conservative.

As previously noted (in Section 2 of this Appendix), it is not advisable at this time to use measures of VL obtained with the present VTE Model 5 as a basis for deriving minimum luminance recommendations for the kinds of visual tasks involved in underground mining (Blackwell, 1982). The reasons for this are summarized in the next section of this report.

A.3.2 Rock Motion Detection. The visual task of sensing the initial motion of rocks, either in a jammed ore path or when barring down loose rock overhead, could be measured with the VTE only in the mine illumination laboratory. Measurements in an actual mine would have endangered the VTE and its operator, and the visual feature being detected, motion, could not be consistently repeated for a check on the stability of the threshold settings. The simulated rocks in the laboratory apparatus, however, were extremely realistic replicas of speckled granite chunks ranging from softball size to football size, fooling the eye even at arm's length. It can therefore be assumed that in this instance, the VTE measures of rock motion fully represent VL readings that would be obtained in actual mines, if it were practical to do so. Table A-3 shows that the VL measures are rank ordered in relation to the error data obtained in performance testing, but in a direction opposite from what would be expected: the target items with the highest VL readings should be visually the easiest to see, but these higher VLs were associated with higher error rates (errors in this context were response times greater than 1.0 sec, an indication that the initial rock motion was undetected). This

TABLE A-3. - VTE measures of rock motion (in lab)^c

VTE Readings VL	Target Rock ^b Position	Errors ^a Out of 420 Trials at .016 fL	Total Errors ^a Out of 2100 Trials at all 5 Lum Levels
20	6 o'clock	19	40
14	4 o'clock	18	29
14	12 o'clock	14	25
12	2 o'clock	6	19
12	10 o'clock	13	16
12	8 o'clock	10	15

^aerror=response time $\geq$ 1.00 sec.

^bviewing dist = 8 ft, L_b = 2 fL.

^cno VTE measures of rock motion in mines.

unexpected result could be due to the considerable difference between the task as experienced in direct performance testing and as viewed through the VTE's narrow field of view. It is interesting to note that the VL for seeing the motion of the rocks (they were repeatedly moved while the VTE operator made threshold settings) was higher than the VL settings for seeing the rock pattern itself. This is probably due to the nature of the rock motion, primarily along the line of sight rather than perpendicular to the line of sight, thus involving some degree of binocular depth perception and size change perception (the present VTE provided only monocular viewing, and the small field of view limited the perception of size-change cues to motion).

A.3.3 Floor Hazard Detection. Tables A-4 and A-5 show how VTE measures of various floor hazards in actual mines compare with those measured in the mine illumination laboratory. The simulated floor hole hazard in the laboratory was covered over with the simulated rock used for rubble detection testing (see Sections 3.1.3 and 3.1.4), and thus no VTE readings for the floor hole could be obtained in the lab. It can be observed that the VL readings obtained both in the mines and in the mine illumination laboratory fall in a fairly restricted range, for the most part between 2 and 10. One interesting exception is found in Table A-4, where a large but uniformly gray rock (about the size and shape of a carry-on suitcase, with irregular contours) has a VL of 7.6 with typical caplamp lighting geometry (light source just above the receiving lens, as was the case for all VTE measures unless otherwise specified); with the light source held to the side, so that good shadow modeling creates black outlines around the very low contrast rock, the VL jumps up to 23.3, a relatively high reading. This begins to define quantitatively the relative advantages of good lighting geometry for improving task visibility while keeping luminance requirements low.

In considering these measures, it should be remembered that the limited field of view of the VTE altered most of the visual tasks in comparison to normal direct binocular viewing; for example, only part of a rock could be seen. The VL readings thus represent the visibility of just a portion of the border between the rock and its background, rather than the visibility of the rock seen as a whole object.

A.3.4 Rib and Back Protrusion Hazard Detection. VTE readings for protrusion hazards in the lab and in the mines are shown in Tables A-6 and A-7. The long linear extent of these target items typically makes them visually much easier in direct viewing rather than as seen through the VTE's narrow field of view. The VL readings represent the contrast thresholds for a small portion of the item seen against its background. In the case of objects that project out away from their backgrounds, both caplamp illumination and vehicle illumination produce higher illumination on the target relative to the background,

TABLE A-4. - VTE measures of floor hazards (in lab)

VL ^a	Viewing Dist.	Background Illum. ^b	Target Description
5.3	8 ft	37 fc	Smooth, mud-coated rock ^c .
13.9	8 ft	37 fc	Small speckled granite rock.
7.6	8 ft	37 fc	Large mud-coated rock (with caplamp lighting geometry).
23.3	8 ft	37 fc	Large mud-coated rock (same illumination as above but with good shadow modelling).
10.4	8 ft	37 fc	Open end of 1-inch pipe on floor.

^aNot able to see entire target in small VTE field of view.

^bSame 12-volt illumination source as used in mines.

^cSame rock used in direct performance measurement, of floor rubble, described in Section 3.1.4.

TABLE A-5. - VTE measures of floor hazards (in mines)

VL ^a	Viewing Dist.	Background Illum.	Target Description ^b
4.8	6.5 ft	15 fc	Small mud-coated rock (copper).
1.6	6.0 ft	74 fc	Small muddy rock (copper).
3.3	6.0 ft	74 fc	Large dirt-covered rock (copper).
3.0	7.5 ft	48 fc	Medium-size dust-covered rock (zinc).
2.1	7.0 ft	50 fc	Small rock, dusty floor (zinc)
3.6	8 ft	30 fc	Partly buried hose (zinc).
6.2	8 ft	30 fc	1-inch diameter hose on floor (zinc).
3.6	7 ft	50 fc	1-inch diameter hose on floor (zinc).
2.7	7 ft	50 fc	1.75-inch diameter hose on floor (zinc).
4.3	7 ft	50 fc	2.25-inch diameter hose on floor (zinc).
3.8	8 ft	30 fc	Aluminum scaling bar on floor (zinc).
5.3	8 ft	42 fc	7.5-inch diameter drill hole (copper).
2.7	8 ft	42 fc	Same as above, difficult viewing angle.

^aTarget not entirely visible in VTE field-of-view.

^bRock sizes: small~softball, medium~football, large>basketball.

TABLE A-6. - VTE measures of rib and back protrusions detection (in lab)

VL	Position of Slipped Rock Bolt	Average Response Time ^a	Viewing Dist.	Background Illum.
10	Lower rib	1.1066	6 ft	70 fc
10	Middle rib	1.0103	6 ft	70 fc
14	Upper rib	0.9904	6 ft	70 fc
10	Right back	0.0399	6 ft	70 fc
14	Center back	0.8924	6 ft	70 fc
8	Left back	0.8877	6 ft	70 fc

^aResponse time obtained at background luminance = 0.0068 fL (see Section 3.1.5).

TABLE A-7. - VTE measures of rib and back protrusions detection (in mine)

VL	Viewing Dist.	Background Illum.	Target Description
23.3	6	75 fc	Drill steel - sticking out from rib.
7.4	8	23 fc	Rock bolt - bent with plate attached, protruding from rib.

due to the greater distance of the background from the source. This often produces a significant increase in luminance contrast, especially when the object and background have nearly the same reflectance (frequently true in underground workplaces, because of a uniform coating of dust and mud from blasting). In the case of the drill steel in Table A-7, the angle of view produced an excellent shadow on the background surface, thus increasing the object's visibility level to 23.3. This relatively high VL, due to the presence of a visible shadow to help delineate the object, is comparable to that obtained with good shadow modeling of a large rock in the laboratory (see Table A-4).

A.3.5 Visibility Measures for Other Hazards. Table A-8 presents VL measures for a variety of other visually detected hazards in underground metal and nonmetal mining. The VL readings fall into a relatively restricted range, due probably to the similar contrast of most objects in the underground workplace (due to dust and mud coatings on object and background), and to the diminishing effect of object size on visibility. The VL measures vary in the expected direction; the larger rusty steel cable is more visible than the smaller one, and the white-rock/dark-rock pattern is more visible than the light-brown/dark-brown rock pattern.

A.3.6 Peripheral Motion Detection. It was not possible to obtain VTE readings of peripheral motion comparable to the direct visual performance measures described in Section 3.1.6 of the main body of this report, due to the limited field of view of the VTE. It is not impossible to imagine a VTE designed for evaluating visual tasks in the peripheral visual field, but the device used here was not suitable for that purpose.

A.3.7 Interpretation of VTE Measures for Minimum Luminance. The mathematical model presented in CIE Report No. 19/2 (1981) is based on a contrast-threshold method for quantifying how easy or difficult a visual task may be. In Volume II, page 7, the Committee (TC-3.1) says:

The model is limited to the population of normal observers above age 20 years and does not necessarily apply to observers with ocular abnormalities or visual deficiencies. In the opinion of the Committee, the model should be used only within the following ranges of model parameters: (a) values of visibility level, VL, between 0 and 100; (b) luminances between 1 and 10,000 cd/m²; and (c) eccentricities of task details with respect to the ocular line of sight no greater than 3 degrees.

TABLE A-8. - VTE measures of other hazards (in mines and in lab)

VL ^a	Viewing dist.	Background illum.	Target description
<u>Muck pile hazards</u>			
5.1	7 ft	46 fc	Drill and rebar (copper).
3.8	7 ft	50 fc	Drill steel in muck pile (zinc).
6.9	6 ft	66 fc	5/8 inch rusty steel cable on small muck (zinc).
2.9	6 ft	66 fc	1/2 inch rusty steel cable on small muck (zinc).
9.1	8 ft	35 fc	Blasting wire in muck (blasting wire from zinc mine measured in lab).
<u>Boot holes</u>			
4.7	8 ft	35 fc	Boot hole surrounded by dust (zinc).
3.8	9 ft	26 fc	Boot hole surrounded by dust (zinc).
2.2	9 ft	26 fc	Boot hole surrounded by dust (zinc).
4.9	9 ft	23 fc	Boot hole surrounded by dust (zinc).
<u>Rock pattern slips</u>			
7.9	11 ft	23 fc	White rock/dark rock (zinc).
3.6	12 ft	23 fc	Dark brown rock/light brown rock (zinc).
<u>Rock bolt plate</u>			
3.6	13 ft	14 fc	Rusted plate on dusty rock (zinc).

^aMost targets not entirely visible in VTE field of view.

The considerable differences between standard visual reference tasks and the visual components of typical mining tasks have been discussed above (see Section 2 of this Appendix). In mining visual tasks, the critical details may be larger than the biggest letter on an eyechart, the background luminances are usually quite low compared with most other work environments, the contrast of objects against the background is typically very low, and motion detection and the perception of object locations in 3-dimensional space are very important. In some tasks, wide-angle vision (i.e., peripheral detection) is very important for sensing and avoiding hazardous situations (especially true in a noisy environment where hearing ceases to provide its early warning function). The contrast vs. luminance tradeoff functions ("iso-visibility contours") for small light disc targets, broken ring targets, and grating targets have been well established over many years of research; these targets were chosen for their relevance to lighting and visual tasks in office and industrial work.

Proper interpretation of mining task visibility measures in terms of minimum luminance would require a reference database specifically geared towards the characteristic visual components of underground mining. Until that kind of database is available, it is appropriate to report visibility level only as a relative measure of how far a target item is above its threshold.

A.4 CONCLUSIONS AND DISCUSSION

Foregoing sections of the main body of this report and of this Appendix should have made it clear that task visibility data were not used in a primary way in developing recommended values of required luminance. Instead, the minimum luminance recommendations were based exclusively upon task performance data. The task visibility data obtained with the VTE has as their primary purpose a comparison between simulated mining tasks in the laboratory and their actual counterparts in underground mines.

Looking at the comparative data presented in the Tables of this Appendix, it can be seen that tasks in the simulated mine workspace cover the range from VL 2.2 to VL 23.3, while similar tasks in the mines ranged from VL 1.6 to VL 23.3; most measures of VL fall between 2 and 10, however. The high VL values noted above are due to contrast enhancement through increased shadow modeling of the target.

It was somewhat disappointing to find that the ranking of task visibilities did not agree more closely with the levels of task performance obtained by direct measurement. Past experience with co-ordinated studies of task visibility and task performance data

suggests that in the future an extensive study be made to examine the relationship between these two measures of human response to lighting. Considering the fruitfulness of this type of approach in past research, it can be expected that a coordinated study using both visibility measurement and performance measurement would point towards an optimal experimental blend of the two approaches. An example of such a program, in the case of interior lighting, is found in CIE Report No. 19/2. It should be possible to obtain the same kinds of tightly-linked visibility and performance data for mining tasks. The availability of the resulting database would greatly facilitate further studies of lighting requirements in underground mining by permitting more of the data collection to be carried out in terms of task visibility measurement, which, in terms of time and expense, would be undeniably more economical than direct performance measurement.

APPENDIX B

METHOD FOR MEASUREMENT OF IN-MINE REFLECTANCE

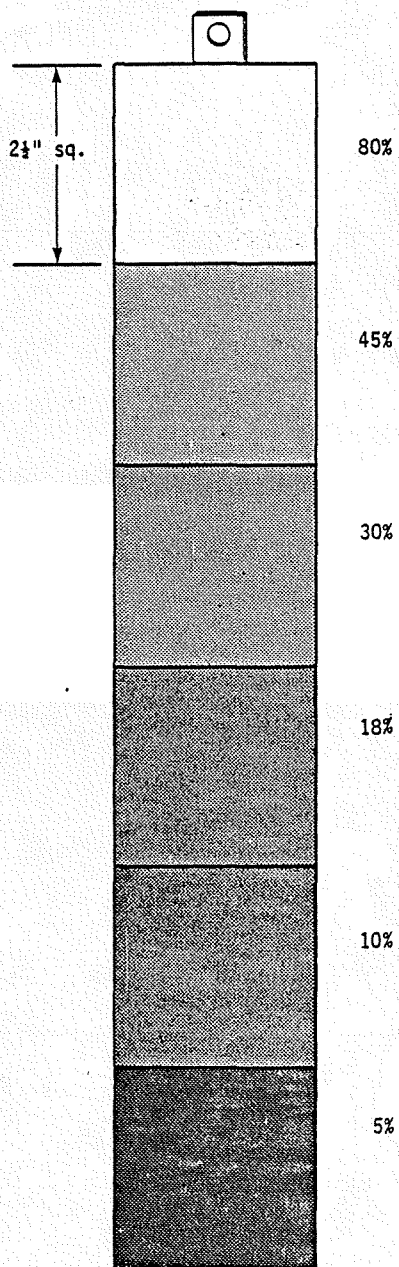


FIGURE B-1. - Recommended gray scale design (reflectance of panel as indicated).

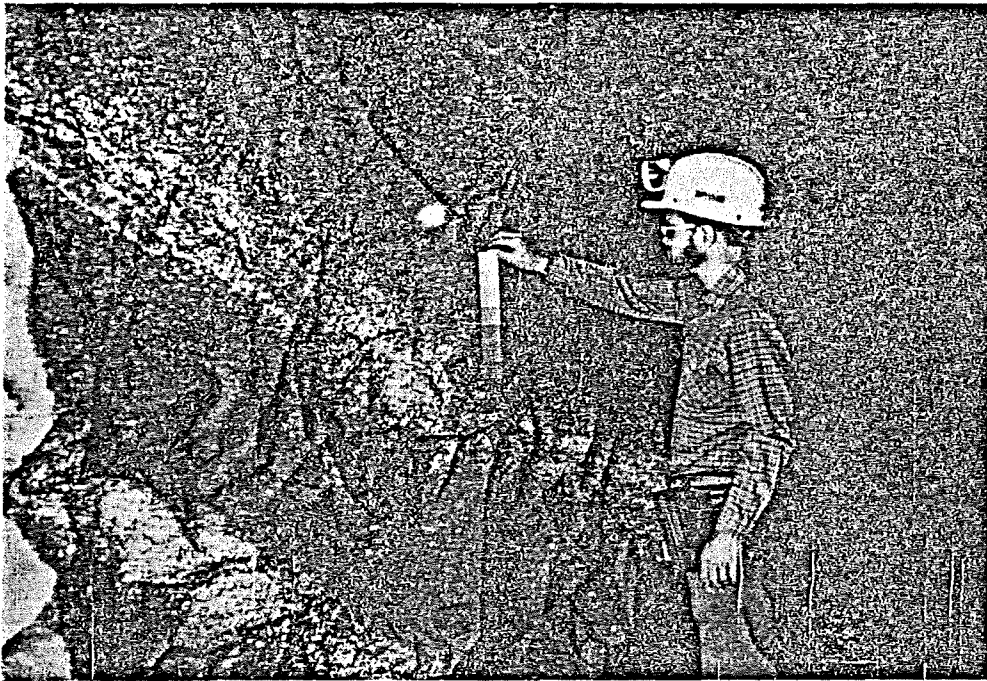


FIGURE B-2. - The gray scale is hung adjacent to the area of interest.

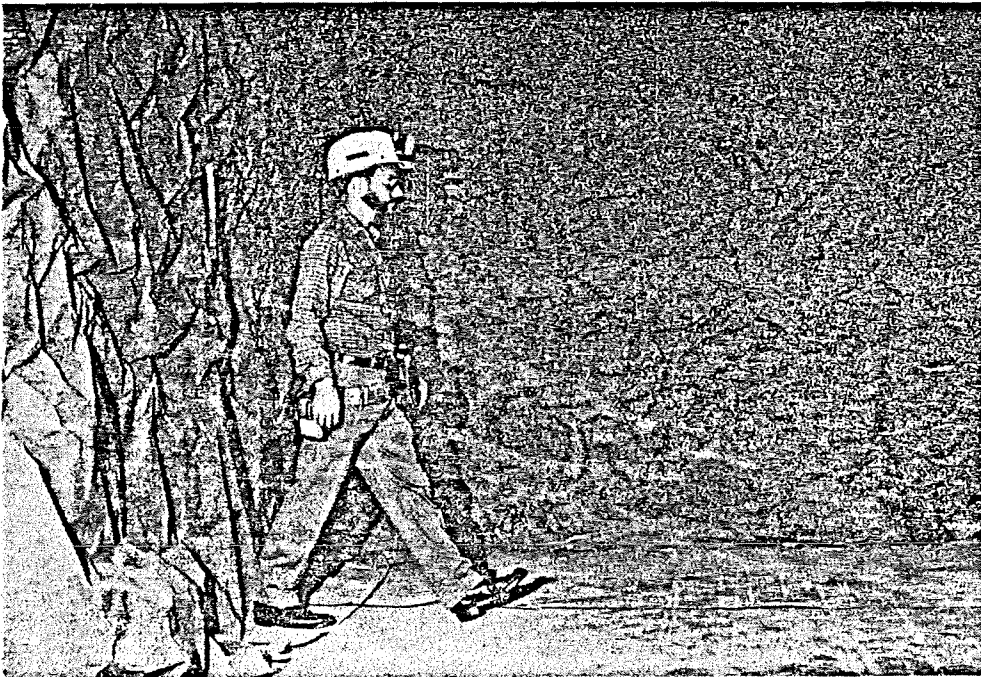


FIGURE B-3. - Pace off or measure six feet.

