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NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
NAVAL AIR STATION, PENSACOLA, FL 32508-5700

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THE FORWARD MASKING EFFECTS OF LOW-LEVEL LASER GLARE ON TARGET LOCATION PERFORMANCE IN A VISUAL SEARCH TASK

M.D. Reddix, J.A. D'Andrea, and P.D. Collyer

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A. J. MATECZUN, CAPT, MC USN
Commanding Officer

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*Reddix, M.D., D'Andrea, J.A. and Collyer, P.D.

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The present study examined the effects of low-intensity laser glare, far below a level that would cause ocular damage or flashblindness, on the visually guided performance of aviators. With a forward-masking paradigm, this study showed that the time at which laser glare is experienced, relative to initial acquisition of visual information, differentially affects the speed and accuracy of target-location performance. Brief exposure (300 ms) to laser glare, terminating with a visual scene's onset, produced significant decrements in target-location performance relative to a no-glare control, whereas a 150 and 300-ms delay of display onset (DDO) had very little effect. The intensity of the light entering the eye and producing these effects was far below the Maximum Permissible Exposure (MPE) limit for safe viewing of coherent light produced by an argon laser. In addition, these effects were modulated by the distance of the target from the center of the visual display. This study demonstrated that the presence of laser glare is not sufficient, in and of itself, to diminish target-location performance. The time at which laser glare is experienced is an important factor in determining the probability and extent of visually mediated performance decrements.

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SUMMARY PAGE

THE PROBLEM

Lasers are now a common element in the tactical military environment. Many factors serve to increase the probability that laser-induced glare will be the most frequent source of laser-evoked visual disruption encountered by naval aviators. The present study examined the effects of low-intensity laser glare, far below a level that would cause ocular damage or flashblindness, on the visually guided performance of aviators.

FINDINGS

This forward-masking study showed that the time at which laser glare is experienced, relative to the initial acquisition of visual information, differentially affects the response latency and accuracy of target-location performance. Brief exposure (300 ms) to laser glare, terminating with a visual scene's onset, produced significant decrements in target-location performance relative to a no-glare control whereas a 150 and 300-ms delay of display onset (DDO) had very little effect. The intensity of the light entering the eye and producing these effects was far below the Maximum Permissible Exposure (MPE) limit for safe viewing of coherent light produced by an argon laser. This study also demonstrated that the presence of low-level laser glare is not sufficient, in and of itself, to diminish target-location performance. The time at which low-level laser glare is experienced is an important factor in determining the probability and extent of visually mediated performance decrements.

RECOMMENDATIONS

Eye protection is needed to prevent mission disruption even at laser intensities that are not harmful to the eye. The type of eye protection most suitable for use in dawn/dusk and nighttime environments should be carefully scrutinized, however, as most if not all available eye protection will reduce the amount of ambient light reaching the retina. Small reductions in ambient light may cause decrements in the acquisition of critical visual information both inside and outside the cockpit. In addition, laser protective eyewear will likely change the apparent color of cockpit displays creating color-based confusions.

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INTRODUCTION

Lasers have become a common element in the tactical military environment (1). At a minimum, naval aircrews currently risk exposure to laser illumination from ground, ship, and air-based rangefinders and target designators (1,2). Furthermore, the use of lasers to simulate "live fire" during military training exercises and as offensive weapons (1) poses additional threats to military aviators because of the potential to disrupt visually guided performance, namely the speed and accuracy of locating critical visual information both inside and outside the cockpit.

The disruption of visual performance due to ocular exposure to laser illumination can be placed into three general categories (2, pp. 9-10). These categories are graded with respect to the source of visual disruption: a) glare, b) flashblindness and afterimage, and c) corneal and retinal damage. The time course and nature of the associated visual disturbance varies for each category. The latter two categories are set apart from the former (glare) in that their disruptive effects remain after laser stimulation ceases. Furthermore, the temporary but lingering effects of flashblindness, as well as the permanently damaging effects of corneal and retinal burns, depend on a rather well-focused, sufficiently powerful, and coherent light source striking the eyes. Many factors serve to attenuate laser power, thus modulating or eliminating the threat of permanent or lingering laser-induced visual deficits: atmospheric turbulence, laser-beam divergence, wavelength and pulse duration of the laser source, distance of the eye(s) from the light source, incidence of a direct or reflected beam on the eye(s), duration of exposure, refractive properties of aircraft windscreens, and laser-protective eyewear. These factors may serve to increase the probability that laser-induced glare, the effects of which last only as long as the light source is present in the visual field, will be the most frequent source of laser-evoked visual disruption encountered by naval aviators.

Glare can result from the combination of several factors, which include scattering of light inside the eye (intra-ocular scattering), and extra-ocular forward light scattering by the atmosphere, aircraft windscreen, and spectacles or prescription contacts. Several recent studies have revealed that laser-induced veiling glare causes decrements in visually mediated human performance. In one study (3), subjects viewed a moving target while seated behind an aircraft canopy. Laser glare was produced by a laser beam propagated over an outdoor range producing a 1-m diameter glare pattern at the subject viewing distance of 1.5 km. Results of both day and night experimental trials showed that the portion of the field-of-view occluded by glare increased as laser irradiance level increased. In another experiment (4), the masking effects of continuous wave (CW) laser glare on head-up-display (HUD) symbology was observed to be wavelength dependent. Army field studies (5,6) demonstrated that laser glare interferes with tube-launched, optically-tracked, wire-guided missiles (TOW) gunners' target tracking ability. Interestingly, notable variations between individual subject responses to laser glare were observed in each of the aforementioned laser glare investigations.

Our own recent investigations of laser glare (7-11) have shown that incident powers of laser illumination well below a threshold that would have produced ocular damage cause predictable decrements in visual search performance when ambient lighting is low ($\approx$ 1.56 cd/m^2). These studies, which required subjects to locate target disks or rectangles in a complex visual array under several conditions of laser-induced glare, have revealed several important factors that affect an aviator's susceptibility to laser-glare performance decrements. First, low-level laser glare (0.09-0.5 μW/cm^2), under low ambient lighting, is very effective in disrupting target-location performance during a visual search task (7-9). Second, under these conditions, the shape of aircraft windscreen (curved F/A-18 vs flat A-4) is an important factor. Most important is the observation that a subject's speed and accuracy of target detection is not disrupted by relatively low-level laser glare unless a windscreen is present in the visual (beam) path (7,8). The interaction of laser light and the windscreen must be present for the decrement in visual performance to occur at laser intensities less than or equal to 0.2 μW/cm^2 (7). Third, as expected, the disruption of visual search performance was ameliorated at higher ambient lighting levels suggesting more intense laser irradiation is necessary to disrupt visual search performance in daylight conditions (8). Fourth, under low-ambient lighting conditions, visual search inside the cockpit on a CRT monitor mounted in the instrument panel is not disrupted by laser glare intensities that are disruptive of visual search through the windscreen (10). Fifth, the chronological age and opacity of the eye's lens correlates well with speed and accuracy of target acquisition in the visual search paradigm (11). Generally, older subjects were more susceptible to laser glare than younger subjects in spite of equal visual search performance of both groups without laser glare. Sixth, the effects of laser glare on a visual search task designed to maximize visual attentional demands were investigated. Brief presentations of laser glare (irradiance: 0.1-0.5 $\mu W/cm^2$), 3700 times below the ANSI maximum permissible exposure (MPE), significantly slowed the speed and reduced the accuracy of target location responses relative to a no-glare control (9). Finally, a 300-ms pulse of low-level laser glare (0.38 $\mu W/cm^2$ at the cornea) experienced shortly (50 ms) after the appearance of critical visual information negatively impacts the speed and accuracy of target-location performance (12). Thus, the time at which laser glare is experienced is an important factor in determining the probability and extent of visually mediated performance decrements.

