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An experimental study was performed in a simulator to measure visual disruption resulting from exposure to discontinuous (strobing) laser glare in a flight control task, and compare this to the disruption from continuous laser glare. Seven pilots performed a nighttime visual approach task across repeated experimental sessions. Flights were assigned to conditions including no-glare (baseline), continuous glare, and strobing glare. The strobing conditions included two additional nested manipulations, whereby the duty cycle and pulse repetition frequency were varied. Flight control was assessed quantitatively using the RMS of the deviation from an ideal linear flight path, and the standard deviation of aircraft heading. Both metrics identified disruption in the flights that included laser stimuli. Disruption was greater in the continuous glare condition than in strobing conditions, except for the strobing condition that combined the most rapid pulse repetition frequency with a higher duty cycle. In some flights in this last condition, deterioration in flight control was greater than in the continuous glare condition. Within strobing conditions, both pulse frequency and duty cycle influenced control error. Findings suggest that strobing lasers with certain temporal profiles can not only obscure scene visibility (as continuous glare does) but also interfere with dynamic visual processing.

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Directed Energy Bioeffects Laboratory, Laser Department

Disruption of visual flight control in a synthetic cockpit, resulting from continuous vs. discontinuous laser glare

Jeremy Beer

Report No. XX??

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Disruption of visual flight control in a synthetic cockpit, resulting from continuous vs. discontinuous laser glare

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Report No. XX??

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EXECUTIVE SUMMARY

Background

Laser exposure at bright but non-injurious power levels can cause visual disruption, which, if sustained and severe, presents an operational threat to vehicle operators, including Naval Aviators. Heretofore, these effects have been documented almost exclusively with continuous laser sources, and it has not yet been determined whether discontinuous exposure will aggravate, attenuate, or alter visual disruption.

Objectives

We performed a study to compare visual flight control during continuous vs. discontinuous laser exposure. There were three objectives: 1) Design a flight laser engagement simulator; 2) Compare flight control among conditions with no laser exposure, conditions including discontinuous, strobing exposure, and conditions including continuous exposure; and 3) Test whether strobing exposure would rival continuous exposure in disrupting visual control.

Approach

A laser engagement simulator was assembled, including a wide-field display, cockpit controls, a laser source, and an apparatus for presenting and monitoring laser stimuli. Subjects performed a simulated night VFR landing task in the conditions described above, and flight control measures were recorded, including RMS error and the standard deviation of heading.

Results

Disruption was greater in the continuous laser condition than in all strobing conditions, except the one in which the most rapid repetition frequency was combined with a higher duty cycle.

Conclusions

In strobing laser exposures, the pauses between flashes allow glimpses of the visual environment during which adaptive recovery occurs. If each flash delivers sufficient integrated energy and the inter-pulse interval affords insufficient recovery time, strobing exposures can potentially maintain visual thresholds at an elevated level that obscures the scene continuously. Our findings indicate that while several factors conspire against this threshold elevation (and therefore that many strobing configurations will not equal the visual disruption from continuous exposure), some strobing configurations with high flash rates and low inter-pulse intervals can equal the disruption from continuous exposure. Furthermore, our findings do not, as yet, preclude the possibility that strobing configurations disrupt motion perception in addition to scene visibility (i.e. that seeing the scene is merely a necessary, not a sufficient condition for flying through it).

ABSTRACT

An experimental study was performed in a simulator to measure visual disruption resulting from exposure to discontinuous (strobing) laser glare in a flight control task, and compare this to the disruption from continuous laser glare. Seven simulator pilots performed a nighttime visual approach task across repeated experimental sessions. Flights were assigned to stimulus conditions including no-glare (baseline), continuous glare, and strobing glare. The strobing glare conditions included two additional nested manipulations, whereby the duty cycle and pulse repetition frequency of the flashing laser were varied. Flight control performance was assessed quantitatively using the root-mean-square (RMS) of the pilot's deviation from an ideal linear flight path, and also the standard deviation of aircraft heading. Both metrics identified visual disruption in the flights that included laser stimuli. This disruption was greater in the continuous glare condition than in strobing glare conditions, with the exception of the strobing condition that combined the most rapid pulse repetition frequency with a higher duty cycle. In some flights in this last condition, the measured deterioration in flight control was greater than in the continuous glare condition. Within the strobing laser conditions, both pulse frequency and duty cycle were observed to influence control error. These findings suggest that strobing lasers with certain temporal profiles can not only obscure scene visibility (as continuous glare does) but also interfere with dynamic visual processing.