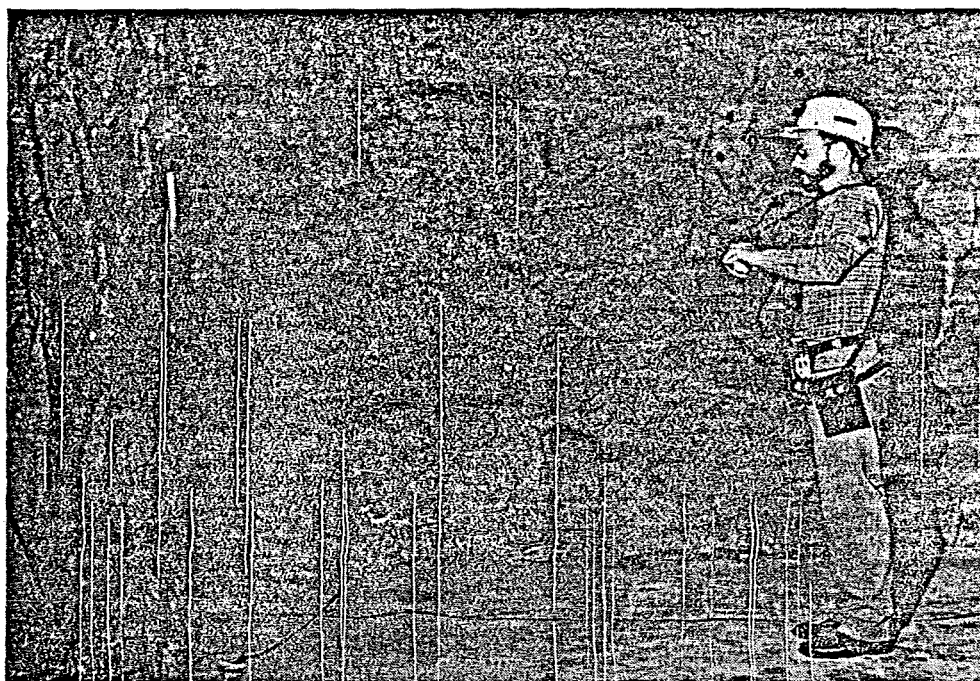


FIGURE B-4. - Remove caplamp so the area will be illuminated by the camera flash.

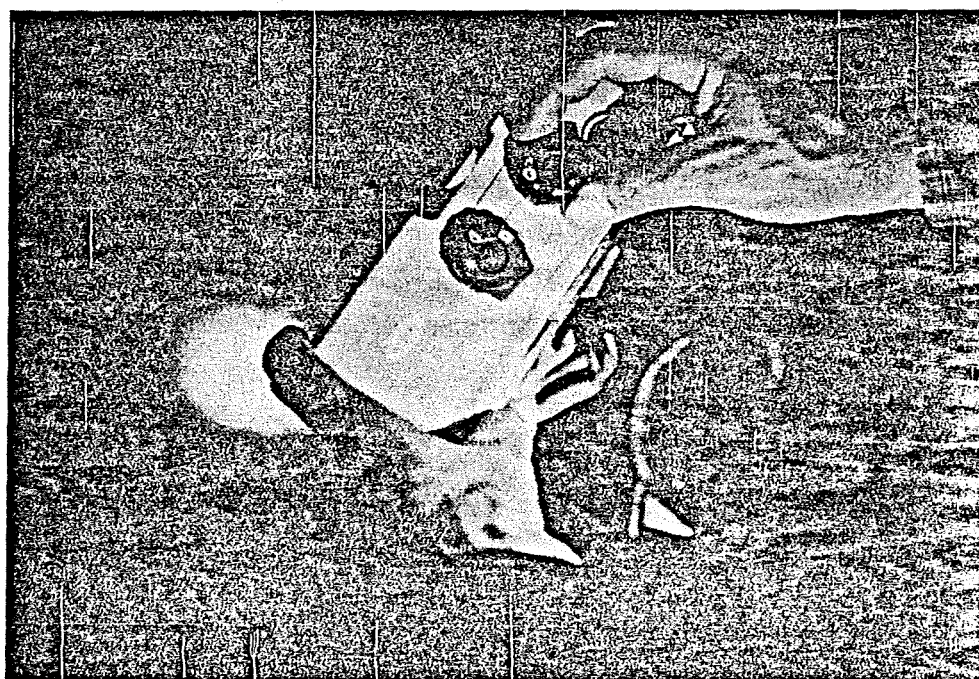


FIGURE B-5. - Set the camera focus and flash controls.



FIGURE B-6. - Take the photograph.



FIGURE B-7. - Sample photograph.

length of the recommended gray scale) and a area of approximately five square feet.

Photographs taken by MSHA inspectors (or others) would be sent to a central technical support facility and analyzed with a Pritchard 1980A (or similar) photometer. The luminance of areas of interest in the photograph would be compared with sections of the gray scale. By shifting the photometer aperture from 30 to 2', a 90:1 ratio is obtained. This is sufficient to allow measurement on the photograph of an entire four to five square foot area with the 30 aperture. Then, by switching to the 2' aperture, it is possible to measure each of the sections of the gray scale. Knowing the reflectance of each panel allows determination of the reflectance of the pictured mine surface. The reflectance and (contrast of specific details) in the pictured scene may also be determined if desired.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
8.5	High speed tramming of mobile equipment (rubber-tired and rail)	Haulageway hazards (people, equipment, rubble, hoses, cables, holes, etc.)	Detect location, judge/adjust path of machine to avoid hazard.	Machine lighting. Blind spots may be extensive, especially to opposite operator.
8.5	Prepare work site (detect and remove loose; inspect muck pile)	Rock surface	Detect changes in grain patten or "slips".	Often caplamp only, dust obscures much of desired detail.
10	Environmental awareness (detection and awareness of hazards while on foot)	Hazards on rib/back (loose rock, protrusions, low headings, etc.)	Detect location. Maintain awareness of location at work site.	Worker may be handling heavy objects. Often caplamp only.
11	Ground support activities (rock bolting, timbering, sandfilling, shotcreting, etc.)	Oversize slabs	Detect presence and boundaries (slab given extra support if too large to bar down).	Often caplamp only, often no shadow modeling, may be in penumbra of lamp.
12	Prepare work site (detect and remove loose; inspect muck pile)	Falling loose and loose sliding down bar	Detect beginning of fall, judge probable path (to decide whether evasive action is required).	Often caplamp only, may be in penumbra, often no shadow modeling of rock surface.
13	Environmental awareness (detection and awareness of hazards while on foot)	Floor hazards (holes, rubble, hoses and cables, etc.)	Detect location on floor. Maintain awareness of location at work site.	Worker may be handling heavy objects. Often caplamp only.
14	Prepare work site (detect and remove loose; inspect muck pile)	Face after blasting ("bootholes", ANFO or stick powder)	Detect bootholes, ANFO or stick powder in holes, ignite wires or caps.	Often caplamp only, often no shadow modeling of rock surface.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
15	High speed tramping of mobile equipment (rubber-tired and rail)	Front & rear clearance during turns, backing, and maneuvering	Judge clearance, adjust path of machine to avoid impact with hazards front, rear, or to sides.	May require simultaneous monitoring of spatial relationships on all sides.
16	Environmental awareness (detection and aware- of hazards while on foot)	Area behind worker (hazards, escape route)	Detect clear path for escape. Maintain awareness of escape route/update as necessary.	Worker may be handling heavy objects. Often caplamp only.
17	Prepare work site (detect and remove loose; inspect muck pile)	Stick, caps, igniter wires, blasting lines, drill steel	Detect in muck pile.	Often caplamp only.
18	Overshot loader operation	Muck	Detect muck flying toward operator from the loader bucket.	Usually caplamp only, operator is man-handling loader.
19	Chute pulling and clearing blocked finger raises	Rocks in chute or raise and bar	Hand-eye coordination, select "safe" place to bar or best place to put explosives.	Usually caplamp only, often must lean out in front of chute to see cause of jam.
20	Truck operation	Dump berm, grizzly or open hole	Judge spatial relationships to align truck while backing in, judge closure rate and speed.	Usually machine lights. Area lights may be a glare source.
21	Chute pulling and clearing blocked finger raises	Rocks in chute or finger raise	Detect oversize or "log jam" of rocks blocking flow of muck.	Usually caplamp only, often must lean out in chute to see cause of jam.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
22	Prepare work site (detect and remove loose; inspect muck pile)	Flaking around bolts, pillars, etc.	Detect locations where chips have flaked off (surface will be relatively dust-free).	Often caplamp only, dust may obscure desired detail.
23.5	Environmental awareness (detection and awareness of hazards while on foot)	Operating machinery hazards (pinch points, crush points, rotating parts, etc.)	Detect location. Maintain awareness of same.	Occurs especially during set-up/maintenance. Machine lights often glare source.
23.5	Environmental awareness (detection and awareness of hazards while on foot)	Haulage equipment	Detect location, detect escape path to get out of the way of vehicle.	Walking to/from worksite, around loading/dumping site. Vehicle lights often glare source.
25	General equipment safety (inspection of powered machinery)	Machine access hazards (climbing on and jumping off)	Detect location of steps/hand holds climbing on, detect floor hazards when jumping/climbing down.	Bigger problem is getting down. Machine lights do not light area but raise adaptation.
26	Overshot loader operation	Rib	Maintain awareness of location and relative position of the operator to avoid being pinched against rib.	Usually caplamp only, operator is man-handling loader.
27	Continuous miner operation	Trailing cables	Maintain awareness of location and useable length remaining.	Machine lighting forward, caplamp to rear where where cables are, dust and blind spots.
28.5	Shaft maintenance	Girders, timbers	Detect cracks, rot, etc.	Caplamp only, cage usually moving.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
28.5	Shaft maintenance	Guides	Detect excessive wear, absence of grease.	Caplamp only, cage is usually moving.
30.5	Rail operation	Switches	Determine orientation of switch throw arm, detect any gap between switch points and rails.	Machine lights (rarely caplamp only), train is in motion.
30.5	Prepare work site (detect and remove loose; inspect muck pile)	Conglomerate	Detect	Often caplamp only, dust may obscure desired detail.
32	Rail operation	Rail cars and rib (or other fixed objects)	Detect any movement of rail cars (while working around the cars).	Usually caplamp only, may be doing heavy work at time.
33	High speed tramping of mobile equipment (rubber-tired and rail)	Ribs & other fixed objects	Judge relative velocity of the machine.	Machine lighting.
34.5	Rail operation	Couplers, chains, and wedges on rail	Detect uncoupled cars, unconnected safety chains, wedges left on rails.	Usually caplamp only, may be in shadows. May only be a quick glance to check these.
34.5	Low speed tramping of mobile equipment (drills, bolters, mines, etc.)	Haulageway hazards (people, equipment, rubble, hoses, cables, holes, etc.)	Detect location, judge/adjust path of machine to avoid hazard.	Machine lighting likely. Blind spots are likely, especially to side opposite operator.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
36	Rail operation	Track	Detect significant change in gauge, undulations in track, debris on track (tools, muck, etc.).	Machine lights (rarely caplamp only), train is in motion.
37	Tugger operation	Load, unloading site, other workers	Select "safe" position to unload, maintain awareness of position of the load and other workers.	Often caplamp only, caplamp may be used for signaling.
38	Machine maintenance (especially on site)	Wiring	Detect burnt areas, disconnected wiring, broken or missing wiring.	Often caplamp only, machinery dust and grease covered, access limited.
39	LHD operation	Truck, rail car, or dump site and back	Judge closure rate and distance, judge clearance so LHD does not hit truck, etc. or the back.	Machine lighting, LHD in motion. Other machine lights may be glare source.
40	Low speed tramming of mobile equipment (drills, bolters, miners, etc.)	Hazards on rib/back (pipe, rock bolts, vent tubing, timber sets, low headings)	Detect location, judge/adjust path of machine to avoid hazard.	Machine lighting likely.
41	Machine maintenance (especially on site)	Missing parts	Detect that part is missing.	Often caplamp only, machinery dust and grease covered, access limited.
42	Slusher operation	Cable burrs, frays, splices	Detect and avoid injuring hands while strings cables.	May be caplamp or portable luminaires. Worker may be working on broken muck.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
43	Rail operation	Car, rails, and road bed	Select "safe" placement of rerailling device, predict path of car on rerailling attempt.	Usually several workers with caplamp only. Rail bed may be in water or muddy.
44	High speed tramming of mobile equipment (rubber-tired and rail)	Warning signs	Detect presence and read.	Machine lighting. Signs may be dust-covered.
45	Overshot loader operation	Pinch points on loader	Maintain awareness of location of pinch points relative position of operator extremities.	Usually caplamp only, operator is man-handling loader.
46	Machine maintenance (especially on site)	Machine, floor and blocks or jacks	Select "safe" position for blocks and jacks so machine can't shift or fall.	Often caplamp only. Access may be restricted.
47.5	Rail operation	Other trains, rail cars	Detect and judge distance and closure rate.	Machine lights (rarely caplamp only), train is in motion.
47.5	Low speed tramming of mobile equipment (drills, bolters, miners, etc.)	Front and rear clearance during turns, maneuvering	Judge clearance, adjust path of machine to avoid impact with ribs or other hazards front, rear, or to sides.	May require simultaneous monitoring of spatial relationships on all sides.
49.5	Slusher operation	Cables and blocks	Detect slack or tension in cables.	Portable luminaires are frequently used. Dust may reduce visibility.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
49.5	Slusher operation	Cables and ribs or timber	Detect cables rubbing rib or timber. Judge whether bucket will clear timber or rib.	Portable luminaires, dust and mist, shadows are frequently present.
53	LHD operation	Muck pile (oversize rock, steel, explosives)	Detect presence and location.	Machine lighting, LHD may be in motion.
53	Electrical installation and repair	Switch positions and power lock-outs	Detect switch position, condition of power lock-out.	Often caplamp only.
53	Explosives loading and blasting	Wire ends and connections	Detect unconnected ends, loosely twisted ends, missed holes and missed wiring.	Often caplamp only.
53	General equipment safety (inspection of powered machinery)	Breaks in electric cables	Detect location.	Worker is inspecting cable but may not have reason to expect a break.
53	General equipment safety (inspection of powered machinery)	Missing parts, loose or missing fasteners, etc.	Detect that parts are not present or are loose.	Worker may be looking for other targets at the time, probably doesn't expect missing part.
56.5	LHD operation	Muck pile, ribs, and bucket	Judge clearance so that bucket will not impact ribs or other solid objects.	Machine lighting, LHD is in motion.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
56.5	Machine maintenance (especially on site)	Engine, suspension components	Detect dents, cracks, breaks.	Often caplamp only, machinery dust and grease covered, access limited.
58	General production (common to virtually all jobs)	Small objects (miscellaneous tools and parts)	Detect location on work site floor or other environmental surfaces.	Caplamp is often only illumination source, floor may be strewn with rubble.
59	Chute pulling and clearing blocked finger raises	Rim of rail car, ladder to chute platform	Foot-eye coordination in climbing onto platform using rail car and ladder.	Usually caplamp only.
60.5	Rail operation	Locomotive and rail cars	Judge closure rate and distance.	Machine lights or caplamp only. Precision not usually required.
60.5	General equipment safety (inspection of powered machinery)	Air valve or electric switch	Determine that power is OFF (or locked out) to set-up or maintenance.	Usually caplamp only, machinery dust and grease covered.
62	Environmental awareness (detection and awareness of hazards while on foot)	Other workers	Detect location/change of location. Maintain awareness of same.	Worker may be handling heavy objects. Often caplamp only.
63	Continuous miner operation	Floor condition	Detect debris, broken ore.	Machine lighting; dust, blind spots of miner may reduce visibility.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
64	Ground support activities	Existing timber posts	Detect cracks, bows, etc.	Often caplamp only.
65.5	Machine maintenance (especially on site)	Hoses and couplers	Detect cracks and leaks.	Often caplamp only, machinery dust and grease covered, access limited.
65.5	Ground support activities	Existing timbersets	Detect cracks, bows, etc.	Often caplamp only.
67	Chute pulling and clearing blocked finger raises	Muck in the chute	Detect that enough has been left in the chute.	Usually caplamp only, often must lean out in front of chute to be able to see up chute.
68	Chute pulling and clearing blocked finger raises	Muck spilled on tracks	Detect presence and remove prior to motorman moving cars (derailing hazard)	Usually caplamp only, rails may be in shadow of cars.
69	High speed tramming of mobile equipment (rubber-tired and rail)	Signal lights	Detect presence, make color discrimination.	Hue and intensity highly variable, may be difficult to discriminate if color-blind.
70	Track maintenance	Points and track	Detect gap between points and rail, detect throw arm not fully seated, detect bent or worn points.	Often caplamp only, often coated with mud/dirt.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
71	Slusher operation	Knots, frays, or paint marks on cables	Detect location as an aid to determining what the bucket is doing where bucket is out of sight.	Portable luminaires, dust and mist frequently present. Cables are in motion.
72	Machine maintenance	Parts	Detect and evaluate wear.	Often caplamp only, machinery dust and grease covered, access limited.
73	Truck operation	Muck in truck bed	Detect oversize or overload that would impact low back during tramping.	Machine lights do not light this area, caplamp only or area lights.
74	Electrical maintenance and repair	Wiring, especially at junction boxes and connections	Discriminate color coding, visually track wiring thru junction box, etc.	Often caplamp only.
75.5	Slusher operation	Slusher bucket and muck	Judge when bucket is full of muck, detect if bucket has turned over.	Portable luminaires, dust and mist, shadows are frequently present.
75.5	Slusher operation	Draw hole and bucket	Judge closure rate of bucket on the hole (do not drop bucket down draw hole).	Portable luminaires, dust and mist.
77	Continuous miner operation	Mud seam, line on rib (or other indicator of grade level)	Detect location and any change in grade level of miner cut.	Machine lighting; dust may reduce visibility.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
78	Sampling (collecting, documenting samples)	Worksite layout	Scan site to draw map of site showing pillars, strata, spads, sample locations.	Usually caplamp only, may have to climb on muck pile
79	Track maintenance	Spikes, clamps, fish plates	Detect loose or missing.	Often caplamp only, often coated with muck/dirt.
81	Rail operation	Powder car interior	Detect any exposed sparking metal or breaks in wood insulation.	Usually caplamp only.
81	Ground support activities	Ribs and back	Surfaces are optimally wet (reflectance change) for application of gunite or shotcrete.	Often caplamp only.
81	General equipment safety (inspection of powered machinery)	Fluid leaks, worn or cut hoses	Detect puddles on floor, leaks at couplers and from hoses.	Worker probably looking for leaks/wear/cuts at the time.
83	Ground support activities	Rock surface and shotcrete or gunite	Judge that coverage is complete, shotcrete is sticking, estimate depth of coverage.	Often caplamp only.
84	Pipe installation and repair	Pipe jack and floor	Judge spatial relationships to position jack base so it is secure and supports pipe in desired location.	Typically two workers using caplamp only.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
85	Ground support activities	Sandfill pipe leaks and movement of pipe	Detect leaks, detect movement of the pipe.	Caplamp only, worker is probably not specifically looking for these two event at the time.
86	Rail operation	Pin and coupler	Align couplers and install pin.	Usually caplamp only.
87	Explosives loading and blasting.	Wires extending from loaded holes	Detect location, discriminate color of wires. Especially detect any unconnected wires.	Often caplamp only.
88	Drilling operations	Irregularities on floor	Detect suitable location for stinger of feedleg drill.	Caplamp only, worker may be attending to drill operation and manhandling drill.
89.5	Drilling operations	Drill rod ends	Judge and manipulate alignment of new rod with rod in the hole.	In rotary drilling requires manhandling heavy drill rod. Caplamp only usually.
89.9	Drilling operations	Steel or rod protruding from drill hole	Judge angular alignment of drill with previously drilled holes.	Usually caplamp only lighting. Aerosols may be present.
91.5	Continuous miner operation	Spray painted marks and messages on rib	Detect (and read if message) Use to align miner.	Machine lighting; dust may reduce visibility. Operator may be tramming the miner.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
91.5	Overshot loader operation	Extension or slide rail	Rails are parallel and on an even grade left to right.	Caplamp only.
93	Low speed tramming of mobile equipment (drills, bolters, miners)	Warning signs	Detect presence and read.	Often caplamp only. Signs may be dust-covered.
94.5	Track maintenance	Track	Detect movement of track when car passes over it, detect variation in gage or grade.	Often caplamp only.
94.5	Electrical installation and repair	Voltage tags on cables	Read tag.	Often caplamp only, probably only glances at the tag.
97	Drilling operations	Concavities on face	Detect and evaluate to select suitable point for collaring drill.	Frequently caplamp only lighting, usually no shadow modeling.
97	Drilling operations	Back and any already drilled holes	Judge spatial relationships in selecting points to drill.	Usually caplamp only, severe aerosols/dirty eyewear may be present.
97	Roadway maintenance (road grader)	Roadway	Detect rocks/rubble, mudholes, ruts and estimate correct blade depth needed.	Usually machine lighting.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
99.5	Ground support activities	Flow of sandfill	Rate and direction, amount of fill to go, detect color change when flow changes to cement.	Often caplamp only.
99.5	Ground support activities	Existing sandfill chimney	Detect cracks, bows, debris in tenons.	Often caplamp only.
101	Ground support activities	Timber cribbing	Judge that timber layer is level (by eye only).	Often caplamp only.
102.5	Slusher operation	Oversize in muck pile	Detect presence (avoid catching bucket on the oversize)	Portable luminaires, dust and mist, shadows are frequently present.
102.5	Explosives loading and blasting	Holes in face (wires from holes and ANFO in holes vs. empty holes)	Detect any unloaded holes.	Often caplamp only.
104.5	Drilling operations	Screw feed	Detect location. Maintain awareness of location at all times.	Usually caplamp only. Especially for ring and diamond drilling.
104.5	Explosives loading and blasting	Tags on blasting caps	Read tags in order to select appropriate cap for each hole.	Usually caplamp only, probably only glances at the tag during selection.