With the exception of Reddix et al. (12), these previous glare studies have focused on investigations of the effects of laser-induced glare under conditions of continuous laser irradiation. That is, laser glare was presented continuously during each visual performance trial. In an operational environment, however, laser glare will be experienced most likely before, coincident with, or after the time at which critical visual information becomes available for inspection. Forward, simultaneous, and backward masking paradigms (e.g., 13, p. 7-11) can be used to investigate each of these 'time of laser onset' scenarios, respectively. Most laser-glare research can be conceptualized by a simultaneous masking paradigm where laser glare is presented coincident with the visual information to be inspected. In order to determine an accurate probability of target location failure, however, target-location performance must be observed under both forward (i.e., glare precedes visual target information) and backward (12; glare follows critical visual target information) masking conditions.

The present study continues our previous work of examining the effects of low-level laser glare on the speed and accuracy of target-location performance (7-12). A modified forward-masking paradigm (e.g., 14,15) was used to examine the effect of laser glare, which precedes the onset of critical visual information to be identified, on the target-location performance of student aviators. Subjects participated in the study while seated in a cockpit-familiarization trainer with attached windscreen assembly. Furthermore, the experimental task was designed to maximize the visual attentional demands placed on the subject to a degree that might be expected in normal flight. Subjects were required to locate targets in a complex, briefly presented (about 1 s) visual array. The effects of laser glare were maximized by conducting the study under low ambient light (dawn/dusk) conditions.

The temporal range of forward masking effects, by patterns and diffuse light flashes, varies greatly (14,16) with threshold inter-stimulus intervals (ISIs) for correct target detection as short as 35 ms and as long as 150-300 ms having been observed (e.g., 14,17). In addition, Boynton and Miller (18) found that a masking flash interferes with target identification when it precedes a target stimulus. The temporal range of the forward-masking effects of unpatterned light flashes is generally shorter ($\approx$ 60 ms) compared to that of forward-masking effects of pattern masks (e.g., 14). In addition, both forward and backward masking effects are greatest when masking and target stimuli follow one another immediately (16,19-22), at least for the case where test stimulus and mask contours do not interact (type-A masking functions: 23, 24). In the present study we expected that a masking flash of light (300-ms duration coherent laser glare), presented at various ISIs prior to the onset of a complex visual scene containing a target stimulus, would have a graded effect on a subject's ability to locate a target (target-location performance). That is, short ISIs should cause greater decrements in the speed (response latency) and accuracy of target-location performance compared to relatively longer ISIs.

MATERIALS AND METHODS

SUBJECTS

Ten male student naval aviator volunteers served as subjects. The age of subjects ranged from 23 to 29 years (*M* = 25.0, *SEM* = 0.7). Near binocular Snellen acuity, measured with an Armed Forces Vision Tester (model FSN 7610-721-9390, Braun-Brumfield, Inc., Ann Arbor, MI) of all subjects was at least 20/20 (range, 20/20-20/15; *M* = 16.4, *SEM* = 0.7). Distant binocular acuity, measured with a Multivision Contrast

Tester (model MCT-800, Vistech Consultants, Inc., Dayton, OH) ranged from 20/17 to 20/15 (*M* = 15.4, *SEM* = 0.3). Because lens opacity (the clarity of an eye's lens) may cause decrements in visual performance independent of visual acuity (4), the clarity of the lenses in both eyes of each subject was assessed before their participation in the study using an Opacity Lensmeter (model 701: Interzeag AG; Schlieren, Switzerland). No subject showed signs of pathological opacity of the lens. Furthermore, as a group, subjects had very similar lens opacity scores (left eye, *M* = 9.98, *SEM* = 0.52; right eye, *M* = 9.52, *SEM* = 0.51).

EQUIPMENT

Cockpit Simulator

Subjects participated while seated in a cockpit-familiarization trainer fitted with an F-15 aircraft windscreen assembly. The trainer was located in a separate room, which was isolated from the laser. Subjects were illuminated with an infrared light source and visually monitored using a low-light sensitive closed-circuit television camera (model 6415-2000/0000, Cohu Electronics Division, San Diego, CA). An automated intercom system near the cockpit allowed the experimenter to maintain voice contact with the subject at all times.

Laser

A collimated beam of visible light with a peak spectral radiance of 514 nm was generated by an argon ion laser (Innova 70-2, Coherent Laser Products Division, Palo Alto, CA) and conducted by fiber-optic cable to the center of a visual display in an adjacent room. Peak spectral radiance of the beam was verified at 514 nm using a Spot Spectrascan Fast Spectral Scanning System (model PR-710, Photo Research, Burbank, CA).

The laser was operated at full power output of nearly 800 mW. Laser-beam intensity was limited by a 1.99-mm aperture within the laser's protective housing as well as by passive (e.g., iris diaphragm, prisms, neutral density filters) electromechanical (e.g., electronic shutter) and electro-optical (i.e., electro-optical attenuator) devices external to the laser. Figure 1 shows a schematic representation of the laser beam path through these power limiting devices. The attenuated beam was focused on the polished end of an optical grade fiber-optic cable by a fiber-light coupler (model 714/965-5406, Newport Corp., Fountain Valley, CA). The multi-mode fiber-optic cable (0.22-mm od) consisted of a single-strand core of acrylic polymer (1-mm id) with a fluorine-polymer sheath. The distal end of the fiber-optic cable, inserted through a hole in the center of a rear projection screen, projected a 28.1° cone of laser light toward the cockpit. Beam diameter at the subject viewing distance of 182 cm was approximately 91 cm (measured as the cross section of the beam where the power per unit area was 50% that of the average power).

Laser-irradiance Level. Subjects were exposed to one level of laser irradiance (0.5 $\mu W/cm^2$) for a maximum of 36 s in one 24-h period. Laser-irradiance level was established by placing a radiometer (model 161 with radiometric filter, United Detector Technology, Hawthorne, CA) in the horizontal plane of vision at the subject viewing distance of 182 cm with a) the cockpit windscreen installed, and b) the laser providing the only source of illumination. A Laser Power Controller (model VIS, Cambridge Research & Instrumentation, Inc., Cambridge, MA) was used to attenuate the laser beam to achieve and maintain the irradiance level at 182 cm. The percentage of laser light transmitted through the laser power controller (LPC) necessary to achieve the irradiance level under these conditions was later used to 'software select' and maintain (approx. 0.05-0.02% drift) a desired subject-exposure level.