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INTRODUCTION AND BACKGROUND

Laser exposure can impair human visual performance, even when it is not powerful enough to damage ocular tissue permanently. In particular, exposure to visible (400-700 nm) laser radiation from a source outside the cockpit can threaten aviators' performance of dynamic visual tasks that are necessary to control the aircraft and maintain spatial orientation. This transient visual disruption from non-lethal laser exposure has been observed in the laboratory and in the field (Beer & Gallaway, 1999; D'Andrea & Knepton, 1989; Reddix et al., 1990, 1998; Stamper, Lund, Molchany, & Stuck, 1997a, 1997b). Its mechanisms include disability glare, flash-blindness, and degraded motion perception. Disability glare comprises scattered light in the visual field surrounding a bright source; this can act as a background of additional illumination against which symbols and landmarks are more difficult to distinguish (Finlay & Wilkinson, 1984; Stiles, 1929; Vos, 1984, 2003). Flash-blindness comprises impairment in visual performance that persists following the extinction of a bright source (Bosee et al., 1968; Kosnik, 1995; Menendez & Smith, 1990; Miller, 1965). Degraded motion perception comprises impaired performance for detecting and interpreting the direction of moving visual stimuli, including coherent optic flow, which is necessary for locomotion control (Anderson & Holliday, 1995; Beer & Gallaway, 1999).

This threat to visual performance is rendered more complex by the availability of non-continuous lasers.[1] Since adding a repetitive train of pulses or flashes alters the spatio-temporal profile of a dynamic visual stimulus, strobing lasers might possess a special capacity to impair performance in dynamic visual tasks involving moving targets or flow patterns. This empirical question (namely, whether pulsing or chopping the laser over time aggravates visual disruption in dynamic control tasks) remains unresolved as yet. Of the findings that have been obtained to date, some would seem to support a prediction of greater disruption from discontinuous exposure, while others appear to support the opposite prediction.

Assessing visual effects from discontinuous illumination

The former class of findings includes a number of studies in which visual adaptation to bright light stimuli was measured as a function of the time elapsed from stimulus onset. In determining

[1] In this report, the terms "discontinuous exposure" and "strobing exposure" will be used interchangeably to refer to non-continuous laser exposures presented at a repetition frequency less than the human flicker fusion threshold, and with pulse-widths above the ultra-short temporal domain in which non-linear tissue effects can be induced.

that visual thresholds are highest immediately after the onset of a bright adapting field (after which they decline to an elevated steady-state level), Crawford (1947) demonstrated that a transient bright stimulus could mask target visibility more effectively than a continuous one. This finding was later extended to include a variety of adaptation and test stimuli superimposed in the same visual field location (Finkelstein & Hood, 1981; Hood & Finkelstein, 1986), and also transient glare sources situated at different visual field locations relative to the target (Bichao, Yager, & Meng, 1995). This time history, in which an initial elevation is followed by a decline to a steady state, has also been observed in measurements of the lower threshold of motion following presentation of a glare source (Barraza & Colombo, 2001); this finding extends the comparison of transient vs. continuous sources to motion perception, and demonstrates that under certain conditions, a bright transient glare source can impose the greater visual effect.

Other findings suggest that repetitively pulsed, discontinuous illumination can alter visual orientation mechanisms, and that this capacity varies with the repetition frequency. The rod-in-frame effect, in which the orientation of the surroundings alters the perceived orientation of a vertical pointer, is weakened only slightly in the presence of 2-Hz strobing illumination, but more so at higher frequencies (Cian et al., 1997). A similar dichotomy has been reported in the visual mechanisms that mediate postural stabilization during dynamic oscillations (Amblard et al., 1985); in this study, it was proposed that one mechanism exploits static visual cues, operates below 2 Hz, and is resistant to stroboscopic interference, while a second, more rapid mechanism operates above 4 Hz and is vulnerable to strobing illumination. Discontinuous illumination can also affect the rapidity of responses to a moving instrument symbol (Zeiner & Brecher, 1975), and has been reported to bring about debilitating effects in helicopter pilots (Johnson, 1963).

The above findings do not, however, comprise sufficient evidence from which to draw general conclusions about the effects of discontinuous laser exposure on visual flight control; none employed a laser stimulus, or used a flight task to compare the effects from discontinuous vs. continuous illumination. An initial comparison of this kind was performed in an experiment in which subjects regulated the attitude of a simulated flight instrument (Beer & Gallaway, 1999). Control performance was compared between a continuous laser exposure condition and a discontinuous exposure condition, which delivered the same time-averaged power as the continuous condition via an 8-Hz train of pulses with twice the peak power and a 50% duty

cycle. While both laser sources induced raggedness in visual tracking, and the measured disruption from the strobing laser exceeded that from the continuous laser, it was concluded that further comparison was needed, to include various discontinuous exposure profiles beyond the single configuration that was considered in this study.