TABLE C. Visual tasks important to safety in underground work (Cont'd)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
106	Ground support activities	Bolt head and stinger held in bolter chuck	Alignment of stinger in bolter chuck and head of rock bolt at back.	Often machine lights. Bolt & stinger are 10-15' from operator. Bolter boom tends to lurch.
107	Ground support activities	Drill hole and bolt held in chuck of rock bolter	Alignment of bolt in bolter chuck and drill hole in back.	Often machine lights. Hole and bolt are 10-15' from operator. Bolter boom tends to lurch.
108.5	Drilling operations	Drill holes (in face)	Detect location, judge spatial relationships in selecting points to drill.	Frequently caplamp only lighting. Aerosols may be present.
108.5	Machine maintenance (especially on site)	Parts	Detect correct part from similar appearing parts	Often caplamp only onsite, area lighting in shop or parts storage area.
110	Drilling operations	Surveyor's marks	Detect location and make spatial judgements in aligning drill carrier.	May be caplamp only. Especially critical for rotary and diamond drills.
111	Drilling operations	Pattern marks (paint marks on face)	Judge spatial relationships in selecting points to drill.	Pattern mark may be only a center line or point. Frequently caplamp only.
112	Explosives loading and blasting	ANFO lance and face	Judge amount of lance still in hole based on perception of amount out of hole -- may have a mark on lance near end.	If machine lights present they may be a glare source.

TABLE C. Visual tasks important to safety in underground work (Concluded)

Rank	Mining job class	What must be seen (target)	What must be discriminated	Comments
113	Machine maintenance (especially on site)	Part numbers on parts, on tags or packaging	Detect location and read.	Often caplamp only. If number on part, may be coated with grease/grime.

APPENDIX D

PANEL OF ILLUMINATION AND MINING EXPERTS

Dr. William A. Hustrulid

Professional Specialty: Mining Engineering

Professor of Mining Engineering, Colorado School of Mines

Member, American Institute of Mining Engineering

Member, South African Institute of Mining and Metallurgy

Member, Society of Professional Engineers

Member, American Underground Association

Member, Sigma Xi

Dr. Hustrulid is presently Professor of Mining Engineering at the Colorado School of Mines having alternated between practical experience at Terra Tek, Inc., 1976 - 1977, and Atlas Copco in mining research and academic appointments at the Colorado School of Mines 1969 - 1972 and at the University of Utah 1972 - 1976. He also has been very active as consultant to industry and government including the National Science Foundation and the Bureau of Mines.

Dr. John H. Taylor

Professional Specialty: Visual Performance, Psychophysics, Visibility

Research Psychologist, Department of Psychology, University of California, San Diego

Former Head, Vision Research Branch, Visibility Laboratory, Scripps Institution of Oceanography, University of California, San Diego

Member, Optical Society of America

Member, Association for Research in Vision and Ophthalmology

Member, Sigma Xi

Dr. Taylor is a nationally-recognized expert in visual performance, having been a member of the Committee on Vision of the U.S. National Research Council since 1956. Dr. Taylor was a source of continuity between the present work and the previous work performed in establishing the coal mining illumination standard as well as the preliminary analysis of illumination needs in metal and nonmetal mining.

APPENDIX E

GLARE AND ADAPTATION EFFECTS
CAUSED BY THE MINER'S CAPLAMP

Nearly all underground mine workers use individual caplamps with an intense central beam and a relatively dim surround. The small central hotspot (about 5-10 degrees in diameter) is over 100 times brighter than the wide-angle surround, creating an adverse ratio of luminances in the visual scene. Glare and transient adaptation caused by the hotspot make it difficult to see small or low-contrast visual targets in the dimly lighted area outside the hotspot.

As part of a research program to recommend minimum luminance levels for safe and efficient performance of various underground mining jobs, it was necessary to determine how the glare and transient adaptation produced by the caplamp hotspot affect visual performance for low-luminance tasks in the mesopic region (0.01-0.1 fL).

If minimum luminance levels were determined with subjects fully adapted to low levels of even illumination, unrealistically low thresholds could be obtained. This would be due to an absence of realistic glare and transient adaptation effects produced by the typical caplamp in most underground work environments.

An initial series of pilot experiments confirmed the importance of including realistic glare and adaptation factors present in the mining environment when conducting controlled visual performance studies in the laboratory setting. Accordingly, a number of actual miner's caplamps were obtained for use in the Mine Illumination Research Facility established at Perceptronics, Inc., in Woodland Hills, California.

Two experiments were conducted in order to investigate the magnitude of the glare and adaptation effects associated with the caplamp's central beam. Five subjects (42, 37, 19, 19, and 18 years of age) with 20/20 vision and no known visual anomalies served as trained observers in visual "seeing time" experiments. The experiments compared task performance with and without the caplamp hotspot near the central visual target. The "caplamp illumination" condition was produced with a typical caplamp having a small hotspot and a dim surround; the "even illumination" condition was produced by a point source adjusted to provide an illumination level equal to the caplamp's dim surround 15 degrees from the center of the 5 degree hotspot. Subjects were tested individually, with many repeated trials in each of the two experiments.

The first experiment used a Landolt ring target (broken ring with thickness 1/5th its outer diameter of 4.375 inches, and a 0.875 inch gap equal to 36 minutes of arc from the subject's viewing position 6.5 meters away). The Landolt ring was relatively large but low in contrast (-14 percent), representing a fairly difficult visual task at the low level of the target background luminance (0.014 fL).

The target ring was mounted on a large disc of background material (illustration board) cut in a circle to eliminate overall shape as a cue to gap position. The surfaces were covered with paper of neutral matte reflectance so as to produce a non-specular contrast ratio of 1.16 to 1 between background and ring.

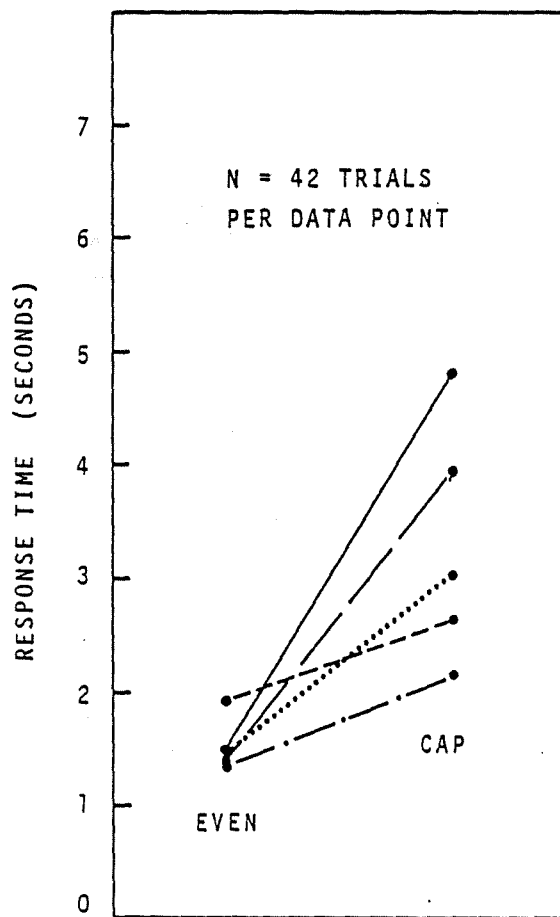
In a paradigm designed to represent the commonly occurring adverse visual effects of caplamp lighting, subjects fixated a 10 degree diameter caplamp hotspot (1.75 fL, at a distance of 6.5 feet) for 10 seconds (this produced a realistic loss of dark adaptation, and averted the subject's gaze to prevent seeing the upcoming target gap position). Then, upon a tone signal from a timing device, the subject looked over at the Landolt ring target, which was set in one of six possible orientations (gap at 12, 2, 4, 6, 8, or 10 o'clock). Simultaneously with the tone, a relay switched off the fixation caplamp and switched on the target-area caplamp, which had its 5 degree diameter hotspot (6.7 fL) only 10 degrees from the left edge of the target ring. Upon seeing the gap orientation, the subject pressed a button to stop the response timer.

The procedure for the even illumination condition was the same, except for the absence of the two caplamps used to produce transient adaptation and glare in the first condition. Subjects fixated the same adaptation location (0.01 fL) for 10 seconds, then upon hearing the tone signal, looked over at the Landolt ring to determine the orientation of the gap. Upon seeing the gap, the subject pressed a button to stop the response timer.

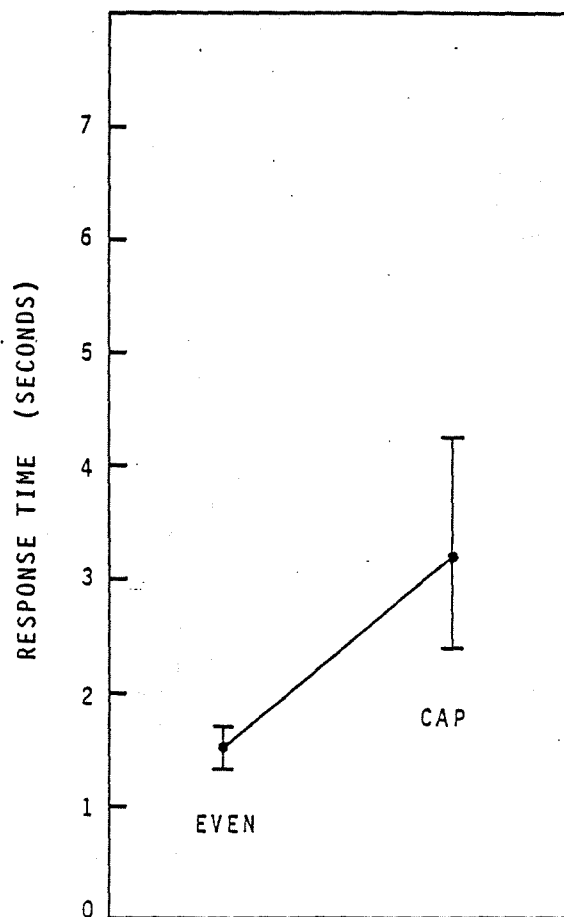
Results of the first experiment are shown in Figure D-1. The geometric means for the caplamp condition vs. the even lighting condition were 3.3 seconds and 1.5 seconds, with a mean difference of 1.8 seconds (standard deviation of the differences = 1.14, $t = 3.55$, $df = 4$, significant at the 0.05 level).

In both conditions, the Landolt ring target had a background luminance of 0.014 fL, but in the caplamp condition there was a 5 degree hotspot (6.7 fL) only 10 degrees from the edge of the target ring (producing significant disability glare), and the subject had fixated another caplamp hotspot (1.75 fL) for 10 seconds just prior to viewing the target. This paradigm simulated the common situation where the mine worker has been looking at targets in the hotspot just prior to looking for targets just outside the hotspot (the eyes move in and out of the hotspot, moving in a scan pattern larger than that of the head-mounted caplamp).

The differences in seeing times indicate that disability glare and transient adaptation effects associated with the caplamp hotspot can significantly interfere with detection of low-contrast targets in



INDIVIDUAL DATA FOR 5 SUBJECTS
(GEOMETRIC MEANS)



AVERAGE RESPONSE TIMES
(MEAN $\pm$ 2 STD ERROR)

FIGURE E-1. - Geometric mean response time for detection of Landolt ring gap under even and caplamp illumination.

the dim area just outside the hotspot.

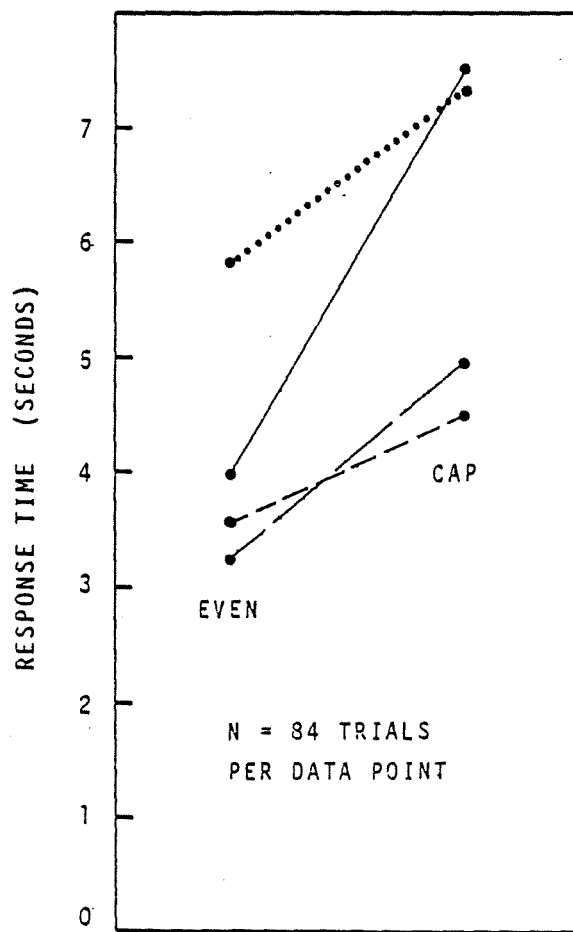
The second experiment sought to determine if the detection of small targets would be similarly affected by the caplamp hotspot. The simulated rock-crack detection task described in Section 2.4.2 was used with the viewing distance reduced to 6 feet (making it possible to see the target crack locations without any supplement to the illumination from a single caplamp). The caplamp condition was the same as that used in the performance testing reported in Section 3 of this report. Subjects fixated a 10 degree diameter hotspot (0.5 fL) for 10 seconds, then upon a tone signal from a timing device, looked up at the crack target. A relay switched the fixation caplamp off and simultaneously switched on a second caplamp with its 5 degree hotspot (1.5 fL) in the center of the hexagonal array of potential target crack locations. Upon locating the open crack (one and only one target crack was presented in each trial), the subject pressed a button to stop the response timer. Again, the procedure for the even illumination condition was identical except for the absence of the two caplamp hotspots. A point source was adjusted to provide even illumination equal to that produced by the caplamp's penumbra in the target locations.

Results of the crack detection experiment are shown in Figure D-2. The geometric means for the caplamp condition vs. the even lighting condition were 4.1 seconds and 6.0 seconds, with a mean difference of 1.9 seconds (standard deviation of the differences = 1.13, $t = 3.36$, $df = 3$, significant at the 0.05 level).

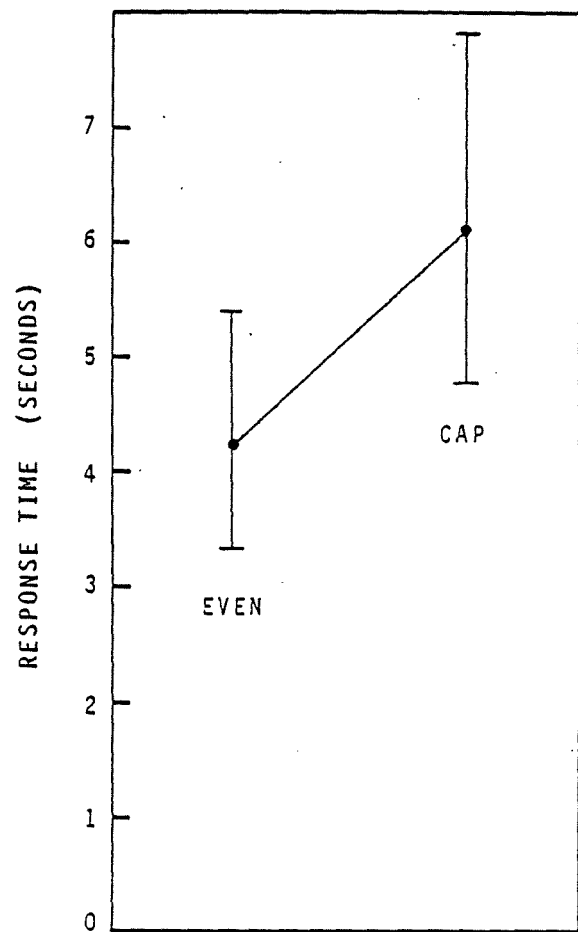
In both conditions, the target cracks had a background luminance of 0.006 fL, but in the caplamp condition, there was a 5 degree hotspot centered approximately 10 degrees from the hexagonal array of six potential crack locations; furthermore, the subject fixated another caplamp hotspot for 10 seconds just prior to searching for the target in each trial.

The differences in seeing times indicate that disability glare and transient adaptation effects associated with the caplamp hotspot can impair detection of small targets like rock cracks, as well as interfering with detection of larger low-contrast targets such as the Landolt ring tested in the first experiment.

The results of these preliminary experiments pointed out the importance of including realistic caplamp glare and adaptation effects in our primary research program to determine minimum luminance requirements for underground mining tasks.



INDIVIDUAL DATA FOR 4 SUBJECTS
(GEOMETRIC MEANS)



AVERAGE RESPONSE TIMES
(MEAN $\pm$ 2 STD ERROR)

FIGURE E-2. - Geometric mean response time for detection of cracks under even and caplamp illumination.

APPENDIX F
INDIVIDUAL OBSERVER VISUAL TASK
PERFORMANCE DATA

TABLE F-1. - Geometric mean response time (seconds) for crack detection

Observer: TP Targets: Wide surface cracks at average distance of eight feet.

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	C	E	F		C	E	F	
0.01 fL ^c	7.0374	2.1829	2.0420	3.1538	6.7015	5.2981	1.9197	4.0848
Geo. mean	0.8474	0.3390	0.3101	0.4988	0.8262	0.7241	0.2832	0.6112
Log mean	0.2302	0.1935	0.3101	0.3040	0.2458	0.1916	0.1304	0.3042
Log SD ^d			0.0673					
0.02 fL								
Geo. mean	5.2770	3.5945	1.2491	2.8722	3.7089	1.6642	1.6817	2.1818
Log mean	0.7224	0.5556	0.0966	0.4582	0.5692	0.2212	0.2257	0.3387
Log SD	0.2602	0.1040	0.0427	0.3124	0.1128	0.2096	0.0789	0.2162
0.03 fL								
Geo. mean	2.5369	1.1745	1.5237	1.6558	2.0902	1.6788	1.4141	1.7056
Log mean	0.4043	0.0699	0.1829	0.2190	0.3202	0.2250	0.1505	0.2319
Log SD	0.0652	0.0542	0.1277	0.1652	0.1715	0.3082	0.1574	0.2232
0.06 fL								
Geo. mean	1.8554	1.4304	1.0135	1.3907	1.3383	1.7764	1.5557	1.5464
Log mean	0.2684	0.1555	0.0058	0.1432	0.1265	0.2495	0.1919	0.1893
Log SD	0.0507	0.1121	0.0732	0.1352	0.0871	0.0923	0.1310	0.1124
0.10 fL								
Geo. mean	1.2733	0.9433	0.8638	1.0124	1.4769	1.1331	0.9679	1.1744
Log mean	0.1049	-0.0253	-0.0636	0.0053	0.1693	0.0543	-0.0142	0.0698
Log SD	0.0678	0.0417	0.0410	0.0887	0.1306	0.0741	0.0391	0.1151
0.20 fL								
Geo. mean	1.6965	0.9628	0.8063	1.0961	1.3759	1.0456	0.9634	1.1149
Log mean	0.2295	-0.0165	-0.0935	0.0399	0.1386	0.0194	-0.0162	0.0473
Log SD	0.0902	0.0264	0.1210	0.1642	0.1157	0.0648	0.0549	0.1038

^aN=7 trials per cell.