Laser Safety. Subject exposure level was correlated with laser irradiance at two fixed locations that were monitored while the subject was seated in the cockpit. One reading was taken in the cockpit near the subject's right shoulder using a radiometer (model 161 with radiometric filter, United Detector Technology, Hawthorne, CA). The second reading, a partial reflection of the laser beam, was measured with a laser power meter (model 45PM, Linconix, Sunnydale, CA) before it entered the fiber-optic cable. Fluctuations in either reading, as well as that of the LPC, would indicate that the power incident on the subject was not at the prescribed level. The laser operator was instructed to terminate the experiment if such an observation

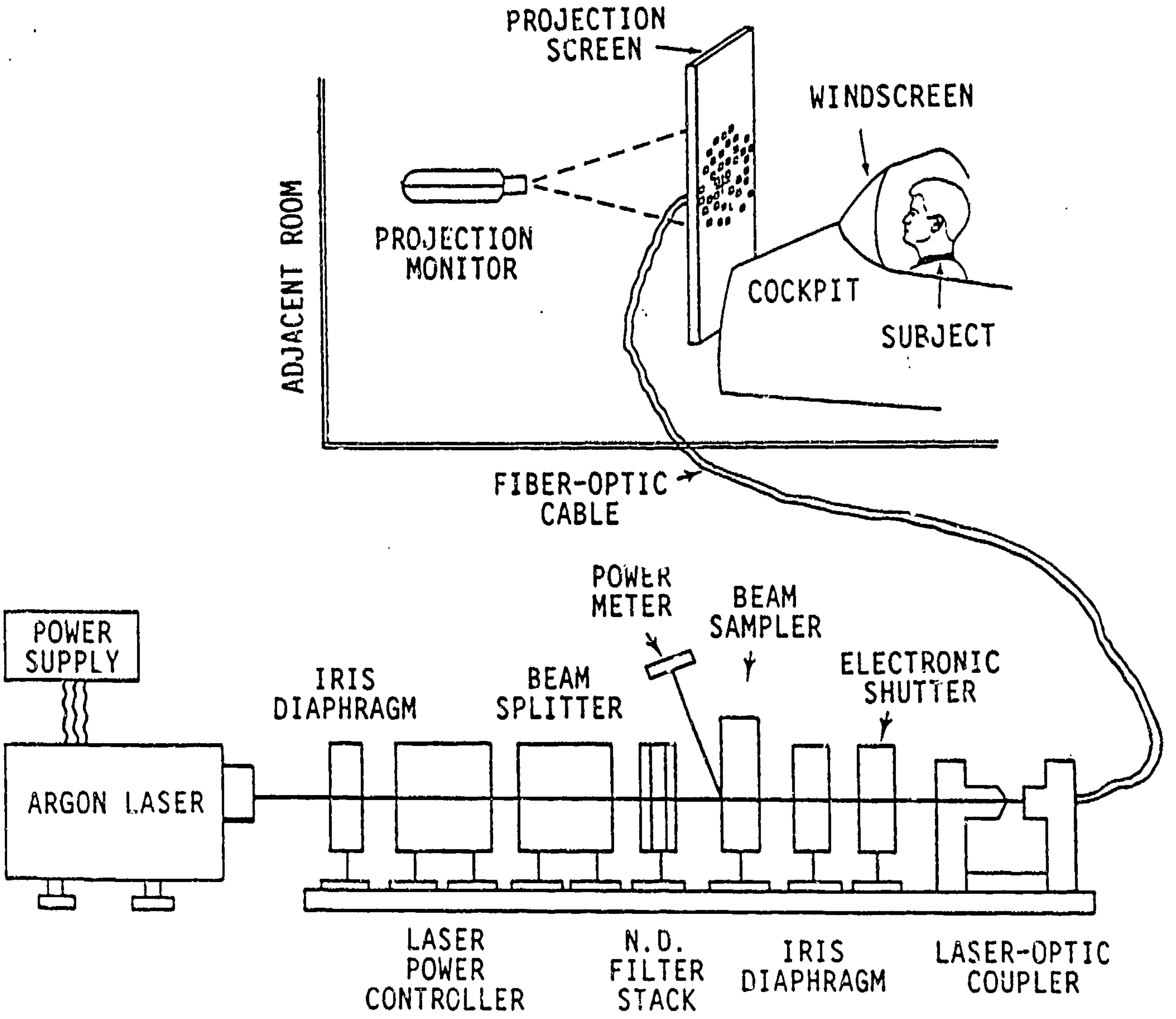

Figure 1. *Schematic Representation of the laser beam path.*

was made. A laser-defeat switch in the cockpit allowed the subject to terminate laser exposure at anytime during the experiment. In addition to the laser, subjects experienced additional illumination from a) the visual stimulus array projected onto a back projection screen, and b) infrared (IR) emitting diodes used to provide sufficient illumination to monitor the subject with closed-circuit television. These illumination sources provided an average of 0.063 $\mu W/cm^2$ (n = 15, SEM = 0.001) additional irradiance measured in the horizontal plane of vision at the subject viewing distance.

The nominal hazard zone (NHZ) for ocular damage (ANSI Z136.1-1986) from the fiber-optic-projected laser beam was determined for two conditions:

1. The LPC failed, and the subject was exposed to unmodulated laser light (5900 $\mu W/cm^2$ at the terminal end of the fiber-optic cable) for a maximum of 36 s.

2. The subject experienced the 0.5 $\mu W/cm^2$ exposure level (2313 $\mu W/cm^2$ at the terminal end of the fiber-optic cable) for a maximum of 36 s.

While seated in the cockpit familiarization trainer (182 cm from the terminus of the fiber-optic cable), the subject was far removed from the NHZ calculated for conditions 1 (10 cm) and 2 (10 cm). Furthermore, the MPE level of 278 $\mu W/cm^2$ (given an exposure duration of 36 s) was a factor of 556 times greater than that attainable at the maximum 36-s subject-exposure level of 0.5 $\mu W/cm^2$.

Visual Stimulus Array

Each 66-cm high by 88-cm wide, computer-generated, visual stimulus array consisted of 119 randomly placed distractor rectangles (12-mm high, 10-mm wide) and one target rectangle (7-mm high by 6-mm wide). This computer-generated visual array was converted to an analog video signal and rear-projected onto a diffused projection screen using a High Resolution, High Brightness Monochrome Projection Monitor (model 38-B02503-71, Electrohome Limited, Ontario, Canada). The projected display occupied 10.77 vertical by 13.591 horizontal degrees of visual angle. At a subject viewing distance of 182 cm, a distractor rectangle spanned 0.378 vertical by 0.315 horizontal degrees of visual angle, whereas the target spanned 0.220 by 0.189 degrees of visual angle. Approximately 24% of the display area was occupied by the distractor and target stimuli.

Forty visual stimulus arrays were generated; each contained one target. At the center of each display a 3- by 3-cm crosshair divided the scene into four equal quadrants (see Fig. 2). Targets occurred equally often in each of the four quadrants at each of five eccentricities measured from the center of the display. Thus, for the set of 40 stimulus arrays, 2 targets appeared at each of 5 eccentricities within a quadrant. Table A-1 shows the average target-to-crosshair distance and visual angle at each eccentricity.

A Pritchard Photometer with 6' arc aperture (model PR-1980A, Photo Research, Burbank, CA) was used to measure the luminance of a) each target rectangle, b) the distractor rectangle nearest the target, and c) the background midway between the target and its closest distractor. These measurements, made at the subject viewing distance with the windscreen in place, were used to compute target-background and distractor-background brightness contrast $[(L_{Max} - L_{Min})/(L_{Max} + L_{Min})]$ at each target location across the 40 displays. Target, background, and distractor scotopic luminance varied systematically as a function of display quadrant and target eccentricity (see Table A-2). A 4 x 5 (display quadrant x target eccentricity) ANOVA ($p < .05$), however, showed that neither target-background nor distractor-background brightness contrast (M = 0.72, n = 40, SEM = 0.01; M = 0.74, n = 40, SEM = 0.01, respectively) varied reliably as a function of target location within the visual display.