In contrast to the above findings, which do not rule out the hypothesis that strobing laser exposure possesses a specific capacity for visual disruption, are findings from a series of experiments that appear to disconfirm this hypothesis (Stamper et al., 1997b). These experiments measured effects of various laser characteristics, including temporal continuity, on visual target tracking in laboratory and field conditions. Non-injurious laser glare fields were superimposed on moving vehicle targets, which subjects pursued using an optical tracking device. In three comparisons between repetitively pulsed and continuous exposure conditions, the discontinuous laser was observed to impair tracking performance less than the continuous source. It was proposed that the off-periods between flashes of the strobing laser allowed scene visibility, which aided the human controller. The findings were interpreted as evidence that continuous laser exposure impairs performance of dynamic visual tasks more than discontinuous exposure, and that for a strobing laser, it is the power averaged over time (not the peak power) that determines the extent of visual disruption.

Measuring visual disruption in a simulated flight environment

Empirical questions remain, if we wish to determine conclusively whether discontinuous laser exposure presents a lesser or greater impediment to visual flight control than continuous exposure. In particular, while both peak power and average power have been proposed as a predictor of the visual disruption from a discontinuous laser source, neither has been tested

explicitly and confirmed as such.[2] Similarly, while at least three different combinations of duty cycle and repetition frequency have been used in vision studies including strobing sources, these temporal variables have not yet been manipulated systematically, and their role in visual disruption has not been determined.

Note that the power and temporal characteristics of the strobing glare source must be considered in conjunction. Since the off period between flashes comprises a repeating incidence of the initial phase of dark adaptation, detecting visual information within this off period depends on both the initial light-adapted state (which depends on the power of the glare stimulus and also varies over time, even within the on-period), and on the recovery of sensitivity, which varies over time and commences once each flash is extinguished.

In addition, it is useful to consider that the pilot's ability to perform control tasks can depend not only on the visibility of the instruments and external scene, but also on their capacity to induce a motion signal in the visual system. Discontinuous illumination might impair visual processing of a moving stimulus without rendering that stimulus invisible, as in the hypothetical task of navigating through a party (or trying to play tennis) in a space illuminated by a strobe light. This implies that one objective in measuring the disruption of visual control tasks from strobing glare should be to determine whether that disruption results from the persistence of elevated thresholds between flashes, from some higher-order interference with motion perception, or both.

The experiment described below was performed to address these questions. In this study, we designed a dynamic task for measuring flight control performance in a visual simulator, superimposed continuous and discontinuous laser glare fields on the display, varied the duty cycle and pulse repetition frequency of the strobing exposures, and measured the disruption in

[2] In the Stamper et al. (1997b) study, the discontinuous and continuous lasers were not matched explicitly for average power, but according to the percentage of the ANSI maximum permissible exposure level. The conclusion that average (not peak) power determines the extent of visual disruption was drawn from an observation that similar tracking error scores occurred in the highest-powered discontinuous exposure condition as in the lowest-powered continuous exposure condition, and these two conditions delivered approximately the same average energy over time. The conditions were not matched exactly for average power, however, and it is possible that doing this would reduce or reverse the performance disparity observed between discontinuous and continuous conditions. The Beer & Gallaway (1999) study, on the other hand, matched discontinuous and continuous laser conditions according to cumulative exposure. With the duty cycle and repetition frequency used, this did amount to matching the sources for average power, with a peak power twice as great in the discontinuous condition; the study concluded that this matching, coupled with the greater disruption observed in the strobing condition, constituted a reasonable argument for performing the comparison between sources matched for peak power.

control performance. The flight control task comprised a final runway approach in simulated nighttime VFR conditions. Subjects completed the approach task with the aid of a synthetic head-up display (HUD), which depicted primary flight reference information. The task required subjects to maintain the HUD flight path indicator on an external location (the landing point) while keeping the aircraft in a level orientation throughout the flight. This task is appropriate for our experimental objectives, because it requires manual tracking of a moving target (the flight path indicator) in a dynamic environment, a competence that is directly relevant to the visual requirements of low-altitude flight.

The experiment was designed to address the question of peak vs. average power, assess the influence of the laser's temporal characteristics, and determine whether there is a temporal strobing configuration that induces greater visual disruption than continuous exposure. Following a rationale presented in the Beer & Gallaway (1999) study (in which strobing exposures with a peak power twice that of the continuous exposures were observed to disrupt vision more), we presented a variety of laser conditions, including both continuous and strobing exposures. All exposure conditions including the continuous condition were matched for peak power. Among the strobing conditions, the duty cycle (the percentage of time the source is illuminated) was varied between 10%, and 50%, and the pulse repetition frequency (the number of flashes per second) was varied within a range of 0.8 Hz to 7.2 Hz. This design enabled several worthwhile comparisons. For example, comparing a 2.4-Hz, 50% train of laser flashes against a 7.2-Hz, 50% train enables a contrast between two conditions that deliver the same peak power, average power, and cumulative radiant energy, but present different primary temporal frequency components and between-flash recovery durations. Conversely, contrasting a 2.4-Hz, 50% train of flashes against a 2.4-Hz, 10% train enables a comparison between conditions that deliver the same fundamental temporal frequency and peak power, but differ in their inter-pulse adaptation duration, high-frequency temporal profile, average power, and cumulative energy delivery.