^bN=21 trials per cell.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

TABLE F-1 . - Geometric mean response time (seconds) for crack detection (Cont'd)

Observer: JM Targets: Wide surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	C	E	F		C	E	F	
0.01 fL ^c								
Geo. mean	7.1560	6.6342	3.4669	5.4802	6.3339	5.6865	4.6652	5.5182
Log mean	0.8547	0.8218	0.5399	0.7388	0.8017	0.7548	0.6689	0.7418
Log SD ^d	0.3160	0.4609	0.3104	0.3789	0.3853	0.2184	0.2288	0.2788
0.02 fL								
Geo. mean	2.2078	1.4265	1.1668	1.5432	6.0952	1.7650	1.8598	2.7148
Log mean	0.3440	0.1543	0.0670	0.1884	0.7850	0.2467	0.2695	0.4337
Log SD	0.2076	0.2117	0.0714	0.2048	0.2878	0.2618	0.1645	0.3441
0.03 fL								
Geo. mean	2.3814	1.2517	1.0311	1.4539	1.9824	1.4384	1.6158	1.6640
Log mean	0.3768	0.0975	0.0133	0.1625	0.2972	0.1579	0.2084	0.2212
Log SD	0.0916	0.0628	0.1050	0.1799	0.1906	0.1424	0.1711	0.1710
0.06 fL								
Geo. mean	1.2096	0.7882	0.9748	0.9759	1.7935	1.0455	0.8380	1.1626
Log mean	0.0827	-0.1034	-0.0111	-0.0106	0.2537	0.0193	-0.0767	0.0654
Log SD	0.1069	0.0898	0.1244	0.1286	0.0931	0.0358	0.0823	0.1589
0.10 fL								
Geo. mean	1.4579	0.9510	0.9284	1.0878	1.2098	0.9093	0.8146	0.9641
Log mean	0.1637	-0.0218	-0.0322	0.0366	0.0827	-0.0413	-0.0890	-0.0159
Log SD	0.1688	0.0772	0.0782	0.1438	0.1100	0.0416	0.0367	0.1003
0.20 fL								
Geo. mean	1.0568	0.8172	0.8164	0.8900	1.7239	0.9757	0.9338	1.1624
Log mean	0.0240	-0.0877	-0.0881	-0.0506	0.2365	-0.0107	-0.0298	0.0654
Log SD	0.0741	0.0559	0.0636	0.0820	0.1325	0.0603	0.0692	0.1524

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-1. - Geometric mean response time (seconds) for crack detection (Cont'd)

Observer: BB Targets: Wide surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	C	E	F		C	E	F	
0.01 fL ^c								
Geo. mean	4.3953	1.4812	1.5749	2.1724	11.2827	4.9083	2.2620	5.0035
Log mean	0.6430	0.1706	0.1973	0.3369	1.0524	0.6909	0.3545	0.6993
Log SD ^d	0.0576	0.1485	0.1029	0.2451	0.1933	0.1762	0.1816	0.3401
0.02 fL								
Geo. mean	5.9989	2.7764	1.3210	2.8021	2.3785	0.9466	1.3316	1.4419
Log mean	0.7781	0.4435	0.1209	0.4475	0.3763	-0.0238	0.1244	0.1589
Log SD	0.2852	0.2265	0.3116	0.3802	0.1487	0.0736	0.2176	0.2261
0.03 fL								
Geo. mean	1.5782	0.9500	1.1030	1.1825	3.5781	2.1957	1.3216	2.1816
Log mean	0.1982	-0.0223	0.0426	0.0728	0.5537	0.3416	0.1241	0.3388
Log SD	0.0776	0.1709	0.1514	0.1626	0.1665	0.0756	0.1140	0.2160
0.06 fL								
Geo. mean	2.3201	1.4363	0.8771	1.4298	1.5742	0.9398	1.1729	1.2017
Log mean	0.3655	0.1572	-0.0570	0.1553	0.1971	-0.0270	0.0693	0.0798
Log SD	0.1777	0.0794	0.0658	0.2095	0.0855	0.1445	0.1389	0.1520
0.10 fL								
Geo. mean	0.9960	0.7964	1.0754	0.9484	1.6223	1.0647	0.7316	1.0811
Log mean	-0.0018	-0.0989	0.0316	-0.0230	0.2101	0.0172	-0.1357	0.0339
Log SD	0.0418	0.0966	0.0638	0.0881	0.0683	0.1123	0.0706	0.1662
0.20 fL								
Geo. mean	1.2989	0.7396	0.8121	0.9205	1.0870	0.9949	0.9460	1.0076
Log mean	0.1136	-0.1310	-0.0904	-0.0360	0.0362	-0.0022	-0.0241	0.0033
Log SD	0.0719	0.0434	0.0941	0.1296	0.0599	0.0477	0.2248	0.1326

^aN=7 trials per cell.

^bN=21 trials per cell.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

TABLE F-1 . - Geometric mean response time (seconds) for crack detection (Cont'd)

Observer: JG Targets: Wide surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	C	E	F		C	E	F	
0.01 fL ^c								
Geo. mean	2.7471	2.3502	2.4862	2.5225	2.7835	1.6881	1.5703	1.9468
Log mean	0.4389	0.3711	0.3955	0.4018	0.4446	0.2274	0.1960	0.2893
Log SD ^d	0.1869	0.1865	0.1709	0.1746	0.2328	0.1500	0.1285	0.2020
0.02 fL								
Geo. mean	2.5022	1.8623	1.1916	1.7708	3.7747	1.8837	1.0164	1.9334
Log mean	0.3983	0.2701	0.0761	0.2482	0.5769	0.2750	0.0071	0.2863
Log SD	0.1751	0.3661	0.1766	0.2778	0.1493	0.2279	0.0574	0.2831
0.03 fL								
Geo. mean	2.4890	1.6951	1.0321	1.6330	1.9063	1.0776	1.1126	1.3173
Log mean	0.3960	0.2292	0.0137	0.2130	0.2802	0.0325	0.0464	0.1197
Log SD	0.1156	0.2302	0.0658	0.2166	0.1003	0.1541	0.0595	0.1574
0.06 fL								
Geo. mean	1.3230	1.0190	1.1058	1.1424	2.1516	1.2406	0.9703	1.3734
Log mean	0.1216	0.0082	0.0437	0.0578	0.3328	0.0936	-0.0130	0.1378
Log SD	0.0834	0.1479	0.0585	0.1097	0.0504	0.0985	0.1114	0.1713
0.10 fL								
Geo. mean	2.0180	1.4835	1.0611	1.4700	1.1350	0.9686	1.1318	1.0756
Log mean	0.3049	0.1713	0.0258	0.1673	0.0550	-0.0139	0.0538	0.0316
Log SD	0.1083	0.0955	0.0952	0.1504	0.0810	0.1152	0.1592	0.1210
0.20 fL								
Geo. mean	1.0921	1.0048	0.8579	0.9801	1.4759	1.1877	0.7518	1.0964
Log mean	0.0383	0.0021	-0.0665	-0.0087	0.1691	0.0747	-0.1239	0.0400
Log SD	0.0942	0.1423	0.0846	0.1134	0.0684	0.1504	0.0241	0.1550

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-1 . - Geometric mean response time (seconds) for crack detection (Concluded)

Observer: SB Targets: Wide surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	C	E	F		C	E	F	
0.01 fL ^c								
Geo. mean	1.9364	3.2428	1.8481	2.2640	4.0192	4.8438	2.4426	3.6229
Log mean	0.2870	0.5109	0.2667	0.3549	0.6041	0.6852	0.3879	0.5591
Log SD ^d	0.1169	0.1859	0.1807	0.1927	0.1449	0.2344	0.1899	0.2239
0.02 fL								
Geo. mean	2.8961	2.4277	1.7989	2.3299	1.8846	1.4476	1.1959	1.4832
Log mean	0.4618	0.3852	0.2550	0.3673	0.2752	0.1607	0.0777	0.1712
Log SD	0.0841	0.2405	0.1765	0.1910	0.0788	0.1879	0.0545	0.1423
0.03 fL								
Geo. mean	1.7145	1.2515	1.3938	1.4408	2.0705	1.2468	0.9155	1.3320
Log mean	0.2341	0.0974	0.1442	0.1586	0.3161	0.0958	-0.0383	0.1245
Log SD	0.1188	0.1202	0.1181	0.1270	0.0792	0.0592	0.0764	0.1646
0.06 fL								
Geo. mean	2.2437	2.6966	1.5273	2.0984	1.1668	0.9229	0.9514	1.0081
Log mean	0.3510	0.4308	0.1839	0.3219	0.0670	-0.0348	-0.0216	0.0035
Log SD	0.1853	0.2673	0.2405	0.2454	0.0418	0.0520	0.0514	0.0654
0.10 fL								
Geo. mean	1.1964	1.2669	1.1717	1.2110	1.2756	1.1232	0.9259	1.0988
Log mean	0.0779	0.1028	0.0688	0.0832	0.1057	0.0504	-0.0335	0.0409
Log SD	0.0364	0.1569	0.1611	0.1257	0.0584	0.0449	0.0362	0.0739
0.20 fL								
Geo. mean	1.3705	1.1147	1.2175	1.2298	1.2013	1.0015	1.0998	1.0978
Log mean	0.1369	0.0472	0.0855	0.0898	0.0796	0.0007	0.0413	0.0405
Log SD	0.0691	0.1206	0.1191	0.1071	0.0985	0.0739	0.1098	0.0962

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-2 . - Geometric mean response time (seconds) for crack detection

Observer: TP Targets: Narrow surface cracks at average distance of eight feet.

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	A	B	D		A	B	D	
0.01 fL ^c								
Geo. mean	7.7791	9.0228	18.6203	10.9333	5.4882	9.7358	8.9248	7.8127
Log mean	0.8909	0.9553	1.2700	1.0388	0.7394	0.9884	0.9506	0.8928
Log SD ^d	0.1522	0.1568	0.2619	0.2524	0.1885	0.1650	0.1533	0.1961
0.02 fL								
Geo. mean	4.3390	3.4851	4.7200	4.1481	2.9458	4.2252	5.8958	4.1866
Log mean	0.6374	0.5422	0.6739	0.6178	0.4692	0.6258	0.7705	0.6210
Log SD	0.3151	0.2544	0.1450	0.2424	0.1537	0.1180	0.1203	0.1775
0.03 fL								
Geo. mean	3.2168	3.5987	4.0977	3.6200	3.2511	4.8546	3.9511	3.9655
Log mean	0.5074	0.5561	0.6125	0.5587	0.5120	0.6862	0.5967	0.5983
Log SD	0.1445	0.2224	0.2363	0.1995	0.1124	0.2955	0.1618	0.2077
0.06 fL								
Geo. mean	2.0589	2.8580	1.6520	2.1342	2.2122	3.8915	4.0725	3.2729
Log mean	0.3136	0.4561	0.2180	0.3292	0.3448	0.5901	0.6099	0.5149
Log SD	0.2070	0.1299	0.0657	0.1710	0.1770	0.2682	0.1043	0.2225
0.10 fL								
Geo. mean	1.5053	2.2949	3.0833	2.2002	1.6222	1.6207	1.6401	1.6277
Log mean	0.1776	0.3608	0.4890	0.3425	0.2101	0.2097	0.2149	0.2116
Log SD	0.0994	0.1411	0.0939	0.1695	0.1149	0.1470	0.0835	0.1120
0.20 fL								
Geo. mean	1.3470	1.4676	1.8301	1.5351	1.3564	1.6878	2.4227	1.7701
Log mean	0.1294	0.1666	0.2625	0.1861	0.1324	0.2273	0.3843	0.2480
Log SD	0.0710	0.0768	0.0908	0.0952	0.1185	0.1274	0.1449	0.1634

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-2 . - Geometric mean response time (seconds) for crack detection (Cont'd)

Observer: JM Targets: Narrow surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	A	B	D		A	B	D	
0.01 fL ^c								
Geo. mean	16.7453	27.9769	14.3620	18.8787	16.0198	12.9113	20.7519	16.2516
Log mean	1.2239	1.4468	1.1572	1.2760	1.2047	1.1110	1.3171	1.2109
Log SD ^d	0.2548	0.1604	0.2912	0.2622	0.2396	0.4623	0.2121	0.3198
0.02 fL								
Geo. mean	3.3912	3.9837	6.6280	4.4738	25.8498	13.1388	9.1069	14.5701
Log mean	0.5304	0.6003	0.8214	0.6507	1.4125	1.1186	0.9594	1.1635
Log SD	0.1706	0.1267	0.1709	0.1961	0.2955	0.3225	0.2702	0.3410
0.03 fL								
Geo. mean	4.4646	4.2299	3.4801	4.0355	3.9973	4.2441	8.4597	5.2357
Log mean	0.6498	0.6263	0.5416	0.6059	0.6018	0.6278	0.9274	0.7190
Log SD	0.0763	0.3905	0.2163	0.2526	0.2393	0.1252	0.1213	0.2219
0.06 fL								
Geo. mean	1.5631	1.4657	3.0009	1.9015	3.3064	2.3414	2.4623	2.6713
Log mean	0.1940	0.1660	0.4773	0.2791	0.5194	0.3695	0.3913	0.4267
Log SD	0.1794	0.0980	0.1184	0.1936	0.2121	0.0704	0.1676	0.1673
0.10 fL								
Geo. mean	1.9669	1.7519	1.5387	1.7438	1.6928	1.4336	3.7466	2.0872
Log mean	0.2938	0.2435	0.1872	0.2415	0.2286	0.1564	0.5736	0.3196
Log SD	0.0533	0.1070	0.0725	0.0886	0.0716	0.0599	0.0931	0.2001
0.20 fL								
Geo. mean	1.1802	0.9906	1.8072	1.2832	2.3408	1.9643	1.8851	2.0542
Log mean	0.0720	-0.0041	0.2570	0.1083	0.3694	0.2932	0.2753	0.3126
Log SD	0.1219	0.1058	0.0986	0.1528	0.1487	0.1552	0.0869	0.1337

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-2. - Geometric mean response time (seconds) for crack detection (Cont'd)

Observer: BB Targets: Narrow surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	A	B	D		A	B	D	
0.01 fL ^c								
Geo. mean	5.7785	10.3103	27.2234	11.7492	20.7266	20.8682	15.4322	18.8284
Log mean	0.7618	1.0133	1.4349	1.0700	1.3165	1.3195	1.1884	1.2748
Log SD ^d	0.3829	0.2154	0.1657	0.3836	0.2703	0.2874	0.3303	0.2887
0.02 fL								
Geo. mean	5.1547	3.3195	6.1576	4.7231	2.9625	4.2371	6.7628	4.3949
Log mean	0.7122	0.5211	0.7894	0.6742	0.4717	0.6271	0.8301	0.6430
Log SD	0.1966	0.2921	0.1892	0.2476	0.1178	0.2581	0.3068	0.2739
0.03 fL								
Geo. mean	2.8008	4.3816	7.0143	4.4154	5.1800	3.6325	4.5105	4.3946
Log mean	0.4473	0.6416	0.8460	0.6450	0.7143	0.5602	0.6542	0.6429
Log SD	0.1270	0.2510	0.2958	0.2790	0.3214	0.2335	0.2168	0.2563
0.06 fL								
Geo. mean	3.6656	3.2183	3.2419	3.3692	2.1414	3.0809	3.6790	2.8953
Log mean	0.5641	0.5076	0.5108	0.5275	0.3307	0.4887	0.5657	0.4617
Log SD	0.3413	0.2404	0.2235	0.2607	0.1584	0.2345	0.2851	0.2418
0.10 fL								
Geo. mean	1.5110	1.9765	2.1111	1.8474	1.7159	2.0482	2.5594	2.0797
Log mean	0.1793	0.2959	0.3245	0.2666	0.2345	0.3114	0.4081	0.3180
Log SD	0.0939	0.1942	0.1516	0.1581	0.2725	0.0710	0.2053	0.2043
0.20 fL								
Geo. mean	1.3567	1.4442	1.8856	1.5459	1.5261	2.2151	2.3287	1.9893
Log mean	0.1325	0.1596	0.2755	0.1892	0.1836	0.3454	0.3671	0.2987
Log SD	0.2710	0.1302	0.1831	0.2030	0.0961	0.1266	0.2795	0.1951

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-2 . - Geometric mean response time (seconds) for crack detection (Cont'd)

Observer: JG Targets: Narrow surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	A	B	D		A	B	D	
0.01 fL ^c								
Geo. mean	5.9433	6.0129	10.9926	7.3238	8.7268	9.2093	10.2484	9.3738
Log mean	0.7740	0.7791	1.0411	0.8647	0.9409	0.9642	1.0107	0.9719
Log SD ^d	0.2236	0.3407	0.4007	0.3381	0.3495	0.3637	0.1389	0.2881
0.02 fL								
Geo. mean	3.5163	3.6540	4.9293	3.9861	3.8651	5.5629	3.9586	4.3988
Log mean	0.5461	0.5628	0.6928	0.6005	0.5872	0.7453	0.5975	0.6433
Log SD	0.3859	0.2027	0.2680	0.2882	0.3062	0.2670	0.2297	0.2661
0.03 fL								
Geo. mean	1.8220	3.2404	4.3788	2.9569	3.3207	4.1849	4.1152	3.8527
Log mean	0.2605	0.5106	0.6414	0.4708	0.5212	0.6217	0.6144	0.5858
Log SD	0.2031	0.1883	0.2178	0.2519	0.1548	0.2007	0.1202	0.1607
0.06 fL								
Geo. mean	2.4967	2.5443	3.5521	2.8258	1.5731	2.5579	2.0092	2.0070
Log mean	0.3974	0.4056	0.5505	0.4511	0.1968	0.4079	0.3030	0.3026
Log SD	0.1001	0.0680	0.0481	0.1014	0.1522	0.1518	0.0523	0.1499
0.10 fL								
Geo. mean	2.0260	1.7412	2.1192	1.9553	1.8923	1.5673	3.4889	2.1791
Log mean	0.3066	0.2409	0.3262	0.2912	0.2770	0.1951	0.5427	0.3383
Log SD	0.2164	0.1891	0.1903	0.1925	0.0833	0.0989	0.1018	0.1767
0.20 fL								
Geo. mean	1.6195	1.6980	2.0133	1.7690	1.1724	1.4466	1.4244	1.3418
Log mean	0.2094	0.2299	0.3039	0.2477	0.0691	0.1603	0.1536	0.1277
Log SD	0.2165	0.1552	0.0960	0.1606	0.0694	0.1552	0.0701	0.1093

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-2 . - Geometric mean response time (seconds) for crack detection (Concluded)

Observer: SB Targets: Narrow surface cracks at average distance of eight feet

Luminance level	Run 1 ^a				Run 2 ^a			
	Target designation			Across targets ^b	Target designation			Across targets ^b
	A	B	D		A	B	D	
0.01 fL ^c								
Geo. mean	7.9778	4.5829	12.1495	7.6301	4.4661	8.2645	3.4413	5.0268
Log mean	0.9019	0.6611	1.0846	0.8825	0.6499	0.9172	0.5367	0.7013
Log SD ^d	0.1621	0.3342	0.1424	0.2811	0.2775	0.1689	0.1083	0.2488
0.02 fL								
Geo. mean	7.8475	4.4790	3.0425	4.7466	2.9022	3.0992	2.9188	2.9721
Log mean	0.8947	0.6512	0.4832	0.6764	0.4627	0.4912	0.4652	0.4731
Log SD	0.2216	0.2031	0.1951	0.2617	0.1299	0.2650	0.1686	0.1866
0.03 fL								
Geo. mean	2.6838	2.0279	8.3133	3.5633	3.0071	2.6362	2.7157	2.7819
Log mean	0.4287	0.3071	0.9198	0.5519	0.4781	0.4210	0.4339	0.4443
Log SD	0.1912	0.0948	0.3796	0.3613	0.0841	0.1385	0.2232	0.1532
0.06 fL								
Geo. mean	5.1325	3.5395	1.7222	3.1510	2.0888	1.5004	2.4549	1.9742
Log mean	0.7103	0.5489	0.2361	0.4984	0.3199	0.1762	0.3900	0.2954
Log SD	0.2291	0.1923	0.1239	0.2686	0.0487	0.0629	0.0771	0.1095
0.10 fL								
Geo. mean	2.3134	1.4466	4.1604	2.4057	1.4051	1.6943	1.4527	1.5123
Log mean	0.3643	0.1603	0.6191	0.3813	0.1477	0.2290	0.1622	0.1796
Log SD	0.1280	0.0566	0.1617	0.2252	0.1424	0.0379	0.0964	0.1030
0.20 fL								
Geo. mean	2.7237	2.2188	1.5187	2.0937	1.2612	1.3488	1.9603	1.4940
Log mean	0.4352	0.3461	0.1815	0.3209	0.1008	0.1299	0.2923	0.1743
Log SD	0.1370	0.0681	0.0987	0.1468	0.0604	0.0524	0.1375	0.1227

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of eight feet.^dSD Standard deviation of time in log seconds.