Experimental Control and Data Acquisition

Experimental control and data acquisition were under microcomputer control (COMPAQ Deskpro 386/20, model 2571). An analog-to-digital I/O board (model DASCON-1, Metrabyte Corporation, Taunton,

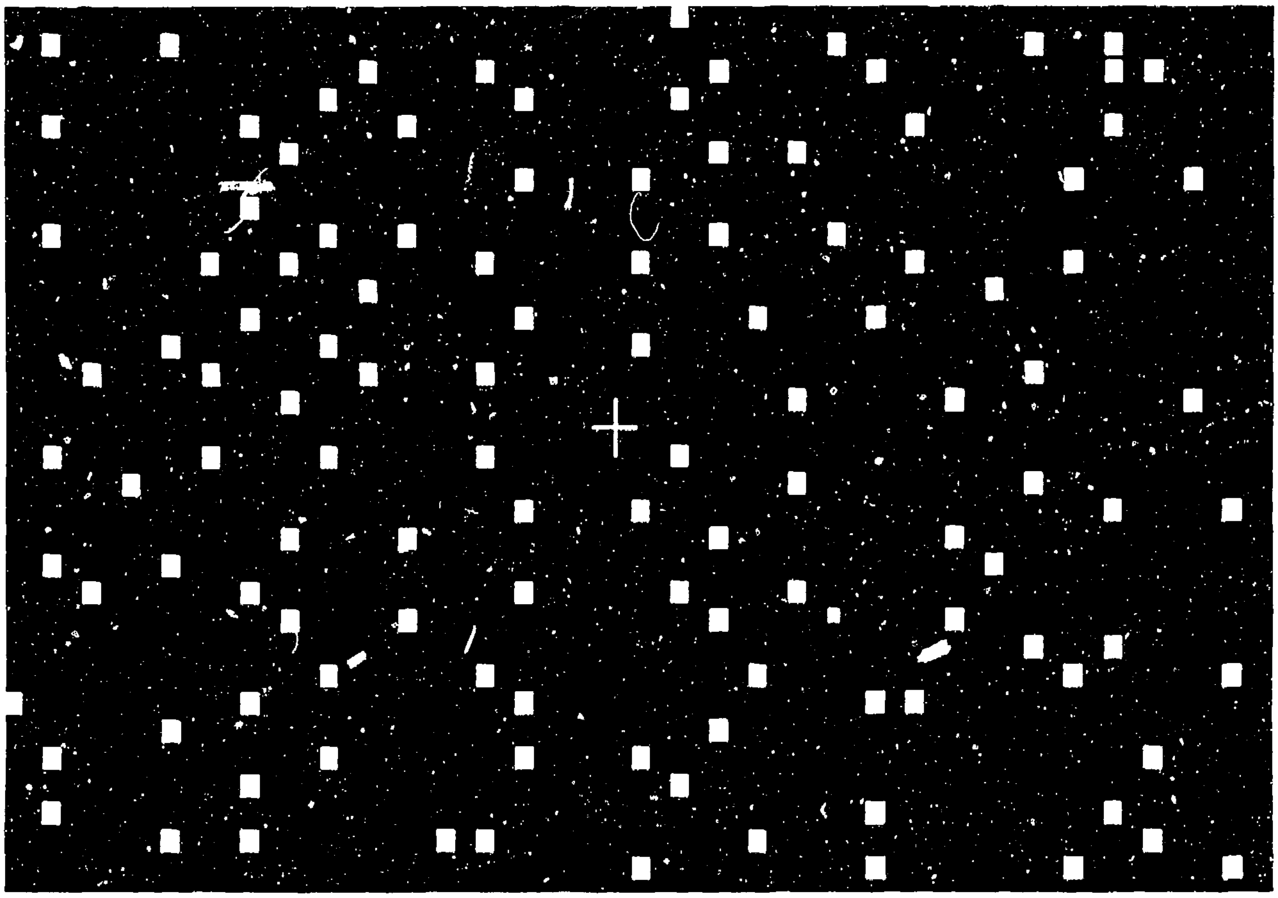

Figure 2. *Example of a visual display with 119 distractor rectangles and 1 target rectangle.*

MA), multifunction timer (model CTM-5, DASCON-1, Metrabyte Corporation, Taunton, MA), and solid state controllers (BRS/LVE, Inc.) were used to monitor subject responses and control the onset and duration of the visual display, laser exposure, and auditory feedback. A compiled algorithm, written in GW-BASIC source code (Microsoft Corp., Redmond, WA), provided control over the function of these peripheral devices.

Visual Assessment

Subjects were monitored for potential decrements in visual capability caused by their exposure to low levels of coherent light. Before (on day 1) and after (on day 5) their participation, subjects received a visual assessment battery to determine their visual acuity (Armed Forces Vision Tester), contrast sensitivity (Vistech, Multivision Contrast Tester) with and without incandescent central glare, lens opacity (Interzeag, Opacity Lensmeter), and color sensitivity (Farnsworth Munsell 100 Hue Test, Kollmorgen Corp., Baltimore, MD).

PROCEDURES

Subjects were tested separately. Each subject sat in the cockpit-familiarization trainer in a completely darkened room for the first 5 min of each experimental session. At the completion of this dark-adaptation period, the center of the rear-projection screen was illuminated by the word "GO." Subjects were told that pressing the display-advance button, held in their nondominant hand, would reveal the visual display and that their task was to identify the location of the single target rectangle as quickly as possible (without sacrificing accuracy) by pressing one of four response keys. Each response key corresponded to a different quadrant of the visual display. The keys were placed in a 3.5-cm wide by 2.5-cm long grid on an aviator's knee-board. Subjects responded with their dominant hand.

The display remained on until the subject responded or for about 900 ms ($n = 30$, $M = 903.53$, $SEM = 1.10$), whichever occurred first. A 1-s pause followed the subject response, after which the word 'GO' reappeared in the center of the display indicating that the response had been recorded and the next trial was ready to begin. Correct target-location responses were followed immediately by a high-pitched tone, whereas incorrect responses were followed by a low-pitched tone.

Three delay-of-display-onset (DDO) conditions were used in a modified forward-masking paradigm. The cockpit windscreen was illuminated for 300 ms by laser glare followed by the appearance of the target scene either 0, 150, or 300 ms later. The DDO was time-locked to laser-glare offset (see Fig. 3).