METHODS

Subjects

Seven male volunteer subjects participated. Subjects were selected for uncorrected or corrected

visual acuity of 20/20 or better, and were recruited from military and civilian personnel at Brooks City Base, Texas. Volunteers were sought who had completed flight time in simulators or real aircraft; of the seven participants, four, including two Flight Surgeons, had flown actual flight hours at some point in their lives, and the remainder had flown simulators. Subjects were administered ophthalmic exams by the USAF School of Aerospace Medicine Consultation Service before and after participating. If the pre-experimental exam determined that a candidate had a scotoma, lesion, history of eye disease, hypersensitivity to light, or any other serious visual defect, that candidate was not selected to participate.[3] Experimental methods were approved by Institutional Review Boards for Brooks City Base and the Naval Health Research Center.

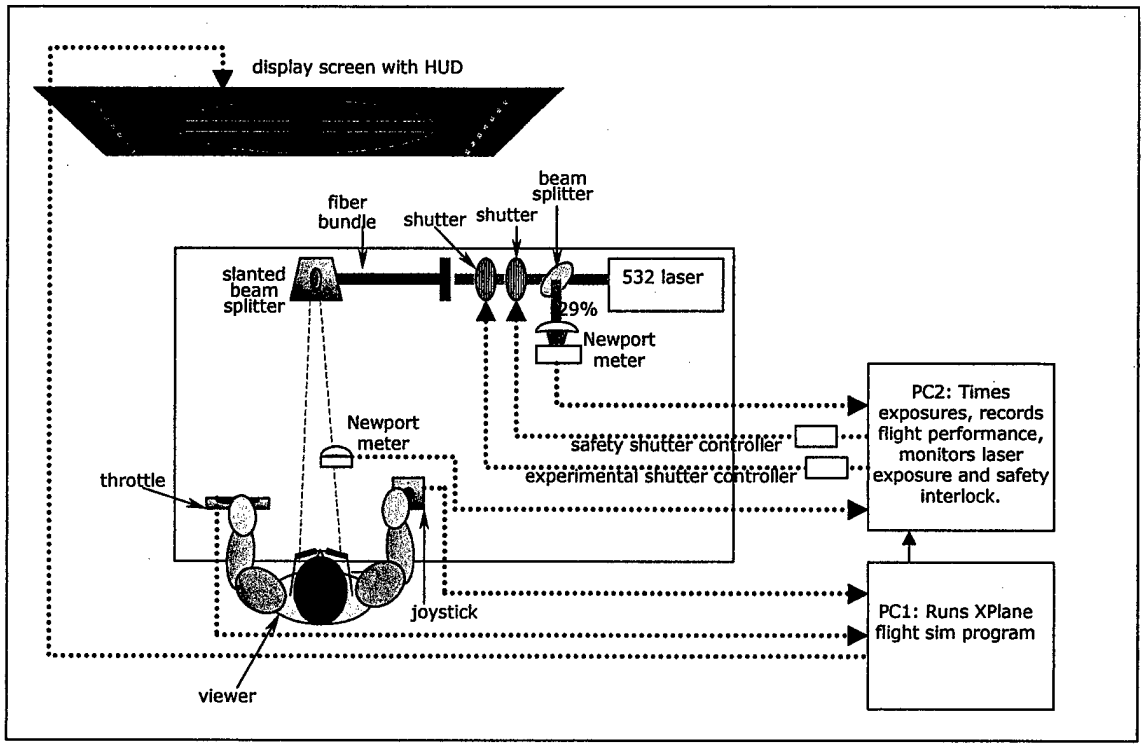

Figure 1. Optical bench layout

The experiment included eight 12-flight sessions on separate days, including four training sessions with no laser exposure, and four experimental test sessions. Flight sessions typically lasted 30-40 minutes. The training sessions were included in order to achieve stable performance and thereby ensure that the experiment recorded distinctions among visual conditions, not

[3] One candidate with a minor color vision defect was permitted to participate, as no other clinical defect was identified; the deficit was noted in the subject's experimental file and analyses were performed both with and without his data included.

artifacts associated with climbing a learning curve (Jones, Kennedy, & Bittner, 1981). Training sessions were also used as a screening instrument; if a subject crashed repeatedly in training or failed to steer the aircraft well enough to keep the runway in sight on the display, that subject was not included in the experimental sessions. Minor complications were encountered during two subjects' data collection. The first, whose entrance exam identified a minor color vision defect as described above, lost three flights at the beginning of his second session; these three flights were repeated before he completed his fourth session. The second subject was forced to interrupt his participation for several weeks in the middle of the experiment, between the second and third sessions. This subject was given extra practice sessions before he resumed participation in his third experimental session.