TABLE F-3 . - Geometric mean response time (seconds) and errors for rock motion detection

OBSERVER: TP RUN: 1 TARGETS: Six small rocks at average distance of eight feet

Luminance Level	TARGET POSITION ^a						Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.5047	0.5349	0.5550	0.4780	0.5188	0.4989	0.5143
Log mean	-0.2969	-0.2718	-0.2557	-0.3205	-0.2850	-0.3020	-0.2888
Log SD ^d	0.0987	0.1053	0.0809	0.1063	0.0888	0.0799	0.0936
Errors ^e	1	0	1	0	0	1	3
0.03 fL							
	0.4483	0.4996	0.4581	0.4459	0.4633	0.4542	0.4609
	-0.3484	-0.3014	-0.3390	-0.3507	-0.3341	-0.3428	-0.3364
	0.1065	0.1035	0.0683	0.0473	0.0460	0.0669	0.0755
	1	1	0	0	0	0	2
0.06 fL							
	0.4107	0.4444	0.3911	0.3802	0.4174	0.4142	0.4098
	-0.3865	-0.3523	-0.4077	-0.4199	-0.3794	-0.3828	-0.3875
	0.0462	0.1045	0.0525	0.0368	0.0335	0.0466	0.0608
	0	0	1	1	0	0	2
0.10 fL							
	0.3945	0.3898	0.3775	0.3585	0.4046	0.3708	0.3824
	-0.4039	-0.4091	-0.4231	-0.4455	-0.3930	-0.4308	-0.4175
	0.0573	0.0407	0.0792	0.0412	0.0332	0.0374	0.0518
	0	0	1	0	0	0	1
0.40 fL							
	0.3397	0.3607	0.3339	0.3590	0.3621	0.3483	0.3504
	-0.4689	-0.4428	-0.4764	-0.4449	-0.4412	-0.4581	-0.4554
	0.0450	0.0398	0.0375	0.0436	0.0495	0.1270	0.0647
	0	0	0	0	0	0	0

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time ≥ 1.0 seconds.

TABLE F-3. - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: TP RUN: 2 TARGETS: Six small rocks at average distance of eight feet.

Luminance Level	TARGET POSITION ^a						Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.4778	0.4554	0.4922	0.4683	0.4914	0.4624	0.4737
Log mean	-.3208	-.3416	-.3079	-.3294	-.3086	-.3350	-0.3245
Log SD ^d	0.1016	0.0815	0.0665	0.0905	0.0904	0.0995	0.0875
Errors ^e	1	0	2	0	1	0	4
0.03 fL							
	0.4080	0.4102	0.3995	0.3934	0.4402	0.3924	0.4070
	-.3894	-.3870	-.3985	-.4052	-.3563	-.4063	-0.3904
	0.0361	0.0426	0.0350	0.0299	0.0744	0.0436	0.0477
	0	0	0	0	0	0	0
0.06 fL							
	0.3645	0.3857	0.3829	0.3738	0.3888	0.3678	0.3771
	-.4383	-.4138	-.4169	-.4274	-.4103	-.4344	-0.4235
	0.0238	0.0472	0.0473	0.0458	0.0354	0.0297	0.0396
	0	0	0	0	0	0	0
0.10 fL							
	0.3373	0.3691	0.3723	0.3486	0.3845	0.3545	0.3607
	-.4720	-.4328	-.4291	-.4577	-.4151	-.4504	-0.4429
	0.0385	0.0306	0.0462	0.0285	0.0456	0.0464	0.0433
	0	0	0	0	0	0	0
0.40 fL							
	0.3394	0.3594	0.3206	0.3443	0.3541	0.3296	0.3410
	-.4693	-.4444	-.4940	-.4631	-.4509	-.4812	-0.4673
	0.0262	0.0376	0.0449	0.0413	0.0330	0.0473	0.0415
	0	0	0	0	0	0	0

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3 . - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: JM RUN: 1 TARGETS: Six small rocks at average distance of eight feet.

Luminance Level	TARGET POSITION ^a						Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.5148	0.5222	0.5070	0.4736	0.5677	0.5256	0.5198
Log mean	-.2884	-.2822	-.2950	-.3246	-.2459	-.2793	-0.2841
Log SD ^d	0.1038	0.0675	0.0993	0.0358	0.0404	0.0582	0.0740
Errors ^e	1	2	4	4	1	4	16
0.03 fL							
	0.4966	0.5043	0.5198	0.4488	0.5350	0.5366	0.5090
	-.3040	-.2973	-.2842	-.3479	-.2717	-.2704	-0.2933
	0.0791	0.0849	0.1066	0.0452	0.0615	0.1003	0.0845
	1	3	0	4	0	1	9
0.06 fL							
	0.4315	0.4651	0.4310	0.4449	0.4799	0.4832	0.4555
	-.3650	-.3325	-.3655	-.3517	-.3188	-.3158	-0.3415
	0.0578	0.1012	0.0678	0.0629	0.0864	0.0947	0.0798
	0	2	2	0	1	0	5
0.10 fL							
	0.4109	0.4074	0.4196	0.4022	0.4178	0.4062	0.4107
	-.3863	-.3900	-.3771	-.3956	-.3790	-.3912	-0.3865
	0.0605	0.0620	0.1172	0.0564	0.0371	0.0549	0.0679
	1	0	0	1	1	0	3
0.40 fL							
	0.3497	0.3640	0.3578	0.3727	0.4003	0.3561	0.3664
	-.4563	-.4389	-.4464	-.4287	-.3976	-.4484	-0.4360
	0.0527	0.0578	0.0577	0.0316	0.0437	0.0345	0.0499
	0	0	0	0	0	0	0

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3 . - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: JM RUN: 2 TARGETS: Six small rocks at average distance of eight feet

Luminance Level	TARGET POSITION ^a						Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.4988	0.5549	0.4919	0.4797	0.5987	0.4862	0.5184
Log mean	-.3020	-.2558	-.3082	-.3190	-.2228	-.3132	-0.2854
Log SD ^d	0.0801	0.0788	0.0388	0.0534	0.0917	0.0348	0.0742
Errors ^e	2	1	3	4	4	6	20
0.03 fL							
	0.4812	0.4804	0.4396	0.4197	0.4923	0.4894	0.4672
	-.3177	-.3184	-.3569	-.3770	-.3078	-.3103	-0.3305
	0.1109	0.0509	0.0775	0.0418	0.0752	0.0828	0.0789
	0	0	1	1	0	0	2
0.06 fL							
	0.4505	0.4607	0.4457	0.4519	0.4944	0.4411	0.4568
	-.3463	0.3366	-.3510	-.3450	-.3060	-.3555	-0.3403
	0.0619	0.0868	0.0795	0.0687	0.0760	0.0660	0.0732
	0	0	0	0	1	1	2
0.10 fL							
	0.4659	0.4536	0.4450	0.4225	0.4662	0.4344	0.4491
	-.3317	-.3434	-.3516	-.3741	-.3314	-.3621	-0.3476
	0.1104	0.0406	0.0496	0.0485	0.0751	0.0849	0.0731
	0	1	1	4	0	1	7
0.40 fL							
	0.4038	0.4227	0.4103	0.4002	0.4343	0.4100	0.4136
	0.3938	-.3739	-.3869	-.3977	-.3622	-.3872	-0.3834
	0.0785	0.0529	0.0519	0.0550	0.0558	0.0526	0.0581
	0	0	1	1	0	0	2

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3 . - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: BB RUN: 1 TARGETS: Six small rocks at average distance of eight feet.

Luminance Level	TARGET POSITION ^a						Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.4095	0.4257	0.3815	0.3964	0.4153	0.4497	0.4140
Log mean	-.3878	-.3709	-.4185	-.4019	-.3816	-.3470	-0.3830
Log SD ^d	0.0379	0.1274	0.0363	0.1106	0.0536	0.1025	0.0888
Errors ^e	3	0	3	3	3	1	13
0.03 fL							
	0.3818	0.3695	0.3680	0.3655	0.3949	0.3740	0.3754
	-.4182	-.4324	-.4342	-.4371	-.4035	-.4272	-0.4255
	0.0946	0.0363	0.0715	0.0684	0.0471	0.0568	0.0638
	1	0	0	0	0	0	1
0.06 fL							
	0.3989	0.3948	0.3543	0.3613	0.3848	0.3411	0.3714
	-.3991	0.4037	-.4506	-.4422	-.4148	-.4671	-0.4301
	0.0927	0.1043	0.0976	0.0855	0.1115	0.0588	0.0939
	3	0	1	2		0	6
0.10 fL							
	0.3154	0.3448	0.3003	0.3299	0.3414	0.3508	0.3300
	-.5012	-.4624	-.5224	-.4816	-.4667	-.4550	-0.4815
	0.0368	0.0879	0.0494	0.0704	0.0566	0.1013	0.0725
	0	0	0	0	0	0	0
0.40 fL							
	0.3092	0.3211	0.3111	0.3123	0.3203	0.3035	0.3129
	-.5097	-.4934	-.5071	0.5055	-.4944	-.5178	-0.5046
	0.0539	0.0683	0.0989	0.0510	0.0560	0.0686	0.0665
	0	0	0	0	0	0	0

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3. - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: BB RUN: 2 TARGETS: Six small rocks at average distance of eight feet.

Luminance Level							Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.4228	0.4487	0.3938	0.3911	0.4350	0.4437	0.4239
Log mean	-.3739	-.3478	-.4047	-.4077	-.3615	-.3529	-0.3727
Log SD ^d	0.0892	0.1434	0.0467	0.0606	0.0658	0.0971	0.0914
Errors ^e	1	0	2	3	0	0	6
0.03 fL							
	0.3813	0.3809	0.3745	0.3594	0.3925	0.3949	0.3804
	-.4187	-.4192	-.4266	-.4444	-.4062	-.4035	-0.4198
	0.1285	0.0819	0.1035	0.0544	0.0430	0.1068	0.0892
	1	1	0	0	0	0	2
0.06 fL							
	0.3453	0.3608	0.3105	0.3495	0.3607	0.3367	0.3435
	-.4617	-.4427	-.5079	-.4566	-.4429	-.4727	-0.4641
	0.0817	0.0751	0.0458	0.0615	0.0404	0.0550	0.0636
	1	0	0	0	0	0	1
0.10 fL							
	0.3414	0.3637	0.3249	0.3612	0.3531	0.3274	0.3448
	-.4668	-.4393	-.4882	-.4423	-.4521	-.4850	-0.4625
	0.0640	0.0532	0.1130	0.0976	0.0674	0.0692	0.0795
	0	1	1	1	0	0	3
0.40 fL							
	0.3228	0.2914	0.3056	0.3062	0.3142	0.3023	0.3070
	-.4910	-.5356	-.5148	-.5140	-.5029	-.5196	-0.5128
	0.1350	0.0358	0.0697	0.0552	0.0397	0.0600	0.0734
	0	1	0	0	1	0	2

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3. - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: JG RUN: 1 TARGETS: Six small rocks at average distance eight feet

Luminance Level							Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.4385	0.3908	0.4207	0.4082	0.5625	0.3842	0.4315
Log mean	-.3581	-.4080	-.3760	-.3891	-.2499	-.4155	-0.3650
Log SD ^d	0.0896	0.0745	0.0607	0.0951	0.1460	0.0540	0.1063
Errors ^e	2	1	1	0	0	1	5
0.03 fL							
	0.3947	0.4284	0.4282	0.3818	0.4370	0.4289	0.4163
	-.4037	-.3681	-.3683	-.4182	-.3595	-.3677	-0.3806
	0.0420	0.0524	0.0697	0.0673	0.0671	0.0780	0.0655
	0	0	1	1	0	0	2
0.06 fL							
	0.3896	0.4302	0.3984	0.4120	0.4494	0.3864	0.4104
	-.4093	-.3664	-.3997	-.3851	-.3473	-.4129	-0.3868
	0.1106	0.0997	0.0620	0.0715	0.0657	0.0817	0.0840
	1	1	0	0	0	0	2
0.10 fL							
	0.3576	0.3893	0.3893	0.3761	0.3994	0.3990	0.3849
	-.4467	-.4097	-.4097	-.4246	-.3985	-.3990	-0.4147
	0.1113	0.1185	0.1174	0.0935	0.0721	0.1588	0.1128
	0	0	0	0	0	0	0
0.40 fL							
	0.4032	0.3867	0.3465	0.3863	0.4128	0.3747	0.3844
	-.3945	-.4126	-.4603	-.4130	-.3843	-.4264	-0.4152
	0.1014	0.1038	0.0867	0.0949	0.1002	0.1123	0.1002
	0	0	0	0	0	0	0

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3. - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: JG RUN: 2 TARGETS: Six small rocks at average distance eight feet

Luminance Level							Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.5242	0.4563	0.5307	0.4549	0.5721	0.4761	0.5026
Log mean	-.2764	-.3408	-.2751	-.3421	-.2426	-.3223	-0.2988
Log SD ^d	0.1015	0.0615	0.0926	0.0318	0.0778	0.0620	0.0821
Errors ^e	1	1	2	4	1	0	9
0.03 fL							
	0.4406	0.4916	0.4815	0.4814	0.5227	0.4258	0.4728
	-.3560	-.3084	-.3174	-.3175	-.2818	-.3708	-0.3253
	0.0957	0.1102	0.0877	0.0898	0.0588	0.0725	0.0894
	1	1	0	2	0	0	4
0.06 fL							
	0.4268	0.4555	0.3871	0.4324	0.4719	0.4701	0.4397
	-.3697	-.3415	-.4122	-.3641	-.3262	-.3278	-0.3568
	0.0783	0.0790	0.0478	0.0527	0.0941	0.0549	0.0743
	0	0	0	1	0	0	1
0.10 fL							
	0.4114	0.4157	0.3780	0.4362	0.4619	0.4151	0.4185
	-.3857	-.3813	-.4225	-.3603	-.3354	-.3818	-0.3783
	0.0645	0.0628	0.0532	0.0603	0.0565	0.0631	0.0642
	0	0	0	2	0	0	2
0.40 fL							
	0.3836	0.4287	0.3611	0.4524	0.4464	0.3955	0.4102
	-.4161	-.3678	-.4424	-.3445	-.3503	-.3985	-0.3870
	0.0390	0.0862	0.0710	0.0717	0.0922	0.1117	0.0868
	0	0	0	0	1	0	1

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3. - Geometric mean response time (seconds) and errors for rock motion detection (Cont'd)

OBSERVER: SB RUN: 1 TARGETS: Six small rocks at average distance eight feet							
Luminance Level							Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							
Geo. mean	0.4473	0.4852	0.4806	0.4353	0.4834	0.4508	0.4633
Log mean	-.3494	-.3141	-.3182	-.3612	-.3157	-.3460	-0.3341
Log SD ^d	0.0711	0.0789	0.0503	0.0687	0.0593	0.0557	0.0652
Errors ^e	1	1	0	0	0	0	2
0.03 fL							
	0.3756	0.4001	0.4211	0.3943	0.4472	0.3800	0.4021
	-.4252	-.3979	-.3756	-.4042	0.3495	-.4203	-0.3957
	0.0876	0.0729	0.0643	0.0794	0.0508	0.0732	0.0750
	0	1	1	0	0	0	2
0.06 fL							
	0.3473	0.3135	0.3222	0.3419	0.3684	0.3344	0.3375
	-.4593	-.5037	-.4918	-.4661	-.4336	-.4758	-0.4717
	0.0566	0.0434	0.0405	0.0665	0.0838	0.0757	0.0653
	0	0	0	0	0	0	0
0.10 fL							
	0.3482	0.3234	0.3411	0.3154	0.3609	0.3018	0.3312
	-.4581	-.4902	-.4672	0.5011	-.4426	-.5203	-0.4799
	0.0717	0.0450	0.0665	0.0567	0.0652	0.0490	0.0638
	0	0	0	0	0	0	0
0.40 fL							
	0.3003	0.3234	0.2907	0.2887	0.3113	0.2890	0.3003
	-.5225	-.4903	-.5365	-.5395	-.5068	-.5391	-0.5224
	0.0505	0.0608	0.0436	0.0286	0.0438	0.0376	0.0477
	0	0	0	0	0	0	0

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-3 . - Geometric mean response time (seconds) and errors for rock motion detection (Concluded)

OBSERVER: SB RUN: 2 TARGETS: Six small rocks at average distance eight feet

Luminance Level							Across Targets ^b
	12	2	4	6	8	10	
0.016 fL ^c							0.3731
Geo. mean	0.3781	0.3690	0.3484	0.4087	0.3950	0.3465	-0.4281
Log mean	-.4224	-.4330	-.4579	-.3886	-.4034	-.4603	0.0645
Log SD ^d	0.0718	0.0768	0.0423	0.0806	0.0385	0.0403	
Errors ^e	1	0	0	1	0	0	2
0.03 fL							0.3471
	0.3309	0.3552	0.3261	0.3430	0.3877	0.3431	-0.4596
	-.4804	-.4495	0.4867	-.4647	-.4115	-.4646	0.0520
	0.0393	0.0465	0.0549	0.0383	0.0612	0.0379	
	0	0	0	0	0	0	0
0.06 fL							0.3313
	0.3130	0.3398	0.3322	0.3335	0.3461	0.3241	-0.4798
	-.5044	-.4688	-.4787	-.4769	-.4609	-.4893	0.0565
	0.0498	0.0519	0.0798	0.0590	0.0459	0.0443	0
	0	0	0	0	0	0	
0.10 fL							0.3141
	0.3061	0.3241	0.3033	0.3062	0.3416	0.3053	-0.5029
	-.5142	-.4893	-.5181	-.5140	-.4665	-.5153	0.0636
	0.0480	0.0440	0.0844	0.0346	0.0975	0.0384	0
	0	0	0	0	0	0	
0.40 fL							0.2993
	0.2882	0.2998	0.3049	0.2924	0.2965	0.3148	-0.5239
	-.5402	-.5232	-.5159	-.5341	-.5280	-.5020	0.0471
	0.0385	0.0357	0.0335	0.0591	0.0535	0.0540	0
	0	0	0	0	0	0	

^aN = 14 trials per cell minus errors.

^bN = 84 trials per cell minus errors.

^cCaplamp penumbra only at an average distance of eight feet.

^dSD Standard deviation of time in log seconds.

^eObserver's response time $\geq$ 1.0 seconds.