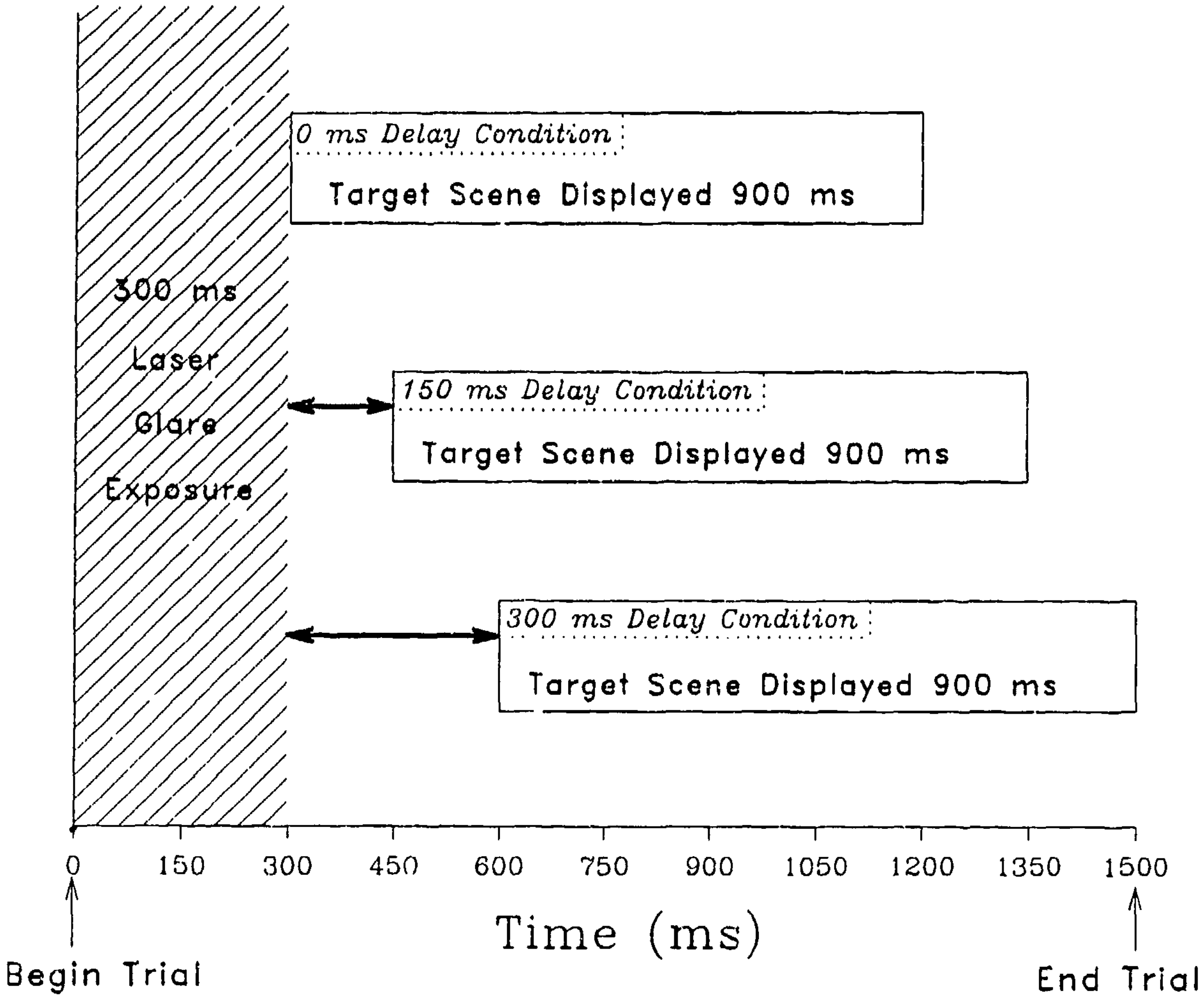

Figure 3. *Time course of events for each delay-of-display-onset condition.*

A no-laser-glare condition served as a control. The control and three DDO conditions were assigned equally to each of the 20 target locations. Thus, for the 160-trial display set, each DDO condition occurred twice at each of the 20 target locations. The order of presentation of the 160-trial display set was randomized such that no single target-location or DDO condition occurred more that two times in succession. Twelve such quasi-random orderings of the 160-trial display set were generated. A display set was presented in 4 blocks of 40 displays separated by 1-min rest periods. The method of random selection without replacement was used to choose a display set to be viewed by a subject. Subjects viewed one display set each day.

Days 1-3 were training days, serving to stabilize subject performance, and involved no laser exposure. On days 4 and 5, each subject viewed a display set that included the three DDO conditions and a no-laser-glare control. Each subject was exposed to the same laser irradiance level (0.38 $\mu W/cm^2$).

Responses latencies were measured relative to visual display onset. Subjects were shown their performance records at the completion of each of the five experimental sessions. Furthermore, on the following day, each subject was shown how his previous day's performance compared to that of the other subjects.

RESULTS

Training and laser-exposure data were analyzed separately. Only correct target-location responses were used in the analyses. A completely within-subjects repeated-measures analysis of variance (ANOVA) design was used to evaluate the effects of the experimental treatments on the latency and accuracy of target-location responses. Post-hoc pairwise comparisons among means were carried out using Tukey's HSD test at the 0.05 probability level.

Training data consisted of latencies and accuracies of target-location responses measured over 3 days (days 1-3) of practice. On each day, subjects responded to one hundred and sixty 900-ms visual displays without concomitant laser exposure. Each target appeared at 1 of 5 eccentricities for a maximum of 32 correct responses at each eccentricity on each of the 3 training days.

Laser exposure data consisted of latencies and accuracies of target-location responses over 2 days (days 4-5). On both days, subjects experienced 3 DDO conditions, as well as a no-laser-glare control and viewed one hundred and sixty 900-ms visual displays . Again, each target appeared at 1 of 5 eccentricities for a maximum of 8 trials per eccentricity (5) per experimental condition (4) per day (2).

TRAINING DATA

Individual subject performance, both response latency and accuracy, improved over the 3-day training period. A three-by-five way repeated-measures ANOVA of the data (training day by target eccentricity) revealed that speed of target location varied as a function of days of practice [$F(2, 18) = 20.30, p < .001$] and target eccentricity [$F(4, 36) = 51.25, p < .001$]. Post-hoc tests revealed that the mean ($M \pm SEM$) response latencies (in milliseconds) were significantly lower on days 2 and 3 compared to day 1 (847 ± 24, 767 ± 20, and 968 ± 27, respectively). In addition, subjects responded most rapidly to targets near the center of the display (see Fig. 4, upper graph). That is, the latencies of target location responses were significantly lower for targets 1.6 and 3.7° from the center of the display (719 ± 23 and 761 ± 23, respectively) compared to targets 5.9, 6.7, and 8.1° from the center of the display (838 ± 24, 942 ± 29, and 1044 ± 33, respectively). Targets appearing at an eccentricity of 5.9° from the center of the display were responded to significantly faster (838 ± 24) than targets appearing 6.7 and 8.1° from the center of the display (942 ± 29 and 1044 ± 33, respectively). Finally, subjects responded significantly faster to targets 6.7° from the center of the display (942 ± 29) compared to targets appearing 8.1° from the center of the display (1044 ± 33).

A three-by-five way repeated-measures ANOVA (training day by target eccentricity) revealed that accuracy of target-location responses also varied as a function of days of practice [$F(2, 18) = 15.88, p < .001$] and target eccentricity [$F(4, 36) = 23.37, p < .001$]. As with response latency, post-hoc tests revealed that subjects' mean (*M* ± *SEM*) accuracy of target-location performance was significantly elevated on days 2 (27.24 ± 0.62) and 3 (28.14 ± 0.50) compared to day 1 (23.84 ± 0.84). Finally, mean (*M* ± *SEM*) accuracy of target-location performance varied reliably as a function of target eccentricity. That is, target-location accuracy was greater for targets appearing at eccentricities 1.6, 3.7, and 5.9° (27.3 ± 0.59, 25.9 ± 0.95, and 25.28 ± 0.92, respectively) compared to targets at eccentricities 6.7 and 8.1° (21.1 ± 1.07 and 19.5 ± 1.07, respectively). Figure 4 (lower graph) summarizes these findings.