Flight simulator and control software

The apparatus included a visual display, flight controls, two personal computers (Dell, Inc., Austin, TX), simulation and experimental control software, and an optical bench incorporating two shutters, two optical power sensors, and a laser system (Figure 1). The display comprised a rear-projection visual system (Roadster X4 DLP, Christie Digital Inc., Ontario, CA) operating in 1024 x 768 pixel format at an update rate of 72 Hz. This system was used to depict a synthetic flight environment including a head-up display (HUD) instrument and an out-the-window view of the external terrain. The screen was 1.52 m high and 2.13 m wide. The subject and the screen were on opposite sides of the optical bench, on which the flight controls, laser, and steering optics were mounted. The viewing position was 2.06 m from the screen (yielding a 41 deg x 55 deg image), and was fixed using a headrest mounted to the optical bench. A digital joystick and throttle (CH Products, Inc., Vista, CA) were mounted to the bench and connected via a USB interface to the computer running the simulation.

The simulation software was run on one computer, which included an Nvidia GeForce 256 graphics card. Flights were rendered in XPlane (Laminar Research, Inc., Columbia, SC), an off-the-shelf simulation program that offers a variety of data output options and flight models. An Ethernet link was used to deliver data output from XPlane to the second computer, which was used to record flight data and control the timing of the experimental trials (see below). A Cessna 172 flight model was employed because it offers a forgiving platform on which pilots can train

with relative ease. A green head-up display (HUD) instrument was added to the out-the-window view, to provide primary flight information to support the landing approach task.[4] The luminance of the HUD symbols was approximately 30 Cd/m^2, determined as the mean of measurements at several locations on the instrument.[5] Measured C.I.E. (1931) chromaticity coordinates for the HUD symbols were (.29, .65). The simulated scene comprised a rural airport as viewed during final approach in clear, nighttime conditions. This scene provided the elements of a marginal VMC (visual meteorological conditions) environment, including the low ambient light levels at which pilots can be particularly vulnerable to glare and flash-blindness. The airport was situated in hilly terrain, with a transverse ridge approximately halfway along the flight path. The runway included white lights whose luminance and chromaticity coordinates were approximately 15 Cd/m^2 and (.36, .37) respectively.[6] The surrounding terrain included a transverse ridge that the aircraft must clear in order to land. The sky included stars rendered in a manner similar to the runway lights. Mean luminance levels for the night sky, the ground terrain, the runway pavement, and the "painted" runway markings were .4, .6, .9, and 1.2 Cd/m^2 respectively.

The second computer was used to run the experimental control software, which regulated the timing of laser exposures, sampled the power of the laser stimulus, prevented overexposure, and recorded aircraft state variables and pilot control behavior. The control software comprised a virtual instrument (VI) written in LabView (National Instruments, Inc., Austin, TX), which controlled laser exposure using electromechanical shutters in the beam path (Vincent Associates, Inc., Rochester NY).

One shutter was designated the experimental shutter, and regulated the presentation of glare stimuli in laser exposure conditions. The LabView VI included a switch allowing the experimenter to select between continuous and discontinuous (strobing) configurations for the

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[4] While the HUD is not a standard equipment item on the Cessna, it was incorporated in the flight task because it includes operationally relevant aspects of fine manual control and low altitude flight.

[5] The luminance and chromaticity of features in the environment were measured using a Minolta CS-100A chroma meter with a close-up lens.

[6] Since the runway lights comprised small groups of pixels too small to overfill the light meter's collection area, their luminance was measured with the aircraft on the runway, its bore-sight pointing into the distance, slightly to one side of the centerline. This yielded a foreshortened perspective view in which several distant runway lights were clustered together. While this display configuration came closer to overfilling the collection area, it is likely that the runway lights' actual luminance was greater than the measured value and came closer to 50 Cd/m^2, which was the luminance of the largest white symbol on the screen, the movable mouse arrow.

experimental shutter. In the continuous configuration, the VI signaled the shutter controller to present uninterrupted exposures. In the discontinuous configuration, the VI signaled the shutter controller to present chopped exposures, yielding an exposure time history with a rectangular waveform. In the latter case, the duty cycle and repetition frequency were configured using mechanical settings on the shutter controller, with specific duration (time on) and interval (time off) values for each strobing exposure condition. The duty cycle and repetition frequency were verified on the optical bench using a Newport 818-SL detector connected to a Tektronic 2230 oscilloscope.