TABLE F-4. - Geometric mean response time (seconds) for floor hole detection

Observer: TP

Targets: Small hole at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	8.8053	2.8348	4.7677	4.9188	7.0334	2.6332	4.2702	4.2924
Log mean	0.9447	0.4525	0.6783	0.6919	0.8472	0.4205	0.6305	0.6327
Log SD ^d	0.1204	0.0916	0.1830	0.2437	0.2063	0.2264	0.1874	0.2655
0.013 fL								
Geo. mean	3.0566	2.0252	1.9261	2.2845	3.0634	1.4256	1.6595	1.9352
Log mean	0.4852	0.3065	0.2847	0.3588	0.4862	0.1540	0.2200	0.2867
Log SD	0.1322	0.1561	0.0920	0.1535	0.1445	0.1287	0.0913	0.1881
0.030 fL								
Geo. mean	1.5701	1.0870	1.6039	1.3989	1.5020	1.0628	1.1120	1.2108
Log mean	0.1959	0.0362	0.2052	0.1458	0.1767	0.0264	0.0461	0.0831
Log SD	0.2198	0.0479	0.2776	0.2112	0.0516	0.0544	0.0561	0.0854
0.047 fL								
Geo. mean	1.3807	0.9776	1.2149	1.1792	1.3324	1.0319	1.1720	1.1724
Log mean	0.1401	-0.0099	0.0846	0.0716	0.1246	0.0136	0.0689	0.0691
Log SD	0.0863	0.0212	0.0481	0.0842	0.0332	0.0403	0.0641	0.0649
0.093 fL								
Geo. mean	1.4627	0.9888	1.1034	1.1686	0.9922	0.8440	1.0492	0.9578
Log mean	0.1652	-0.0049	0.0427	0.0677	-0.0034	-0.0737	0.0209	-0.0187
Log SD	0.3014	0.0426	0.0389	0.1834	0.0528	0.0401	0.0305	0.0573
0.147 fL								
Geo. mean	0.9993	0.8757	0.9260	0.9323	0.8839	0.7762	0.8864	0.8472
Log mean	-0.0003	-0.0576	-0.0334	-0.0304	-0.0536	-0.1100	-0.0524	-0.0720
Log SD	0.0578	0.0383	0.0675	0.0582	0.1005	0.0530	0.0325	0.0703

^aN=7 trials per cell.

^bN=21 trials per cell.

^cCaplamp penumbra only at an average distance of six feet.

^dSD Standard deviation of time in log seconds.

TABLE F-4 . - Geometric mean response time (seconds) for floor hole detection (Cont'd)

Observer: JM

Targets: Small hole at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	4.2976	1.8618	2.2368	2.6158	2.7413	2.1145	1.8820	2.2178
Log mean	0.6332	0.2699	0.3496	0.4176	0.4379	0.3252	0.2746	0.3459
Log SD ^d	0.2489	0.0638	0.0730	0.2117	0.2275	0.1655	0.1182	0.1812
0.013 fL								
Geo. mean	4.6803	1.3447	1.8201	2.2542	2.0656	1.2816	1.4205	1.5551
Log mean	0.6703	0.1286	0.2601	0.3530	0.3150	0.1077	0.1524	0.1917
Log SD	0.2730	0.0418	0.0836	0.2844	0.1025	0.0487	0.0867	0.1202
0.030 fL								
Geo. mean	1.5581	1.2295	1.2709	1.3453	1.6599	1.1395	1.1438	1.2934
Log mean	0.1926	0.0897	0.1041	0.1288	0.2201	0.0567	0.0584	0.1117
Log SD	0.1812	0.0470	0.0518	0.1161	0.0588	0.0428	0.0431	0.0912
0.047 fL								
Geo. mean	1.4605	1.3171	1.2439	1.3375	1.5945	1.0789	1.1027	1.2379
Log mean	0.1645	0.1196	0.0948	0.1263	0.2026	0.0330	0.0425	0.0927
Log SD	0.1188	0.1773	0.0854	0.1294	0.0855	0.0623	0.0675	0.1053
0.093 fL								
Geo. mean	1.2809	0.9859	1.1022	1.1165	1.2084	0.9595	1.0274	1.0600
Log mean	0.1076	-0.0062	0.0423	0.0479	0.0822	-0.0180	0.0117	0.0253
Log SD	0.1322	0.0555	0.0444	0.0950	0.0695	0.0392	0.0230	0.0626
0.147 fL								
Geo. mean	1.1618	0.9396	1.0986	1.0625	0.9771	0.6989	0.8453	0.8327
Log mean	0.0651	-0.0270	0.0409	0.0263	-0.0101	-0.1556	-0.0730	-0.0795
Log SD	0.0772	0.0693	0.0919	0.0858	0.0256	0.0396	0.0557	0.0730

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-4 . - Geometric mean response time (seconds) for floor hole detection (Cont'd)

Observer: BB

Targets: Small hole at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	4.5345	1.5749	2.2683	2.5302	2.7896	1.4873	1.5772	1.8705
Log mean	0.6565	0.1973	0.3557	0.4032	0.4455	0.1724	0.1979	0.2720
Log SD ^d	0.1057	0.0541	0.1895	0.2304	0.2462	0.0579	0.1393	0.2024
0.013 fL								
Geo. mean	2.7632	1.2607	1.6757	1.8006	1.8639	1.4015	1.2536	1.4850
Log mean	0.4414	0.1006	0.2242	0.2554	0.2704	0.1466	0.0982	0.1717
Log SD	0.1298	0.1038	0.1340	0.1858	0.0712	0.0810	0.1040	0.1107
0.030 fL								
Geo. mean	1.8235	0.9810	1.2878	1.3207	1.5003	1.0514	1.1525	1.2205
Log mean	0.2609	-0.0083	0.1098	0.1208	0.1762	0.0218	0.0616	0.0865
Log SD	0.1118	0.0523	0.1153	0.1460	0.0632	0.0777	0.0627	0.0932
0.047 fL								
Geo. mean	1.5559	1.0050	1.1319	1.2096	1.2358	1.0774	1.0771	1.1277
Log mean	0.1920	0.0022	0.0538	0.0827	0.0920	0.0324	0.0323	0.0522
Log SD	0.0537	0.0465	0.0981	0.1056	0.1160	0.0842	0.0880	0.0965
0.093 fL								
Geo. mean	1.1062	0.8940	1.0318	1.0068	1.0786	0.9410	1.0157	1.0102
Log mean	0.0438	-0.0487	0.0136	0.0029	0.0329	-0.0264	0.0068	0.0044
Log SD	0.0658	0.0791	0.0806	0.0818	0.0414	0.0462	0.0739	0.0584
0.147 fL								
Geo. mean	1.2988	0.9343	0.9123	1.0345	1.1266	0.8427	1.0449	0.9974
Log mean	0.1135	-0.0295	-0.0399	0.0147	0.0518	-0.0742	0.0191	-0.0011
Log SD	0.0686	0.0510	0.0672	0.0932	0.0699	0.0616	0.0831	0.0876

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-4 . - Geometric mean response time (seconds) for floor hole detection (Cont'd)

Observer: JG

Targets: Small hole at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	3.4394	1.5595	2.4971	2.3749	6.2396	2.0269	4.1539	3.7453
Log mean	0.5365	0.1930	0.3974	0.3756	0.7952	0.3068	0.6185	0.5735
Log SD ^d	0.2589	0.0797	0.1642	0.2258	0.3472	0.1431	0.2105	0.3137
0.013 fL								
Geo. mean	2.6951	1.6170	1.5486	1.8898	3.0559	1.3780	1.6321	1.9013
Log mean	0.4306	0.2087	0.1899	0.2764	0.4851	0.1393	0.2127	0.2790
Log SD	0.2023	0.1456	0.1288	0.1902	0.1156	0.0838	0.1002	0.1799
0.030 fL								
Geo. mean	1.6938	1.2472	1.4324	1.4464	1.6486	1.3304	1.7224	1.5575
Log mean	0.2289	0.0959	0.1561	0.1603	0.2171	0.1240	0.2361	0.1924
Log SD	0.1035	0.0543	0.1029	0.1019	0.1026	0.1037	0.0904	0.1066
0.047 fL								
Geo. mean	1.6028	1.0704	1.1573	1.2569	1.8112	1.0832	1.1851	1.3247
Log mean	0.2049	0.0295	0.0634	0.0993	0.2580	0.0347	0.0737	0.1221
Log SD	0.1349	0.0839	0.0803	0.1248	0.0717	0.0526	0.1131	0.1271
0.093 fL								
Geo. mean	1.3846	1.0437	1.0550	1.1510	1.0876	0.9901	0.8503	0.9711
Log mean	0.1413	0.0186	0.0233	0.0611	0.0365	-0.0043	-0.0704	-0.0127
Log SD	0.0615	0.0976	0.0570	0.0914	0.0523	0.0603	0.0659	0.0725
0.147 fL								
Geo. mean	1.1889	0.9934	0.9809	1.0503	1.1337	0.8365	1.0283	0.9917
Log mean	0.0752	-0.0029	-0.0084	0.0213	0.0545	-0.0775	0.0121	-0.0036
Log SD	0.0378	0.1462	0.0759	0.1005	0.0763	0.0746	0.1099	0.1011

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-4. - Geometric mean response time (seconds) for floor hole detection (Concluded)

Observer: SB

Targets: Small hole at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	2.6176	1.5790	1.4771	1.8277	3.1027	1.6106	1.4606	1.9398
Log mean	0.4179	0.1984	0.1694	0.2619	0.4917	0.2070	0.1645	0.2878
Log SD ^d	0.2118	0.0798	0.0577	0.1712	0.2727	0.1125	0.0613	0.2223
0.013 fL								
Geo. mean	1.9357	1.2054	1.4648	1.5063	1.6415	1.0737	1.1840	1.2779
Log mean	0.2868	0.0811	0.1658	0.1779	0.2152	0.0309	0.0734	0.1065
Log SD	0.1628	0.0698	0.0887	0.1388	0.0785	0.0286	0.0556	0.0977
0.030 fL								
Geo. mean	1.2751	1.0591	1.0212	1.1131	1.3680	1.0234	1.0474	1.1361
Log mean	0.1055	0.0249	0.0091	0.0465	0.1361	0.0100	0.0201	0.0554
Log SD	0.0649	0.0853	0.0961	0.0899	0.0400	0.0199	0.0474	0.0686
0.047 fL								
Geo. mean	1.3310	0.9008	0.9214	1.0337	1.1744	1.0710	0.9950	1.0777
Log mean	0.1242	-0.0454	-0.0356	0.0144	0.0698	0.0298	-0.0022	0.0325
Log SD	0.0940	0.0411	0.0591	0.1027	0.0556	0.0505	0.0304	0.0537
0.093 fL								
Geo. mean	1.2973	0.9568	1.0455	1.0908	1.2343	1.0684	1.0182	1.1032
Log mean	0.1130	-0.0192	0.0193	0.0377	0.0914	0.0287	0.0078	0.0427
Log SD	0.1492	0.0458	0.0721	0.1100	0.0318	0.0359	0.0375	0.0494
0.147 fL								
Geo. mean	1.0031	0.8541	0.8471	0.8987	0.9992	1.0029	0.7899	0.9250
Log mean	0.0014	-0.0685	-0.0720	-0.0464	-0.0004	0.0012	-0.1024	-0.0339
Log SD	0.0559	0.0397	0.0471	0.0572	0.1099	0.0780	0.0999	0.1045

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-5 . - Geometric mean response time (seconds) for floor hole detection

Observer: TP		Targets: Small hole at average distance ten feet (far positions)						
Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	32.8771	31.2007	28.4908	30.8026	23.3787	20.6789	15.9283	19.7472
Log mean	1.5169	1.4942	1.4547	1.4886	1.3688	1.3155	1.2022	1.2955
Log SD ^d	0.1089	0.1949	0.1751	0.1576	0.1602	0.1211	0.1015	0.1423
0.010 fL								
Geo. mean	10.4181	13.5366	11.6709	11.8069	9.3553	9.7364	9.2038	9.4292
Log mean	1.0178	1.1315	1.0671	1.0721	0.9711	0.9884	0.9640	0.9745
Log SD	0.1713	0.1354	0.2408	0.1843	0.1554	0.0983	0.0873	0.1120
0.017 fL								
Geo. mean	3.8945	6.4316	6.0848	5.3416	4.0208	5.4559	3.1040	4.0831
Log mean	0.5905	0.8083	0.7842	0.7277	0.6043	0.7369	0.4919	0.6110
Log SD	0.1666	0.0764	0.2308	0.1898	0.1275	0.1276	0.1289	0.1589
0.026 fL								
Geo. mean	1.8541	3.7931	3.3386	2.8809	2.4094	3.6285	2.3853	2.7525
Log mean	0.2681	0.5790	0.5236	0.4595	0.3819	0.5597	0.3775	0.4397
Log SD	0.1085	0.0894	0.1575	0.1797	0.0994	0.1311	0.0766	0.1321
0.052 fL								
Geo. mean	1.4688	2.1362	1.8920	1.8107	1.7161	2.4599	1.6203	1.8983
Log mean	0.1670	0.3296	0.2769	0.2578	0.2345	0.3909	0.2096	0.2784
Log SD	0.1041	0.0526	0.0841	0.1050	0.1146	0.0959	0.0983	0.1279
0.079 fL								
Geo. mean	1.2087	1.6812	1.2960	1.3809	1.2797	1.5466	1.3435	1.3854
Log mean	0.0823	0.2256	0.1126	0.1402	0.1071	0.1894	0.1282	0.1416
Log SD	0.0684	0.1215	0.1150	0.1174	0.0824	0.0888	0.0270	0.0801

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of ten feet.^dSD Standard deviation of time in log seconds.

TABLE F-5. - Geometric mean response time (seconds) for floor hole detection (Cont'd)

Observer: JM		Targets: Small hole at average distance ten feet (far positions)						
Luminescence Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	13.7828	38.1022	21.8230	22.5459	8.0232	15.2375	16.3895	12.6069
Log mean	1.1393	1.5809	1.3389	1.3531	0.9043	1.1829	1.2146	1.1006
Log SD ^d	0.2566	0.2012	0.3627	0.3250	0.1582	0.2177	0.1478	0.2206
0.010 fL								
Geo. mean	6.6463	15.4428	8.8556	9.6867	5.6244	5.7807	3.8182	4.9885
Log mean	0.8226	1.1887	0.9472	0.9862	0.7501	0.7620	0.5819	0.6980
Log SD	0.0462	0.2073	0.1743	0.2166	0.2165	0.1589	0.1458	0.1874
0.017 fL								
Geo. mean	2.6772	5.4794	2.9773	3.5216	2.5505	4.3553	2.3309	2.9584
Log mean	0.4277	0.7387	0.4738	0.5467	0.4066	0.6390	0.3675	0.4711
Log SD	0.1582	0.1790	0.2111	0.2241	0.0818	0.1670	0.0739	0.1646
0.026 fL								
Geo. mean	2.6757	4.1809	2.6528	3.0960	2.2754	3.5132	1.8662	2.4617
Log mean	0.4274	0.6213	0.4237	0.4908	0.3571	0.5457	0.2709	0.3912
Log SD	0.1635	0.2336	0.2383	0.2244	0.1009	0.1751	0.1854	0.1908
0.052 fL								
Geo. mean	1.6954	2.3131	1.6769	1.8735	1.4450	1.8811	1.5499	1.6151
Log mean	0.2293	0.3642	0.2245	0.2727	0.1599	0.2744	0.1903	0.2082
Log SD	0.1404	0.1949	0.0648	0.1516	0.0839	0.0747	0.0655	0.0868
0.079 fL								
Geo. mean	1.5690	1.7897	1.3820	1.5715	1.3061	1.4830	1.2784	1.3529
Log mean	0.1956	0.2528	0.1405	0.1963	0.1160	0.1711	0.1067	0.1313
Log SD	0.1221	0.1286	0.0584	0.1125	0.0977	0.0772	0.0882	0.0885

^aN=7 trials per cell.

^bN=21 trials per cell.

^cCaplamp penumbra only at an average distance of ten feet.

^dSD Standard deviation of time in log seconds.

TABLE F-5. - Geometric mean response time (seconds) for floor hole detection (Cont'd)

Observer: BB		Targets: Small hole at average distance ten feet (far positions)						
Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	21.8884	23.9785	12.8907	18.9135	16.0393	11.5195	12.2843	13.1418
Log mean	1.3402	1.3798	1.1103	1.2768	1.2052	1.0614	1.0894	1.1187
Log SD ^d	0.1478	0.2013	0.2484	0.2281	0.2368	0.1516	0.0957	0.1747
0.010 fL								
Geo. mean	7.1167	10.0317	7.2194	8.0177	5.6003	7.4322	3.9311	5.4695
Log mean	0.8523	1.0014	0.8585	0.9041	0.7482	0.8711	0.5945	0.7380
Log SD	0.1974	0.2720	0.1407	0.2117	0.1115	0.1255	0.1125	0.1603
0.017 fL								
Geo. mean	3.5416	4.3906	2.7889	3.5136	2.5357	4.7039	2.6810	3.1741
Log mean	0.5492	0.6425	0.4454	0.5458	0.4041	0.6725	0.4283	0.5016
Log SD	0.0587	0.0997	0.0893	0.1148	0.0791	0.0735	0.1063	0.1494
0.026 fL								
Geo. mean	2.4763	2.9512	2.2232	2.5328	2.0315	2.3932	2.5161	2.3042
Log mean	0.3938	0.4700	0.3470	0.4036	0.3078	0.3790	0.4007	0.3625
Log SD	0.1145	0.0941	0.1010	0.1111	0.0824	0.3254	0.1071	0.1972
0.052 fL								
Geo. mean	1.6799	2.1061	1.8198	1.8604	1.8707	1.9756	1.4835	1.7633
Log mean	0.2253	0.3235	0.2600	0.2696	0.2720	0.2957	0.1713	0.2463
Log SD	0.1522	0.1124	0.1094	0.1268	0.1068	0.1017	0.1608	0.1317
0.079 fL								
Geo. mean	1.3533	1.6997	1.1931	1.4001	1.6241	1.7935	1.2374	1.5332
Log mean	0.1314	0.2304	0.0767	0.1462	0.2106	0.2537	0.0925	0.1856
Log SD	0.1396	0.0517	0.1288	0.1260	0.0750	0.1271	0.0922	0.1182

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of ten feet.^dSD Standard deviation of time in log seconds.

TABLE F-5 . - Geometric mean response time (seconds) for floor hole detection (Cont'd)

Observer: JG

Targets: Small hole at average distance ten feet (far positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	17.7505	15.8270	10.3974	14.2948	14.7279	13.6657	8.3788	11.9029
Log mean	1.2492	1.1994	1.0169	1.1552	1.1681	1.1356	0.9232	1.0756
Log SD ^d	0.1385	0.1958	0.1069	0.1765	0.2119	0.1734	0.1072	0.1958
0.010 fL								
Geo. mean	4.6653	4.7009	5.1624	4.8377	5.3747	6.6324	4.2307	5.3229
Log mean	0.6689	0.6722	0.7129	0.6846	0.7304	0.8217	0.6264	0.7262
Log SD	0.1605	0.1691	0.1815	0.1631	0.1794	0.2102	0.1820	0.1988
0.017 fL								
Geo. mean	3.2068	4.5816	3.2819	3.6397	2.2889	3.7367	2.3947	2.7360
Log mean	0.5061	0.6610	0.5161	0.5611	0.3596	0.5725	0.3792	0.4371
Log SD	0.1938	0.1014	0.1280	0.1566	0.0741	0.1003	0.1150	0.1354
0.026 fL								
Geo. mean	2.2657	2.8313	2.4072	2.4902	1.8615	2.2956	2.1620	2.0983
Log mean	0.3552	0.4520	0.3815	0.3962	0.2699	0.3609	0.3348	0.3219
Log SD	0.0653	0.0908	0.0891	0.0888	0.0762	0.0617	0.0912	0.0832
0.052 fL								
Geo. mean	1.5460	2.0583	1.4411	1.6614	1.3394	1.8919	1.7390	1.6395
Log mean	0.1892	0.3135	0.1587	0.2205	0.1269	0.2769	0.2403	0.2147
Log SD	0.0704	0.0564	0.1586	0.1212	0.0910	0.1482	0.0749	0.1226
0.079 fL								
Geo. mean	1.1237	2.2264	1.5891	1.5841	1.2981	1.5694	1.2774	1.3755
Log mean	0.0506	0.3476	0.2011	0.1998	0.1133	0.1957	0.1063	0.1385
Log SD	0.2769	0.1083	0.1543	0.2216	0.1254	0.0625	0.0803	0.0977

^aN=7 trials per cell.

^bN=21 trials per cell.

^cCaplamp penumbra only at an average distance of ten feet.

^dSD Standard deviation of time in log seconds.