LASER GLARE DATA

The effect of DDO on target-location performance was examined in a two-by-four-by-five way repeated-measures ANOVA (day-, 4 & 5, by-delay of display onset-, no-onset, 0, 150, and 300 ms, by- target eccentricity, 1.6, 3.7, 5.9, 6.7, 8.1°). Day of testing significantly affected accuracies of target location responses [$F(1, 9) = 5.23$, $p < .05$]. The mean (± *SEM*) accuracy of target-detection responses was significantly improved on day 5 relative to day 4 (139.6 ± 4.1 and 143.8 ± 3.1, respectively). Day of testing, however, did not interact with DDO or target-eccentricity effects reported below.

Response Latency. The main effects of DDO and target eccentricity were significant for latency of target-location responses [$F(3, 27) = 25.38$, $p < .001$; $F(4,36) = 50.42$, $p < .001$, respectively]. As summarized in Figure 5 each of the DDO conditions differed reliably from the control. The mean (± *SEM*) latency of responding for the 0-ms DDO condition was significantly higher than that of the control (795 ± 17). In addition, latency of responding for the 150 and 300 ms DDO conditions (769 ± 16 and 756 ± 15, respectively) was significantly lower compared to the control.

Latency of responding was differentially affected by the location of the target in the visual display. Targets residing at eccentricities 1.6 and 3.7° were responded to the most rapidly, whereas latency of responding was significantly higher for targets located at eccentricities 5.9, 6.7, and 8.1° (757 ± 12, 876 ± 17, and 955 ± 18, respectively) relative to 1.6 and 3.7° (670 ± 10 and 683 ± 10, respectively).

Response Accuracy. Target eccentricity significantly affected accuracy of target-location performance [$F(4, 36) = 13.43$, $p < .001$]. Furthermore, the effect of DDO varied as a function of target eccentricity [$F(12, 108) = 2.32$, $p < .05$]. Figure 6 summarizes this interaction for accuracy of target location responses. Table 1 presents the means for accuracy of responding for each DDO condition across the five target eccentricities. Three pairwise comparisons at each target eccentricity were most important in this study: no-glare control versus DDO of 0, 150, and 300 ms. One reliable difference was observed. Accuracy was significantly lower in the 300 ms DDO condition, compared to the no-glare control, for targets appearing 6.7° from the center of the display.

As with response latency, accuracy of target-location performance varied as a function of a target's distance from the center of the display. The lowest level of accuracy was observed for targets residing farthest from the center of the display (i.e., 6.7 and 8.1°). At target eccentricities 1.6, 3.7, and 5.9°, target-location performance did not vary reliably, irrespective of DDO condition. Relative to eccentricities 1.6-5.9°, however, target-location performance in all DDO conditions was significantly lower at target eccentricity 8.1°. In addition, accuracy was significantly lower at eccentricity 6.7°, relative to 1.6-5.9°, for DDO conditions of 0 and 300 ms.

VISUAL ASSESSMENT COMPARISONS

To determine any possible effects of laser light exposure on visual function, *t* tests ($p < .05$) for related means were conducted on pre- and postvisual assessment measures of a) visual acuity, b) contrast sensitivity, c) lens opacity, and (d) color sensitivity. As expected, no significant differences were found between the pre- and posttest means for any of these measures.

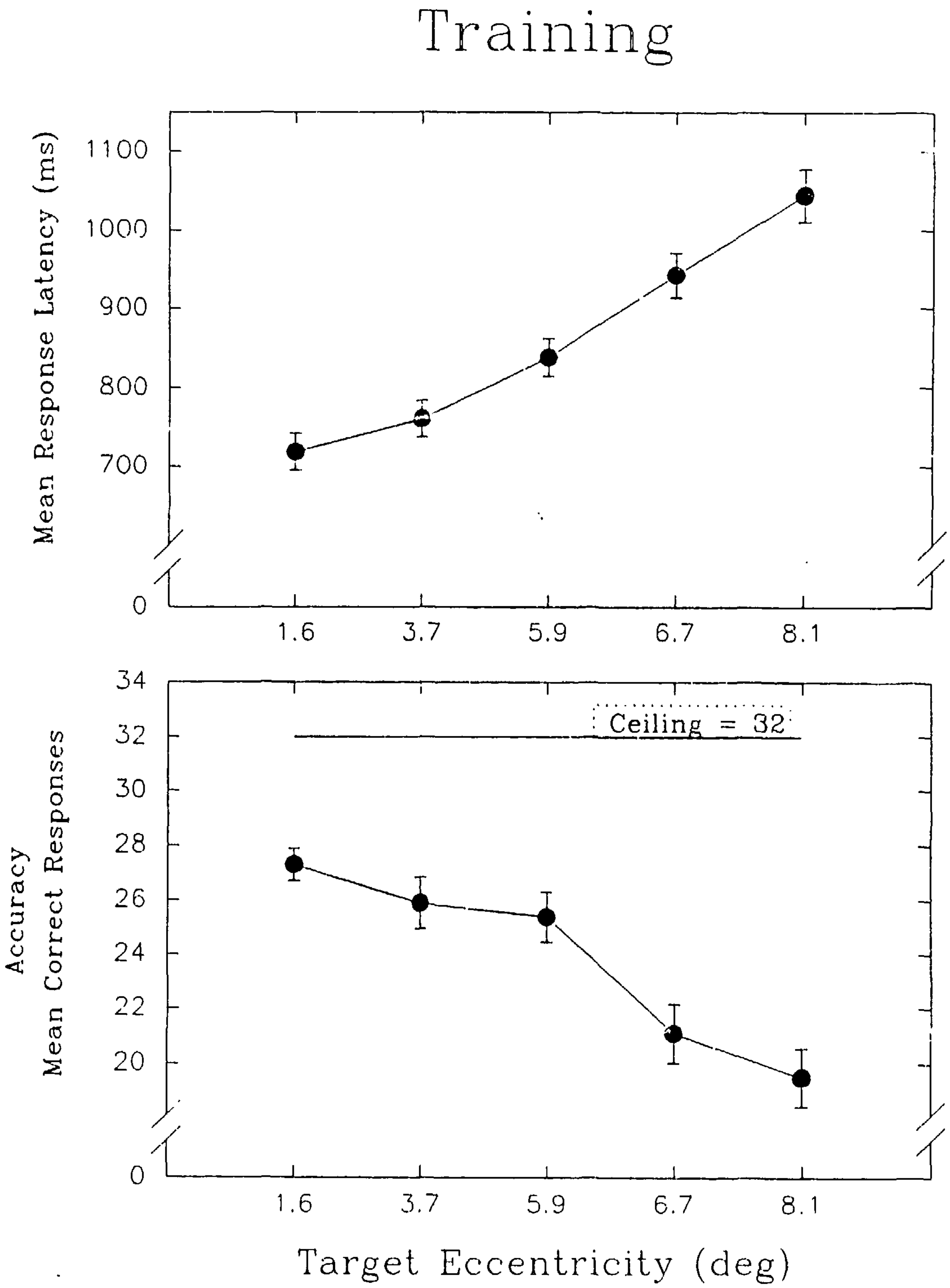

Figure 4. *Latency (mean response time) and accuracy (mean correct responses) of target-location responses as a function of target eccentricity.*