A second shutter was used to block the beam if either of two safety circuits detected excessive power levels from the laser. The safety circuits sampled the output of the laser at separate locations in the beam path. Each circuit comprised an 818-SL optical detector (Newport Corporation, Irvine, CA), a power meter (Newport 1832), a serial connection from the power meter to the LabView computer, comparison logic in the VI, and a second serial connection (shared by both safety circuits) from the LabView computer to the safety shutter.[7]

The VI polled the XPlane data stream from the first computer at ten samples/s and recorded aircraft state variables including aircraft position, altitude, and heading, as well as other variables including pitch, roll, airspeed, and lateral and forward-back joystick deflections. These data were used to calculate indices of flight control performance.

Flight task

The landing approach task was the same for all trials and conditions: Subjects were instructed to follow a three-degree glide slope and land the aircraft on the numbers at the near end of the runway (Figure 2). Instructions stated that the best way to maintain a linear flight path was to use the joystick and throttle to keep the HUD flight path indicator directly over the near end of the runway as much as possible, and to try to keep this intended landing point three-fifths of the way

[7] The first safety circuit sampled the raw beam; a pellicle beam splitter was mounted adjacent to the exit aperture, where it split off a test beam and directed it into the first optical detector. The second circuit sampled the laser illumination reaching the viewing position; the second optical detector was mounted in front of the subject facing the screen, from which location it measured irradiance from the lower shoulder of the beam. Before the experiment, power levels were measured at these two locations in the beam path, with the laser glare system producing the planned experimental irradiance at the viewing position. Each sampling location was assigned a threshold corresponding to 110% of the planned irradiance at the eye. Comparison logic was implemented in the VI to monitor the detectors and close the safety shutter if either meter recorded a power level greater than its threshold.

down from the horizon and the –5-degree line on the HUD climb-dive ladder. The experimenter began each trial by loading a saved situation in the XPlane program. The situation specified the geographic environment, time of day, weather, initial heading, location, and airspeed. These state variables placed the aircraft in a three-degree glide slope 787 ft. (240 m) above ground level and 2.43 nautical miles (4500 m) from the near end of the runway.[8] Once the subject assumed control of the aircraft, the experimenter started the LabView VI. Since there was some variation in the time that elapsed before data recording began, the first recorded aircraft position varied somewhat between flights.

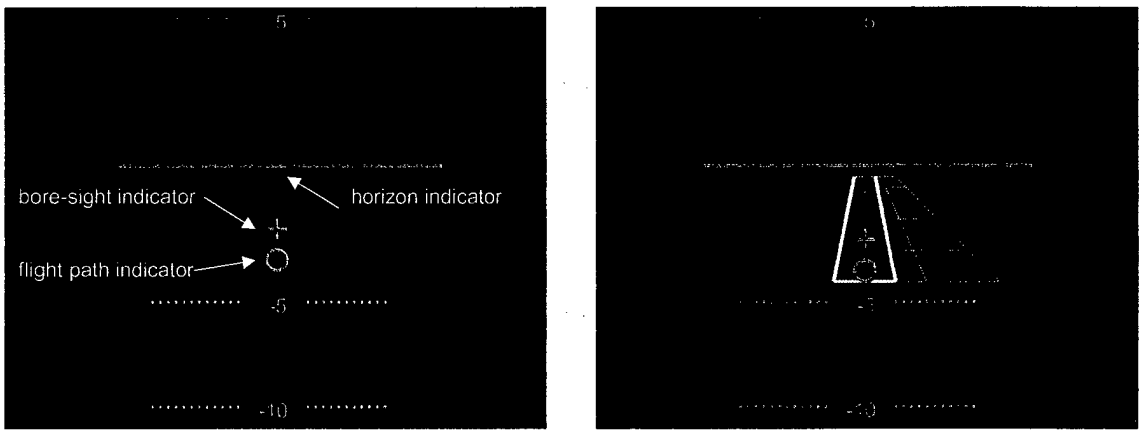

Figure 2. The landing approach task as viewed by the subject

In each flight, the VI was configured to record data for a 96-s period during which the pilot performed the landing task. This period was divided into four 24-s epochs. In trials that included laser exposure, each epoch included one 10-s burst of continuous or discontinuous (depending on the experimental condition) laser light, whose onset time varied randomly within the first 14 s of the epoch. Within each flight, the characteristics of the laser exposure remained uniform across all four bursts. In trials in the baseline condition with no laser exposure, the beam was turned off at the laser, but the VI timing mechanism remained active, so the experimental shutter would emit the same sounds across all conditions.

Control performance was measured using the root-mean-square (RMS) of the instantaneous deviation from an ideal linear flight path, and the standard deviation of the aircraft's heading. These measures were calculated for each flight; for both measures, lower

[8] This distance value is calculated in *xyz* space and thus includes the altitude component.

values indicated better performance. The ideal flight path was defined as a line leading from the first recorded aircraft position to the instructed landing point. An expression was derived for this flight path by translating the *xyz* difference between its end points into a parametric vector equation. A point-line distance formula was used to determine the aircraft's instantaneous flight path error (i.e. its distance from the ideal path) for every sampled frame from the beginning of the flight until the aircraft passed the instructed landing point. The root-mean-square (RMS) of all of the flight path error values was then calculated for each flight. The standard deviation of heading was calculated for each flight using the time history of the aircraft's heading state variable, recorded from the beginning of the flight until the aircraft passed the instructed landing point.