TABLE F-5 . - Geometric mean response time (seconds) for floor hole detection (Concluded)

Observer: SB		Targets: Small hole at average distance ten feet (far positions)						
Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	7.2550	19.4781	10.2234	11.3047	8.7839	13.3339	8.1854	9.8604
Log mean	0.8606	1.2895	1.0096	1.0533	0.9437	1.1250	0.9130	0.9939
Log SD ^d	0.1693	0.2589	0.2848	0.2937	0.1618	0.0818	0.2350	0.1887
0.010 fL								
Geo. mean	5.9927	6.5767	4.2951	5.5318	3.4928	4.2955	3.1245	3.6057
Log mean	0.7776	0.8180	0.6330	0.7429	0.5432	0.6330	0.4948	0.5570
Log SD	0.1424	0.1319	0.1150	0.1480	0.0899	0.0875	0.1160	0.1105
0.017 fL								
Geo. mean	3.2666	4.1534	2.5585	3.2621	2.3147	2.7326	1.7523	2.2296
Log mean	0.5141	0.6184	0.4080	0.5135	0.3645	0.4366	0.2436	0.3482
Log SD	0.1837	0.0944	0.1173	0.1571	0.1020	0.0762	0.0754	0.1150
0.026 fL								
Geo. mean	2.7211	2.9880	1.9839	2.5267	1.4936	2.3967	1.7144	1.8309
Log mean	0.4347	0.4754	0.2975	0.4025	0.1742	0.3796	0.2341	0.2627
Log SD	0.1475	0.1133	0.1196	0.1441	0.1157	0.1841	0.0807	0.1548
0.052 fL								
Geo. mean	1.3726	1.9230	1.5110	1.5859	1.8020	1.6097	1.5686	1.6571
Log mean	0.1376	0.2840	0.1793	0.2003	0.2558	0.2067	0.1955	0.2193
Log SD	0.1012	0.0756	0.1340	0.1190	0.0799	0.1002	0.0817	0.0874
0.079 fL								
Geo. mean	1.2083	1.6426	1.2586	1.3568	1.3449	1.2560	1.2113	1.2696
Log mean	0.0822	0.2155	0.0999	0.1325	0.1287	0.0990	0.0833	0.1037
Log SD	0.0559	0.1118	0.0551	0.0963	0.0731	0.1012	0.0832	0.0844

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of ten feet.^dSD Standard deviation of time in log seconds.

TABLE F-6. - Geometric mean response time (seconds) for floor rubble detection

Observer: TP

Targets: Small rubble at average distance six feet (near positions)

Lumiance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	5.8836	3.3074	6.1131	4.9181	2.2567	2.1164	3.6981	2.6042
Log mean	0.7696	0.5195	0.7863	0.6918	0.3535	0.3256	0.5680	0.4157
Log SD ^d	0.2805	0.1324	0.1660	0.2297	0.1211	0.1574	0.1614	0.1788
0.013 fL								
Geo. mean	1.7153	1.6454	3.3334	2.1111	1.3849	1.2187	4.4690	1.9611
Log mean	0.2343	0.2163	0.5229	0.3245	0.1414	0.0859	0.6502	0.2925
Log SD	0.0860	0.2399	0.2382	0.2392	0.0613	0.1313	0.2073	0.2948
0.030 fL								
Geo. mean	1.0787	1.0604	1.5594	1.2128	0.9762	0.9724	1.5121	1.1281
Log mean	0.0329	0.0255	0.1930	0.0838	-0.0105	-0.0121	0.1796	0.0523
Log SD	0.0805	0.0464	0.1074	0.1110	0.0537	0.0636	0.1302	0.1252
0.047 fL								
Geo. mean	0.9191	1.0007	1.5806	1.1328	0.9215	0.9848	1.3341	1.0658
Log mean	-0.0367	0.0003	0.1988	0.0542	-0.0355	-0.0067	0.1252	0.0277
Log SD	0.0211	0.0307	0.1475	0.1348	0.0258	0.0538	0.0389	0.0816
0.093 fL								
Geo. mean	1.0112	0.9512	1.3240	1.0839	0.8434	0.8954	1.1853	0.9637
Log mean	0.0048	-0.0217	0.1219	0.0350	-0.0740	-0.0480	0.0738	-0.0161
Log SD	0.0733	0.0373	0.0761	0.0886	0.0344	0.0294	0.0526	0.0762
0.147 fL								
Geo. mean	0.8117	0.8060	1.4427	0.9809	0.7972	0.8241	1.2600	0.9389
Log mean	-0.0906	-0.0937	0.1592	-0.0084	-0.0985	-0.0840	0.1004	-0.0274
Log SD	0.0249	0.0251	0.1265	0.1411	0.0481	0.0671	0.0589	0.1081

^aN=7 trials per cell.

^bN=21 trials per cell.

^cCaplamp penumbra only at an average distance of six feet.

^dSD Standard deviation of time in log seconds.

TABLE F-6. - Geometric mean response time (seconds) for floor rubble detection (Cont'd)

Observer: JM

Targets: Small rubble at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	1.3985	1.9132	2.4893	1.8815	2.3483	1.8602	3.0179	2.3625
Log mean	0.1457	0.2818	0.3961	0.2745	0.3708	0.2696	0.4797	0.3734
Log SD ^d	0.0945	0.2143	0.2714	0.2226	0.2262	0.1745	0.1494	0.1973
0.013 fL								
Geo. mean	1.1927	1.1674	1.5582	1.2946	1.3067	1.2012	1.6206	1.3651
Log mean	0.0765	0.0672	0.1926	0.1121	0.1162	0.0796	0.2097	0.1352
Log SD	0.0777	0.1001	0.1251	0.1137	0.1210	0.1461	0.0741	0.1249
0.030 fL								
Geo. mean	1.0712	0.9632	1.8537	1.2413	1.1005	1.0750	1.3427	1.1668
Log mean	0.0299	-0.0163	0.2680	0.0939	0.0416	0.0314	0.1280	0.0670
Log SD	0.0358	0.0490	0.1192	0.1472	0.0651	0.0852	0.1105	0.0953
0.047 fL								
Geo. mean	0.9421	0.8524	1.3410	1.0250	1.0202	0.8757	1.3606	1.0672
Log mean	-0.0259	-0.0693	0.1274	0.0107	0.0087	-0.0577	0.1337	0.0282
Log SD	0.0598	0.0146	0.0445	0.0960	0.0693	0.0382	0.1065	0.1091
0.093 fL								
Geo. mean	0.8562	0.8019	0.9167	0.8570	0.9816	0.8383	1.3365	1.0322
Log mean	-0.0674	-0.0959	-0.0378	-0.0670	-0.0081	-0.0766	0.1260	0.0138
Log SD	0.0514	0.0528	0.1130	0.0778	0.0703	0.0297	0.0990	0.1101
0.147 fL								
Geo. mean	0.6954	0.6636	0.9658	0.7638	0.8840	0.8416	1.1190	0.9407
Log mean	-0.1578	-0.1781	-0.0151	-0.1170	-0.0535	-0.0749	0.0488	-0.0265
Log SD	0.0876	0.0217	0.1001	0.1047	0.0595	0.0653	0.1866	0.1259

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-6. - Geometric mean response time (seconds) for floor rubble detection (Cont'd)

Observer: BB

Targets: Small rubble at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	1.5388	1.4183	2.1543	1.6753	1.3038	1.2804	1.3810	1.3210
Log mean	0.1872	0.1518	0.3333	0.2241	0.1152	0.1074	0.1402	0.1209
Log SD ^d	0.1324	0.1310	0.2034	0.1712	0.1131	0.1446	0.1259	0.1228
0.013 fL								
Geo. mean	1.2733	1.4576	2.1819	1.5938	1.0927	0.9723	1.7061	1.2193
Log mean	0.1049	0.1636	0.3388	0.2024	0.0385	-0.0122	0.2320	0.0861
Log SD	0.0576	0.1857	0.1030	0.1578	0.0974	0.0932	0.1734	0.1615
0.030 fL								
Geo. mean	1.1022	1.1055	1.8505	1.3113	0.8550	0.8245	1.6899	1.0601
Log mean	0.0423	0.0436	0.2673	0.1177	-0.0680	-0.0838	0.2279	0.0254
Log SD	0.0596	0.0788	0.1599	0.1495	0.0504	0.0661	0.1671	0.1790
0.047 fL								
Geo. mean	0.9551	0.9900	1.4670	1.1152	0.9194	0.9273	1.2240	1.0143
Log mean	-0.0200	-0.0044	0.1664	0.0473	-0.0365	-0.0328	0.0878	0.0062
Log SD	0.0398	0.2041	0.0753	0.1489	0.0960	0.0441	0.1228	0.1067
0.093 fL								
Geo. mean	1.0765	0.8522	1.5157	1.1161	0.9032	0.7562	0.7171	0.7882
Log mean	0.0320	-0.0695	0.1806	0.0477	-0.0442	-0.1214	-0.1444	-0.1033
Log SD	0.1094	0.0332	0.1249	0.1403	0.1158	0.0469	0.0721	0.0904
0.147 fL								
Geo. mean	0.9272	0.9955	1.5086	1.1167	0.8259	0.7610	0.9999	0.8565
Log mean	-0.0328	-0.0020	0.1786	0.0479	-0.0831	-0.1186	-0.0001	-0.0673
Log SD	0.0723	0.1438	0.1866	0.1654	0.0714	0.0748	0.0627	0.0836

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-6. - Geometric mean response time (seconds) for floor rubble detection (Cont'd)

Observer: JG

Targets: Small rubble at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	1.6013	1.6635	7.4187	2.7036	2.0816	1.6370	4.7300	2.5260
Log mean	0.2045	0.2210	0.8703	0.4319	0.3184	0.2140	0.6749	0.4024
Log SD ^d	0.0827	0.1424	0.2746	0.3629	0.1260	0.1458	0.1306	0.2390
0.013 fL								
Geo. mean	1.4757	1.1901	2.4355	1.6233	1.6042	1.3787	2.9205	1.8624
Log mean	0.1690	0.0756	0.3866	0.2104	0.2053	0.1395	0.4655	0.2701
Log SD	0.1305	0.0318	0.2197	0.1942	0.0661	0.0951	0.0988	0.1666
0.030 fL								
Geo. mean	1.4632	1.0641	1.2522	1.2493	1.1795	1.1476	1.7963	1.3447
Log mean	0.1653	0.0270	0.0977	0.0967	0.0717	0.0598	0.2544	0.1286
Log SD	0.1118	0.0785	0.0616	0.1004	0.0478	0.1102	0.1857	0.1517
0.047 fL								
Geo. mean	1.1474	1.0057	1.0446	1.0642	1.1329	1.2300	1.5234	1.2852
Log mean	0.0597	0.0025	0.0190	0.0270	0.0542	0.0899	0.1828	0.1090
Log SD	0.0625	0.0921	0.0829	0.0799	0.0768	0.1033	0.0967	0.1042
0.093 fL								
Geo. mean	1.0790	0.9659	0.8894	0.9750	1.1188	0.8324	1.3665	1.0837
Log mean	0.0330	-0.0151	-0.0509	-0.0110	0.0487	-0.0797	0.1356	0.0349
Log SD	0.0888	0.0428	0.1164	0.0907	0.0852	0.0501	0.1361	0.1293
0.147 fL								
Geo. mean	1.0541	0.8306	1.2258	1.0238	0.9443	0.8695	0.9322	0.9147
Log mean	0.0229	-0.0806	0.0884	0.0102	-0.0249	-0.0607	-0.0305	-0.0387
Log SD	0.0942	0.0582	0.1052	0.1099	0.0632	0.0788	0.0790	0.0721

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-6. - Geometric mean response time (seconds) for floor rubble detection (Concluded)

Observer: SB

Targets: Small rubble at average distance six feet (near positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0065 fL ^c								
Geo. mean	1.5096	1.7151	1.6903	1.6357	1.7757	1.6976	1.8152	1.7622
Log mean	0.1789	0.2343	0.2280	0.2137	0.2494	0.2298	0.2589	0.2460
Log SD ^d	0.1002	0.1586	0.1219	0.1251	0.1743	0.1685	0.1404	0.1539
0.013 fL								
Geo. mean	1.4244	1.2151	1.2074	1.2785	1.2885	1.2343	1.9500	1.4583
Log mean	0.1536	0.0846	0.0819	0.1067	0.1101	0.0914	0.2900	0.1638
Log SD	0.0658	0.0479	0.0442	0.0611	0.0538	0.1239	0.2697	0.1890
0.030 fL								
Geo. mean	1.1645	1.1301	1.1645	1.1529	1.1663	1.0851	1.3914	1.2076
Log mean	0.0662	0.0531	0.0661	0.0618	0.0668	0.0355	0.1435	0.0819
Log SD	0.0547	0.0726	0.0804	0.0668	0.0628	0.0736	0.0974	0.0884
0.047 fL								
Geo. mean	1.0328	0.9703	1.0418	1.0145	1.2595	0.9659	1.0535	1.0862
Log mean	0.0140	-0.0131	0.0178	0.0062	0.1002	-0.0151	0.0226	0.0359
Log SD	0.0659	0.0342	0.0907	0.0658	0.0641	0.0661	0.0398	0.0737
0.093 fL								
Geo. mean	1.0019	0.8937	0.8708	0.9204	0.9501	0.9697	1.0543	0.9904
Log mean	0.0008	-0.0488	-0.0601	-0.0360	-0.0222	-0.0134	0.0230	-0.0042
Log SD	0.0533	0.0487	0.1276	0.0847	0.0250	0.0577	0.0852	0.0613
0.147 fL								
Geo. mean	1.0495	0.9291	0.9228	0.9654	1.0954	0.8946	1.0758	1.0178
Log mean	0.0210	-0.0319	-0.0349	-0.0153	0.0396	-0.0484	0.0317	0.0076
Log SD	0.1108	0.0647	0.0543	0.0807	0.0266	0.0234	0.0634	0.0569

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-7. - Geometric mean response time (seconds) for floor rubble detection

Observer: TP

Targets: Small rubble at average distance ten feet (far positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	6.6385	5.4774	3.5490	5.0534	3.8106	4.1022	2.3245	3.3122
Log mean	0.8221	0.7386	0.5501	0.7036	0.5810	0.6130	0.3663	0.5201
Log SD ^d	0.1372	0.1480	0.1356	0.1770	0.2383	0.1770	0.1786	0.2205
0.010 fL								
Geo. mean	2.7489	4.3632	1.8557	2.8129	1.6279	2.4282	1.1418	1.6526
Log mean	0.4392	0.6398	0.2685	0.4492	0.2116	0.3853	0.0576	0.2182
Log SD	0.1521	0.0788	0.1024	0.1901	0.1359	0.1967	0.0310	0.1904
0.017 fL								
Geo. mean	1.3458	1.5105	1.0751	1.2977	0.9588	0.9805	0.9340	0.9576
Log mean	0.1290	0.1791	0.0314	0.1132	-0.0182	-0.0085	-0.0297	-0.0188
Log SD	0.1794	0.1697	0.0292	0.1500	0.0493	0.0406	0.0285	0.0393
0.026 fL								
Geo. mean	1.0758	1.1624	1.0474	1.0941	0.9931	0.9835	0.9310	0.9688
Log mean	0.0317	0.0654	0.0201	0.0391	-0.0030	-0.0072	-0.0311	-0.0138
Log SD	0.0414	0.1246	0.0536	0.0801	0.0342	0.0668	0.0147	0.0438
0.052 fL								
Geo. mean	1.0629	1.1323	1.0543	1.0826	0.8881	0.9892	0.9186	0.9310
Log mean	0.0265	0.0539	0.0230	0.0345	-0.0515	-0.0047	-0.0369	-0.0310
Log SD	0.0978	0.0711	0.0784	0.0802	0.0156	0.0872	0.0374	0.0564
0.079 fL								
Geo. mean	0.8682	0.9100	0.8117	0.8624	0.8875	0.9400	0.8840	0.9035
Log mean	-0.0614	-0.0409	-0.0906	-0.0643	-0.0518	-0.0269	-0.0536	-0.0441
Log SD	0.0303	0.0578	0.0246	0.0436	0.0299	0.0669	0.0123	0.0413

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of ten feet.^dSD Standard deviation of time in log seconds.

TABLE F-7. - Geometric mean response time (seconds) for floor rubble detection (Cont'd)

Observer: JM

Targets: Small rubble at average distance ten feet (far positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	1.2449	1.4711	1.0993	1.2627	2.7655	2.0693	1.5908	2.0880
Log mean	0.0951	0.1677	0.0411	0.1013	0.4418	0.3158	0.2016	0.3197
Log SD ^d	0.1080	0.1241	0.0544	0.1088	0.1041	0.1276	0.1268	0.1519
0.010 fL								
Geo. mean	1.6619	1.1897	1.0461	1.2741	1.5574	1.5577	1.1063	1.3897
Log mean	0.2206	0.0754	0.0196	0.1052	0.1924	0.1925	0.0439	0.1429
Log SD	0.0769	0.1302	0.0898	0.1297	0.2015	0.1348	0.0879	0.1584
0.017 fL								
Geo. mean	1.1863	1.2914	0.9333	1.1265	1.4620	1.3224	1.0952	1.2841
Log mean	0.0741	0.1110	-0.0300	0.0517	0.1650	0.1214	0.0395	0.1086
Log SD	0.0375	0.0497	0.0220	0.0711	0.1522	0.1277	0.1817	0.1568
0.026 fL								
Geo. mean	0.9916	1.0123	0.8567	0.9510	1.2729	1.1331	0.9593	1.1143
Log mean	-0.0037	0.0053	-0.0671	-0.0218	0.1048	0.0543	-0.0180	0.0470
Log SD	0.0712	0.0576	0.0142	0.0606	0.1164	0.0613	0.0478	0.0925
0.052 fL								
Geo. mean	0.8552	1.0111	0.8430	0.9000	1.1678	0.9744	0.8621	0.9937
Log mean	-0.0679	0.0048	-0.0742	-0.0458	0.0674	-0.0112	-0.0644	-0.0028
Log SD	0.0996	0.1451	0.0467	0.1063	0.0436	0.0239	0.0199	0.0627
0.079 fL								
Geo. mean	0.7786	0.8040	0.6919	0.7566	0.9081	0.9098	0.8049	0.8728
Log mean	-0.1087	-0.0947	-0.1600	-0.1211	-0.0419	-0.0411	-0.0943	-0.0591
Log SD	0.0395	0.0699	0.0492	0.0590	0.0478	0.0525	0.0523	0.0546

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of ten feet.^dSD Standard deviation of time in log seconds.

TABLE F-7. - Geometric mean response time (seconds) for floor rubble detection (Cont'd)

Observer: BB

Targets: Small rubble at average distance ten feet (far positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	3.3149	3.3887	1.1407	2.3401	1.3218	1.4547	0.9140	1.2068
Log mean	0.5205	0.5300	0.0572	0.3692	0.1212	0.1628	-0.0390	0.0816
Log SD ^d	0.1342	0.2503	0.0438	0.2755	0.0761	0.1321	0.0468	0.1248
0.010 fL								
Geo. mean	1.8060	1.7286	1.0683	1.4941	1.5573	1.7895	0.9413	1.3791
Log mean	0.2567	0.2377	0.0287	0.1744	0.1924	0.2527	-0.0263	0.1396
Log SD	0.1466	0.1029	0.0545	0.1474	0.1735	0.2099	0.0835	0.1986
0.017 fL								
Geo. mean	1.4341	1.3307	1.0327	1.2538	1.2728	1.0251	0.9385	1.0698
Log mean	0.1566	0.1241	0.0140	0.0982	0.1048	0.0108	-0.0276	0.0293
Log SD	0.1443	0.0663	0.0354	0.1088	0.0678	0.0616	0.0947	0.0919
0.026 fL								
Geo. mean	1.3217	1.2644	0.9780	1.1779	0.9092	1.0432	0.8350	0.9252
Log mean	0.1211	0.1019	-0.0097	0.0711	-0.0413	0.0184	-0.0783	-0.0338
Log SD	0.1434	0.1474	0.0536	0.1306	0.0704	0.1115	0.0701	0.0914
0.052 fL								
Geo. mean	1.0081	1.1699	0.9493	1.0383	0.7973	0.8916	0.7592	0.8142
Log mean	0.0035	0.0681	-0.0226	0.0163	-0.0984	-0.0498	-0.1196	-0.0893
Log SD	0.0671	0.0950	0.0972	0.0918	0.0610	0.0788	0.0657	0.0719
0.079 fL								
Geo. mean	0.9538	0.9616	0.8352	0.9150	0.9480	0.7339	0.7971	0.8216
Log mean	-0.0205	-0.0170	-0.0782	-0.0386	-0.0232	-0.1344	-0.0985	-0.0854
Log SD	0.0805	0.1642	0.0417	0.1067	0.0754	0.0687	0.0648	0.0815

^aN=7 trials per cell.