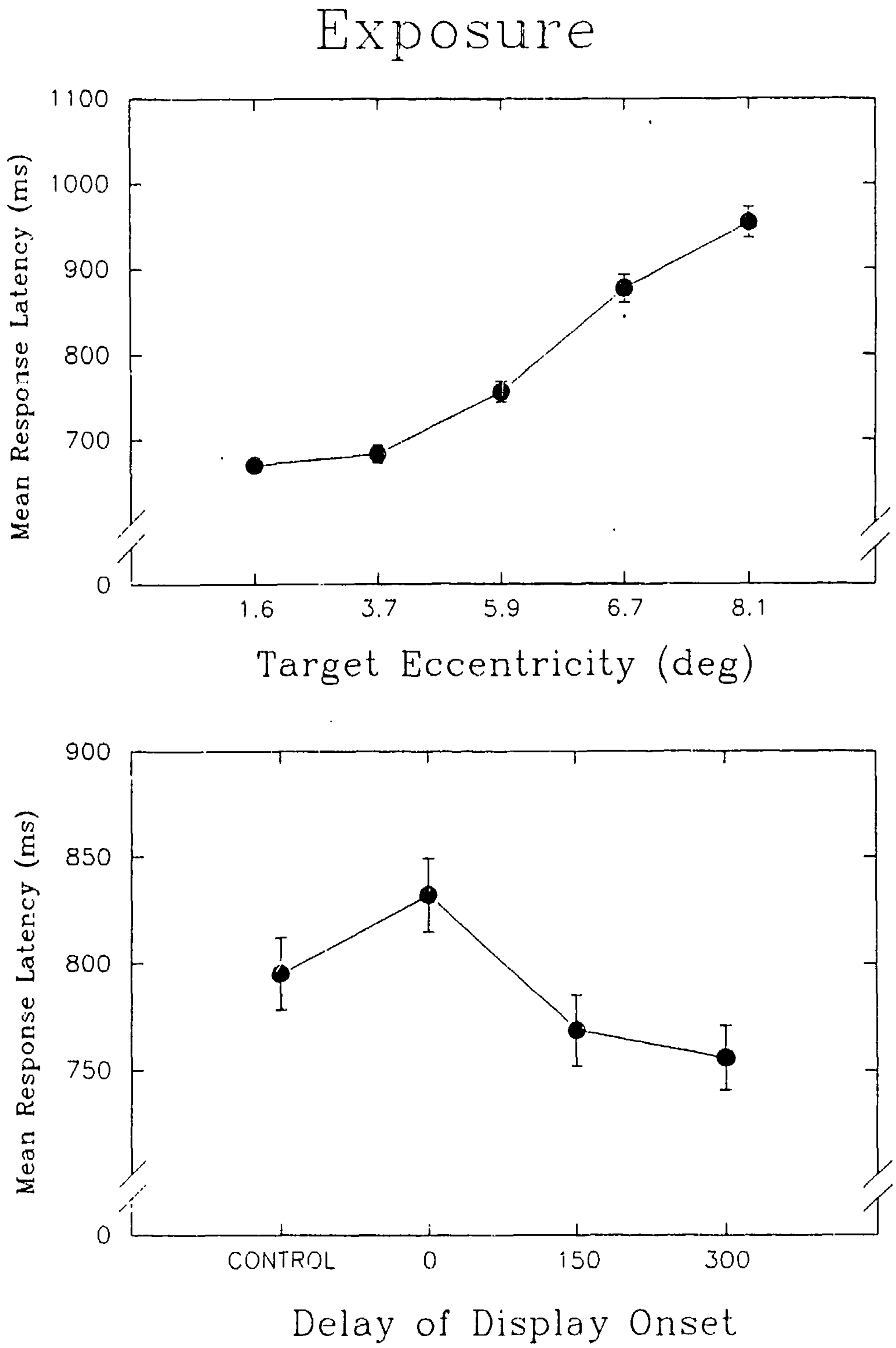

Figure 5. *Latency (mean response time) of target-location responses as a function of delay of laser glare onset (lower graph) and target eccentricity (upper graph).*

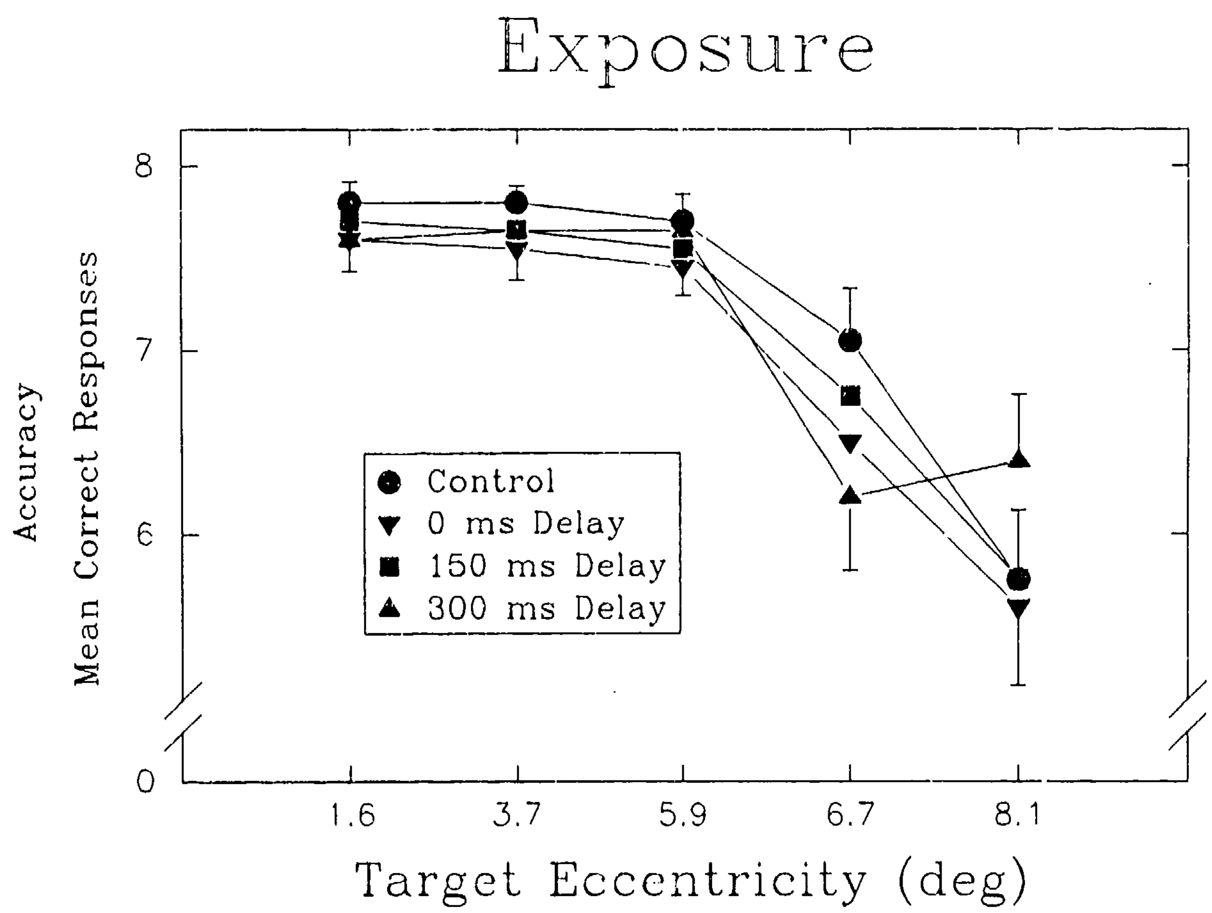

Figure 6. *Accuracy (mean correct responses) of target-location responses as a function of delay-of-display onset and target eccentricity.*

Table 1. Cell Means (± *SEM*) for the Delay-of-Display-Onset by Target-eccentricity Interaction (accuracy of responding).