Laser system

The laser was a 532-nm Verdi system (Coherent Optics, Inc., Santa Clara, CA), enclosed by a black safety box. Holes were cut in the side and end of the safety box to allow the exit of the sampling beam and the main glare beam. The safety and experimental shutters were mounted next to the laser exit aperture, downstream of the sampling pellicle inside the safety box. The next component in the beam path was a Fostec optic fiber bundle (diameter .635 cm). Its terminal was positioned to over-fill the bundle slightly with the raw beam. The fiber bundle conducted the beam outside the safety box to a bench mounting, from which its other terminal served as the experimental glare source. The source pointed upward from the bench in front of the subject, perpendicular to the line of sight. Its image was superimposed on the center of the display using a slanted beam splitter, which was mounted in the same manner as the combiner plate of an aircraft HUD, with its upper edge jutting toward the pilot. The beam splitter reflected 40% of the light striking it and transmitted the remainder; this allowed the pilot to look through it to the display while enabling the experimenter to superimpose the glare stimulus. The orientation of the fiber terminal and beam splitter placed the reflected image of the laser source in the center of the XPlane HUD, as viewed from the headrest. In this location, the glare field could obscure the visibility of primary reference symbols on the HUD, including the flight path indicator and portions of the horizon lines.

The total distance from the terminal source to the beam splitter and then to the viewer was 1.32 m. The visual extent of the source was 4.81 milliradians (16.5 arc-min). The measured

divergence of the beam emerging from the terminal was .233 radians. The laser system delivered approximately 118 mW at the terminal source, and a peak irradiance of approximately 60 $\mu W/cm^2$ at the viewing position in all laser exposure conditions. This exposure was approximately 1.85% of the maximum permissible exposure (MPE) defined by the ANSI Z136.1 (2000) standard.

Design: exposure conditions

Each flight was assigned to one of eight exposure conditions, which specified the temporal characteristics of the laser stimulus presented in the flight's four exposure periods. In the first, baseline condition, no added laser source was presented. Six different strobing (discontinuous-exposure) conditions were presented, among which a two-level duty cycle parameter and a three-level pulse repetition frequency parameter were varied factorially. In these strobing conditions, the levels of duty cycle were 10% or 50%, and the levels of pulse repetition frequency were 0.8, 2.4, or 7.2 flashes per second. In the eighth condition, the laser source was illuminated continuously during the exposure periods.

Each experimental session comprised twelve flights. Half of these represented a single presentation of each of the six possible combinations of duty cycle and pulse repetition frequency. Three flights were presented with no exposure, and three flights were presented with continuous exposure.[9] The design, then, comprised a factorial combination of duty cycle and pulse repetition frequency, combined with an additional two conditions in which pulse repetition frequency was not meaningful (because pulse repetition does not occur when there is no exposure, nor when exposure is continuous).

The total of four experimental sessions yielded 48 flights. This sum included 24 flights representing four session repetitions of each possible combination of duty cycle and repetition

[9] The baseline condition (in which the absence of exposure amounted to a 0% duty cycle) and the continuous exposure condition (in which the uninterrupted exposure amounted to a 100% duty cycle) were assigned three repetitions per session to allow the possibility of considering the experimental design as balanced across four levels of duty cycle. It was decided not to analyze the data in this manner, however, because this would require either the omission of pulse repetition frequency from consideration in the design, or alternatively, additional analyses to identify the effect of pulse repetition frequency. The first option was undesirable because pulse repetition frequency is an important factor in the design. The second option was undesirable because performing successive analyses on partially overlapping subsets of a single dataset can be problematic; in particular, such analyses are not necessarily statistically independent.

frequency, 12 flights representing four session repetitions of flights with no laser exposure, and 12 flights representing four session repetitions of flights with continuous laser exposure. The conditions' presentation order was counterbalanced to the extent allowed by the odd number of subjects, so that an equal number of subjects could begin and finish each session with each condition.

Flight path error RMS and standard deviation of aircraft heading were analyzed using a repeated measures analysis. This analysis was implemented in the SPSS™ Linear Mixed Models procedure, to accommodate the asymmetry resulting from the greater number of repetitions in the baseline and continuous exposure conditions. In this analysis, the exposure conditions were represented in a within-subjects "Laser" manipulation with eight levels, and the repetition across four experimental sessions was represented in a within-subjects "Session" manipulation.