^bN=21 trials per cell.

^cCaplamp penumbra only at an average distance of ten feet.

^dSD Standard deviation of time in log seconds.

TABLE F-7. - Geometric mean response time (seconds) for floor rubble detection (Cont'd)

Observer: JG

Targets: Small rubble at average distance ten feet (far positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c				2.2214				2.0316
Geo. mean	2.3620	3.2420	1.4314	0.3466	2.2871	2.7403	1.3378	0.3078
Log mean	0.3733	0.5108	0.1558	0.1836	0.3593	0.4378	0.1264	0.1833
Log SD ^d	0.1306	0.0927	0.1092		0.1222	0.1791	0.0613	
0.010 fL				1.4082				1.4081
Geo. mean	1.6650	1.5606	1.0747	0.1487	1.5564	1.5843	1.1322	0.1486
Log mean	0.2214	0.1933	0.0313	0.1110	0.1921	0.1998	0.0539	0.0892
Log SD	0.0579	0.1075	0.0399		0.0707	0.0520	0.0558	
0.017 fL				1.1491				1.3070
Geo. mean	1.3238	1.0850	1.0565	0.0604	1.5651	1.3324	1.0706	0.1163
Log mean	0.1218	0.0354	0.0239	0.0832	0.1945	0.1246	0.0296	0.1307
Log SD	0.0496	0.0907	0.0755		0.1601	0.1174	0.0388	
0.026 fL				1.1045				1.3258
Geo. mean	1.1991	1.0750	1.0452	0.0432	1.5932	1.2646	1.1567	0.1225
Log mean	0.0788	0.0314	0.0192	0.0752	0.2023	0.1020	0.0632	0.1433
Log SD	0.0535	0.0995	0.0612		0.1415	0.0618	0.1806	
0.052 fL				1.0063				0.9539
Geo. mean	1.1127	0.9604	0.9536	0.0027	0.9735	1.0432	0.8548	-0.0205
Log mean	0.0464	-0.0175	-0.0206	0.0612	-0.0117	0.0184	-0.0681	0.0611
Log SD	0.0430	0.0613	0.0596		0.0610	0.0480	0.0440	
0.079 fL				0.9812				0.8653
Geo. mean	1.0076	1.0122	0.9263	-0.0082	0.9579	0.8375	0.8077	-0.0628
Log mean	0.0033	0.0053	-0.0333	0.0608	-0.0187	-0.0770	-0.0928	0.1014
Log SD	0.0604	0.0579	0.0648		0.1437	0.0888	0.0465	

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of ten feet.^dSD Standard deviation of time in log seconds.

TABLE F-7 . - Geometric mean response time (seconds) for floor rubble detection (Concluded)

Observer: SB

Targets: Small rubble at average distance ten feet (far positions)

Luminance Level	Run: 1 ^a				Run: 2 ^a			
	Target Position			Across Targets ^b	Target Position			Across Targets ^b
	Left	Center	Right		Left	Center	Right	
0.0055 fL ^c								
Geo. mean	2.2945	3.8151	1.0337	2.0838	2.0714	2.1514	1.2370	1.7665
Log mean	0.3607	0.5815	0.0144	0.3189	0.3163	0.3327	0.0924	0.2471
Log SD ^d	0.2436	0.1636	0.0992	0.2932	0.1248	0.1142	0.0513	0.1483
0.010 fL								
Geo. mean	1.4363	1.7335	1.0057	1.3579	1.5618	1.7242	1.0444	1.4115
Log mean	0.1572	0.2389	0.0025	0.1329	0.1936	0.2366	0.0189	0.1497
Log SD	0.1288	0.1579	0.0595	0.1537	0.1196	0.1553	0.0688	0.1492
0.017 fL								
Geo. mean	1.1954	1.3273	0.9180	1.1335	1.2944	1.3862	1.0238	1.2247
Log mean	0.0775	0.1230	-0.0372	0.0544	0.1121	0.1418	0.0102	0.0880
Log SD	0.0409	0.0369	0.0481	0.0798	0.0690	0.0653	0.0458	0.0817
0.026 fL								
Geo. mean	1.1797	1.2691	0.8867	1.0991	1.3480	1.2937	0.9173	1.1695
Log mean	0.0718	0.1035	-0.0522	0.0410	0.1297	0.1118	-0.0375	0.0680
Log SD	0.0517	0.0895	0.0809	0.0996	0.0627	0.1001	0.0358	0.1023
0.052 fL								
Geo. mean	1.0723	0.9971	0.9080	0.9902	1.1530	1.0602	0.9487	1.0506
Log mean	0.0303	-0.0013	-0.0419	-0.0043	0.0618	0.0254	-0.0229	0.0215
Log SD	0.0500	0.0637	0.0713	0.0664	0.0728	0.0592	0.0433	0.0669
0.079 fL								
Geo. mean	0.9410	0.9265	0.7943	0.8847	1.1176	1.0000	0.9361	1.0152
Log mean	-0.0264	-0.0331	-0.1000	-0.0532	0.0483	-0.0000	-0.0287	0.0065
Log SD	0.0399	0.0547	0.0563	0.0590	0.0387	0.0439	0.0342	0.0494

^aN=7 trials per cell.^bN=21 trials per cell.^cCaplamp penumbra only at an average distance of ten feet.^dSD Standard deviation of time in log seconds.

TABLE F-8. - Geometric mean response time (seconds) for protrusion detection

Observer: TP Targets: Slipped rock bolts at the back (average distance of six feet)

Luminance Level	Run: 1 ^a				Run: 2			
	Target Position			Across Targets ^b	Target Position			Across Targets
	Left	Center	Right		Left	Center	Right	
0.0068 fL ^c								
Geo. mean	0.7933	0.8035	0.8591	0.8181	0.8732	0.8901	0.8605	0.8745
Log mean	-0.1006	-0.0950	-0.0660	-0.0872	-0.0589	-0.0506	-0.0653	-0.0582
Log SD ^d	0.0238	0.0206	0.0348	0.0300	0.0509	0.0371	0.0222	0.0371
0.06 fL								
Geo. mean	0.7723	0.7781	0.8300	0.7931	0.8361	0.7955	0.8285	0.8198
Log mean	-0.1122	-0.1090	-0.0809	-0.1007	-0.0778	-0.0994	-0.0817	-0.0863
Log SD ^d	0.0333	0.0167	0.0476	0.0361	0.0240	0.0303	0.0281	0.0279

Observer: TP Targets: Slipped rock bolts on the rib (average distance of six feet)

Luminance Level	Run: 1				Run: 2			
	Target Position			Across Targets ^b	Target Position			Across Targets
	High	Middle	Low		High	Middle	Low	
0.0068 fL ^c								
Geo. mean	0.9263	0.8983	1.1438	0.9836	0.8693	0.9468	1.0238	0.9445
Log mean	-0.0332	-0.0466	0.0583	-0.0072	-0.0608	-0.0238	0.0102	-0.0248
Log SD ^d	0.0194	0.0768	0.0357	0.0674	0.0191	0.0387	0.0619	0.0509
0.06 fL								
Geo. mean	0.8475	0.8493	1.0208	0.9024	0.8713	0.9114	0.9293	0.9037
Log mean	-0.0719	-0.0709	0.0090	-0.0446	-0.0598	-0.0403	-0.0318	-0.0440
Log SD ^d	0.0238	0.0499	0.0457	0.0552	0.0383	0.0375	0.0409	0.0388

^aN = 7 trials per cell.^bN = 21 trials per cell.^cCaplamp penumbra only at average distance of six feet.^dSD Standard deviation of time in log seconds.

TABLE F-8. - Geometric mean response time (seconds) for protrusion detection (Cont'd)

Observer: JM		Targets: Slipped rock bolts at the back (average distance of six feet)						
Luminance Level	Run: 1 ^a				Run: 2			
	Target Position			Across Targets ^b	Target Position			Across Targets
	Left	Center	Right		Left	Center	Right	
0.0068 fL ^c								
Geo. mean	0.8345	0.7967	0.8363	0.8223	0.8892	0.8725	0.9076	0.8897
Log mean	-0.0786	-0.0987	-0.0776	-0.0850	-0.0510	-0.0592	-0.0421	-0.0508
Log SD ^d	0.0252	0.0323	0.0204	0.0270	0.0322	0.0407	0.0426	0.0375
0.06 fL								
Geo. mean	0.8420	0.8147	0.7776	0.8110	0.8714	0.8833	0.9090	0.8878
Log mean	-0.0747	-0.0890	-0.1092	-0.0910	-0.0598	-0.0539	-0.0414	-0.0517
Log SD ^d	0.0432	0.0757	0.0366	0.0538	0.0377	0.0505	0.0336	0.0399

Observer: JM		Targets: Slipped rock bolts on the rib (average distance of six feet)						
Luminance Level	Run: 1				Run: 2			
	Target Position			Across Targets ^b	Target Position			Across Targets
	High	Middle	Low		High	Middle	Low	
0.0068 fL ^c								
Geo. mean	0.8927	0.9051	0.9997	0.9313	0.9396	0.9970	1.0408	0.9916
Log mean	-0.0493	-0.0433	-0.0001	-0.0309	-0.0270	-0.0013	0.0174	-0.0037
Log SD ^d	0.0285	0.0319	0.1072	0.0671	0.0289	0.0650	0.0450	0.0497
0.06 fL								
Geo. mean	0.8352	0.8185	0.8262	0.8266	0.8476	0.9632	0.9571	0.9211
Log mean	-0.0782	-0.0870	-0.0829	-0.0827	-0.0718	-0.0163	-0.0190	-0.0357
Log SD ^d	0.0171	0.0667	0.0525	0.0476	0.0523	0.0547	0.0627	0.0598

^aN = 7 trials per cell.^bN = 21 trials per cell.^cCaplamp penumbra only at average distance of six feet.^dSD Standard deviation of time in 100 seconds.

TABLE F-8. - Geometric mean response time (seconds) for protrusion detection (Cont'd)

Observer: BB		Targets: Slipped rock bolts at the back (average distance of six feet)						
Lumiance Level	Run: 1 ^a				Run: 2			
	Target Position			Across Targets ^b	Target Position			Across Targets
	Left	Center	Right		Left	Center	Right	
0.0068 fL ^c								
Geo. mean	0.9193	0.8230	0.8737	0.8711	0.8846	0.9375	0.8320	0.8837
Log mean	-0.0365	-0.0846	-0.0586	-0.0599	-0.0532	-0.0280	-0.0799	-0.0537
Log SD ^d	0.0814	0.0606	0.0801	0.0736	0.0507	0.1467	0.0216	0.0885
0.06 fL								
Geo. mean	0.8808	0.8380	0.8306	0.8495	0.7501	0.8165	0.7682	0.7778
Log mean	-0.0551	-0.0767	-0.0806	-0.0708	-0.1249	-0.0880	-0.1145	-0.1092
Log SD ^d	0.0822	0.0574	0.0594	0.0649	0.0408	0.0872	0.0589	0.0638

Observer: BB		Targets: Slipped rock bolts on the rib (average distance of six feet)						
Lumiance Level	Run: 1				Run: 2			
	Target Position			Across Targets ^b	Target Position			Across Targets
	High	Middle	Low		High	Middle	Low	
0.0068 fL ^c								
Geo. mean	1.1554	0.9844	1.0283	1.0536	1.0700	1.0254	1.1226	1.0720
Log mean	0.0627	-0.0068	0.0121	0.0227	0.0294	0.0109	0.0502	0.0302
Log SD ^d	0.0807	0.1046	0.0502	0.0831	0.0742	0.0835	0.0773	0.0762
0.06 fL								
Geo. mean	0.9984	0.8447	0.9882	0.9411	0.8336	0.8993	1.0983	0.9372
Log mean	-0.0007	-0.0733	-0.0052	-0.0264	-0.0791	-0.0461	0.0407	-0.0282
Log SD ^d	0.1149	0.0442	0.1069	0.0956	0.0431	0.1136	0.1863	0.1324

^aN = 7 trials per cell.

^bN = 21 trials per cell.

^cCaplamp penumbra only at average distance of six feet.

^dSD Standard deviation of time in log seconds.

TABLE F-9. Geometric mean response time (seconds)
for peripheral motion detection

Targets: Large cylindrical objects at 60° (average distance 12 feet)

Luminance Level	Observer: TP			Observer: JM		
	Target Position ^a		Across Targets ^b	Target Position		Across Targets
	Left	Right		Left	Right	
0.0018 fL ^c						
Geo. mean	1.4378	1.2939	1.3640	1.5620	2.0357	1.7832
Log mean	0.1577	0.1119	0.1348	0.1937	0.3087	0.2512
Log SD ^d	0.2060	0.0933	0.1596	0.2188	0.1411	0.1909
0.003 fL						
	1.1098	1.2477	1.1767	1.2655	1.3880	1.3254
	0.0452	0.0961	0.0707	0.1023	0.1424	0.1223
	0.0685	0.0796	0.0777	0.1157	0.1094	0.1130
0.006 fL						
	1.1663	1.1107	1.1382	1.2158	1.7537	1.4602
	0.0668	0.0456	0.0562	0.0849	0.2440	0.1644
	0.1231	0.0822	0.1040	0.1285	0.1669	0.1677
0.01 fL						
	1.1533	1.0326	1.0913	1.2314	1.3387	1.2839
	0.0620	0.0139	0.0380	0.0904	0.1267	0.1085
	0.1055	0.0390	0.0822	0.1459	0.1117	0.1297
0.03 fL						
	1.0952	0.9706	1.0310	1.0937	1.1587	1.1257
	0.0395	-0.0129	0.0133	0.0389	0.0640	0.0514
	0.1053	0.0955	0.1027	0.1071	0.0927	0.0998
0.16 fL						
	1.0389	0.8991	0.9665	1.1008	1.2245	1.1609
	0.0166	-0.0462	-0.0148	0.0417	0.0879	0.0648
	0.0945	0.0722	0.0889	0.0908	0.1074	0.1010

^aN = 21 trials per cell.

^bN = 42 trials per cell.

^cCaplamp penumbra only at average distance of 12 feet.

^dSD Standard deviation of time in log seconds.

TABLE F-9. Geometric mean response time (seconds)
for peripheral motion detection (Cont'd)

Targets: Large cylindrical objects at 60° (average distance 12 feet)

Luminance Level	Observer: BB			Observer: JG		
	Target Position		Across Targets ^b	Target Position		Across Targets
	Left	Right		Left	Right	
0.0018 fL ^c						
Geo. mean	1.4127	2.0140	1.6868	1.9207	.3694	2.1333
Log mean	0.1501	0.3041	0.2271	0.2835	0.3746	0.3290
Log SD ^d	0.1093	0.2261	0.1919	0.1694	0.1802	0.1788
0.003 fL						
	1.1998	1.2691	1.2340	1.6831	.0076	1.8382
	0.0791	0.1035	0.0913	0.2261	0.3027	0.2644
	0.1596	0.1240	0.1417	0.1847	0.0955	0.1503
0.006 fL						
	1.0315	1.2213	1.1224	1.5494	1.9629	1.7439
	0.0135	0.0868	0.0501	0.1902	0.2929	0.2415
	0.1101	0.0773	0.1010	0.1187	0.1876	0.1635
0.01 fL						
	0.8797	1.2883	1.0645	1.5229	1.7346	1.6253
	-0.0557	0.1100	0.0272	0.1827	0.2392	0.2109
	0.1029	0.1832	0.1690	0.1274	0.1408	0.1357
0.03 fL						
	0.8686	0.9507	0.9087	1.1879	1.4431	1.3093
	-0.0612	-0.0220	-0.0416	0.0748	0.1593	0.1170
	0.1828	0.0792	0.1406	0.1153	0.1213	0.1245
0.16 fL						
	0.6945	0.7070	0.7007	1.1084	1.2502	1.1772
	-0.1583	-0.1506	-0.1545	0.0447	0.0970	0.0708
	0.0923	0.0874	0.0889	0.1116	0.1667	0.1426

^aN = 21 trials per cell.

^bN = 42 trials per cell.

^cCaplamp penumbra only at average distance of 12 feet.

^dSD Standard deviation of time in log seconds.

TABLE F-9. Geometric mean response time (seconds)
for peripheral motion detection (Concluded)

Targets: Large cylindrical objects at 60° (average distance 12 feet)						
Luminance Level	Observer: SB			Observer:		
	Target Position ^a		Across Targets ^b	Target Position		Across Targets
	Left	Right		Left	Right	
0.0018 fL ^c						
Geo. mean	1.3559	1.3624	1.3591			
Log mean	0.1322	0.1343	0.1333			
Log SD ^d	0.0583	0.0577	0.0573			
0.003 fL						
	1.0611	1.0982	1.0795			
	0.0258	0.0407	0.0332			
	0.0472	0.0527	0.0500			
0.006 fL						
	1.0406	1.1344	1.0865			
	0.0173	0.0548	0.0360			
	0.0514	0.0715	0.0644			
0.01 fL						
	0.9906	1.1315	1.0587			
	-0.0041	0.0536	0.0248			
	0.0426	0.0549	0.0566			
0.03 fL						
	0.9381	1.0270	0.9816			
	-0.0277	0.0116	-0.0081			
	0.0467	0.0817	0.0687			
0.16 fL						
	0.8217	0.8519	0.8367			
	-0.0853	-0.0696	-0.0775			
	0.0489	0.0667	0.0583			

^aN = 21 trials per cell.

^bN = 42 trials per cell.

^cCaplamp penumbra only at average distance of 12 feet.

^dSD Standard deviation of time in log seconds.

APPENDIX G

INDIVIDUAL OBSERVER RELIABILITY DATA

TABLE G . - Test-retest reliability (significance)
of direct performance measures

Performance Measure	Observer					Across Observers
	TP	JM	BB	JG	SB	
Cracks						
Wide	0.9290 (0.01)	0.9375 (0.01)	0.5160 (n.s.)	0.7587 (n.s.)	0.5344 (n.s.)	0.9557 (0.01)
Narrow	0.9137 (0.05)	0.8939 (0.05)	0.9641 (0.01)	0.9475 (0.01)	0.9816 (0.01)	0.9923 (0.01)
Rock Motion						
Time	0.9822 (0.01)	0.9003 (0.05)	0.9198 (0.05)	0.9368 (0.05)	0.9762 (0.01)	0.9872 (0.01)
Error(1.0) ^a	0.6864 (n.s.)	0.7835 (n.s.)	0.6949 (n.s.)	0.8855 (0.05)	0.6124 (n.s.)	0.8535 (n.s.)
Error (0.6) ^b	0.9852 (0.01)	0.7899 (n.s.)	0.7344 (n.s.)	0.8538 (n.s.)	0.8344 (n.s.)	0.9605 (0.01)
Floor Holes						
Near	0.9941 (0.01)	0.9392 (0.01)	0.9987 (0.01)	0.9700 (0.01)	0.9506 (0.01)	0.9868 (0.01)
Far	0.9981 (0.01)	0.9925 (0.01)	0.9967 (0.01)	0.9863 (0.01)	0.9723 (0.01)	0.9982 (0.01)
Floor Rubble						
Near	0.9712 (0.01)	0.9388 (0.01)	0.9079 (0.05)	0.9523 (0.01)	0.9921 (0.01)	0.9939 (0.01)
Far	0.9757 (0.01)	0.8832 (0.05)	0.7770 (n.s.)	0.9186 (0.01)	0.9897 (0.01)	0.9958 (0.01)

^aResponse times ≥ 1.00 seconds considered errors.

^bResponse times ≥ 0.60 seconds considered errors.

n.s. Not significant.