	Delay of laser glare onset (ms)			
Target eccentricity (°)	Control	0	150	300
	Accuracy of responding			
1.6	7.8 (0.1)	7.6 (0.2)	7.7 (0.1)	7.6 (0.2)
3.7	7.8 (0.1)	7.6 (0.2)	7.7 (0.1)	7.7 (0.1)
5.9	7.7 (0.1)	7.5 (0.2)	7.6 (0.2)	7.7 (0.1)
6.7	7.1 (0.3)	6.5 (0.3)	6.8 (0.4)	6.2 (0.4)
8.1	5.8 (0.4)	5.6 (0.4)	5.8 (0.4)	6.4 (0.4)

DISCUSSION

Latency and accuracy of responding to targets in a briefly presented visual array were examined separately for nonlaser training trials and laser-exposure trials. Three training days served to improve performance significantly, without producing a ceiling effect. Latency and accuracy of locating targets close to the center of the visual display were not differentially affected by the number of days an individual participated in the study. More importantly, performance on the final 2 days of training did not differ reliably Finally, subjects responded to targets closer to the center of the visual display more rapidly and with greater accuracy relative to targets in the display's outer perimetry. These observations corroborate previous findings regarding latency and accuracy of target location responses for identical (9,12) and nearly identical (7,8) visual arrays. This is not an unexpected finding as early researchers of visual search (e.g., 25) found that subjects have a tendency to search the center of a display for a target more often than the edges.

Several general observations can be made with respect to the forward-masking effect of laser-induced glare on target-detection performance. Most interesting, DDO affected both the response latency and accuracy of target-detection performance. This occurred even though the visual array was clear, and not masked by glare, for the same amount of time (900 ms) under the control and each of the DDO conditions. The 0-ms DDO condition, where display onset immediately followed masking glare offset, produced the only significant increase in response latency. Longer ISIs (150 and 300 ms) were actually associated with significant decreases (improvement) in response latency relative to the no-glare control. Although the exact locus of this effect cannot be determined from these data, low-level laser glare that precedes and terminates prior to critical visual information impacting the retina can apparently interfere with subsequent visual information processing. Oddly, a 300-ms DDO improved the accuracy of target-location responses relative to the control, 0 and 150 ms DDO conditions for targets appearing 8.1° from the center of the visual display; a likely spurious effect. In short, however, DDO had very little impact on the accuracy of target-location responses.

A theoretical treatment of the potential forward-masking effects of glare may seem to be in order at this point. However, such a treatment of the data is difficult due to differences in the masking paradigm used here and that used in traditional investigations of visual integration and persistence (see 23). Unlike the traditional forward-masking paradigm, our visual display was viewed for durations exceeding threshold target detection exposure durations. The effect of DDO might then be attributed to several factors other than the capacity and duration of visual iconic or short-term memory or visual integration. The overlying question here is not one of visual persistence under conditions of laser-induced glare but rather, *What is the nature of target location failure in a visual search task punctuated by brief pulses of laser glare?* We believe the present study shows that the presence of laser glare is not sufficient in-and-of itself to cause decrements in target-detection performance. The time at which laser glare is experienced, relative to the time at which the visual array to be searched is acquired, differentially influences target-location performance. In the forward-masking case presented here an inter stimulus interval (ISI) of 0 ms (in this particular instance the time between laser-glare offset and visual display onset) had a pronounced detrimental effect on the response latency for detecting succeeding visually presented information. The forward masking ISI at which no detrimental effects on target-location performance would be observed lies somewhere between 0 and 150 ms for these specific experimental conditions. An additional study that varies DDO between 0 and 149 ms will be required to derive an exact function relating latency of responding to DDO and target eccentricity.

Considering the results from a previously conducted backward-masking study (12) as well as those of the present investigation it is possible to define the time course of the effects of brief laser flashes on target-location performance. Brief flashes of laser glare (≈ 300 ms in duration), a) terminating less than 150 ms prior to critical visual information impacting the retina, or b) terminating less than 600 ms after critical visual information impacts the retina can be expected to negatively impact target location performance. This creates an asymmetrical 'window of vulnerability' to the detrimental effects of low-level laser glare. These observations are based on low levels of laser induced glare (0.38 - 0.5 $\mu W/cm^2$) experienced under low ambient, mesopic (dawn/dusk), lighting conditions.

RECOMMENDATIONS

Eye protection is needed to prevent mission disruption even at laser intensities that are not harmful to the eye. The type of eye protection most suitable for use in dawn/dusk and nighttime environments should be carefully scrutinized, however, as most if not all available eye protection will reduce the amount of ambient light reaching the retina. Small reductions in ambient light may cause decrements in the acquisition of critical visual information both inside and outside the cockpit. In addition, laser protective eyewear will likely change the apparent color of cockpit displays creating color-based confusions.

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APPENDIX

TABLE A-1. Mean (± *SEM*) Target Distance Measured as Degrees Visual Angle and Crosshair-to-target Distance.

Degrees visual angle	Viewing distance (cm)
1.602 (0.092)	5.089 (0.292)
3.719 (0.075)	11.828 (0.239)
5.903 (0.167)	18.814 (0.535)
6.667 (0.247)	21.273 (0.796)
8.091 (0.320)	25.875 (1.038)

Table A-2. Mean (± *SEM*) Target, Background, and Distractor Scotopic Luminance (cd/m^2) at Each Quadrant-by-Eccentricity Target Location.[a]

Target eccentricity	Quadrant Upper left	 Upper right	 Lower left	 Lower right
		Target luminance		
1.6°	2.69 (.04)	2.53 (.08)	2.73 (.01)	2.57 (.02)
3.7°	2.57 (.23)	2.46 (.11)	2.37 (.12)	2.21 (.10)
5.9°	2.33 (.18)	2.08 (.17)	1.88 (.20)	1.81 (.14)
6.7°	2.19 (.11)	2.03 (.27)	1.60 (.07)	1.33 (.09)
8.1°	1.90 (.26)	1.56 (.28)	1.36 (.16)	1.25 (.21)
		Background luminance		
1.6°	0.31 (.02)	0.55 (.01)	0.54 (.02)	0.41 (.09)
3.7°	0.45 (.09)	0.38 (.12)	0.48 (.00)	0.33 (.11)
5.9°	0.35 (.10)	0.21 (.01)	0.40 (.02)	0.37 (.19)
6.7°	0.30 (.08)	0.38 (.06)	0.34 (.04)	0.28 (.04)
8.1°	0.23 (.09)	0.22 (.01)	0.17 (.05)	0.12 (.09)
		Distractor luminance		
1.6°	2.86 (.02)	2.74 (.01)	2.86 (.10)	2.80 (.04)
3.7°	2.70 (.04)	2.55 (.04)	2.63 (.22)	2.51 (.21)
5.9°	2.46 (.01)	2.12 (.08)	2.06 (.33)	2.41 (.22)
6.7°	2.48 (.22)	2.38 (.43)	1.73 (.33)	1.43 (.09)
8.1°	1.93 (.47)	1.71 (.40)	1.67 (.07)	1.61 (.15)

[a] Each mean is based on five observations.

Other Related NAMRL Publications

Reddix, M.D., DeVietti, T.L., Knepton, J.C., and D'Andrea, J.A., *The Effect of Three Levels of Laser Glare on the Speed and Accuracy of Target Location Performance When Viewing a Briefly Presented Visual Array*, NAMRL-1359, Naval Aerospace Medical Research Laboratory, Pensacola, FL, November, 1990.

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