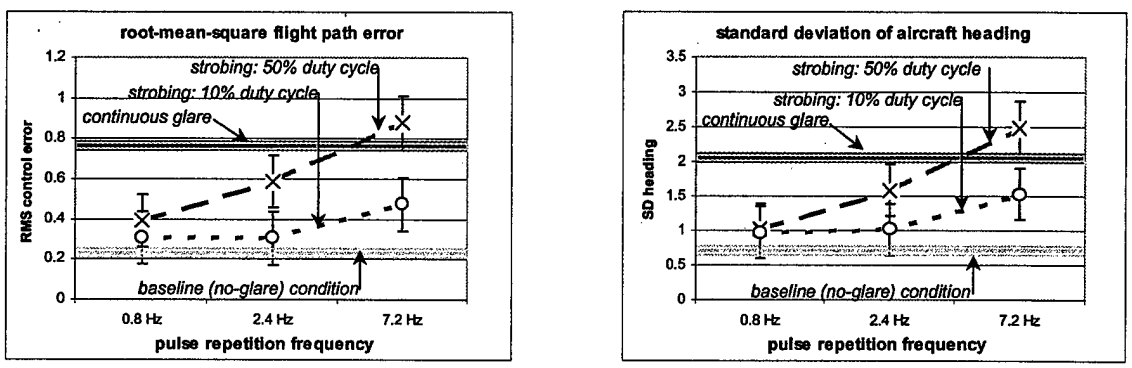

Figure 3. Mean values for RMS flight error (left panel) and SD heading (right panel). Error bars represent standard errors of the mean. Solid gray and green horizontal lines represent the baseline and continuous exposure conditions respectively. Dotted and dashed lines represent strobing conditions with 10% and 50% duty cycles respectively.

RESULTS

RMS flight path error

Results of the 8 x 4 repeated measures analyses of the RMS flight path error and standard deviation (SD) of heading data are shown in Figure 3. In the RMS error analysis, a significant main effect of Laser condition ($F(7, 298)=19.1$, $p<.001$) was identified. The lowest error mean was recorded in the baseline condition. The greatest error mean was recorded in the strobing

condition that combined the 50% duty cycle with the 7.2-Hz pulse repetition frequency. The second-greatest error mean was recorded in the continuous exposure condition, with means from the remaining strobing conditions falling between the continuous-exposure and baseline means.

Pairwise comparisons were performed (alpha=.05) to identify significant differences between RMS error cell means in the various Laser conditions; because measures of human control performance typically exhibit high variance, the relatively liberal Least Significant Difference method was used to preserve sensitivity in this small, asymmetrically configured dataset. Significant RMS differences were identified between the baseline (no glare) condition and the continuous-exposure condition, the 7.2-Hz strobing conditions with both duty-cycle values, and the 2.4-Hz strobing condition with the 50% duty cycle. Notably, the RMS differences separating the baseline condition and the two strobing conditions with the 0.8-Hz pulse repetition frequency, and the difference between baseline and the 2.4-Hz, 10% duty-cycle condition were not identified as significant. The RMS mean in the continuous-exposure condition was significantly greater than those observed in all other conditions save the strobing condition combining the 50% duty cycle with 7.2-Hz repetition, which showed a higher RMS mean. The RMS mean in this 50%-duty-cycle, 7.2-Hz condition was significantly higher than means from all the other strobing conditions, and higher than the baseline mean. RMS means differed between the 2.4-Hz strobing conditions with the two duty cycles.

An effect of Session ($F(3, 298)=2.9$, $p<.05$) on RMS error was identified, with no significant interaction between Glare and Session. Because the Session effect was unexpected, we examined the data and located its origin among data from two subjects who were particularly error-prone on the fourth session.[10]

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[10] Contributing factors for this Session effect were identified. These two subjects were the volunteers with whom we encountered setbacks during data collection, as described above. One subject, who had a slight color defect and exhibited the highest individual mean RMS error scores overall, flew a particularly inconsistent set of landings in the fourth session. This might have resulted from fatigue, because the subject completed the last session after repeating three flights from an earlier session. The second subject was forced to complete his third and fourth flight sessions several weeks after his first two, and while he was given extra practice sessions to regain proficiency, some performance loss was evident in his third and fourth sessions. In order to assess these two subjects' effect on the distribution of the RMS cell means, we repeated the analysis, including only data from the remaining five subjects. The main effect of Laser condition ($F(7, 204)=12.6$, $p<.001$) was again identified. The Session effect was absent ($F(3, 204)=.172$); the RMS mean observed in the last session was the lowest of four. No significant interaction was identified between Glare and Session. The stability of the control performance represented in this abbreviated (N=5) dataset was improved relative to the overall (N=7) dataset, as indicated by lesser overall RMS means (.3925 vs. .494) and standard error values for the per-session means (.109 vs. .12). The distribution of pairwise comparisons was similar to that obtained with the original (N=7) RMS analysis, except that the difference between 10%-duty-

SD heading

The analysis of the standard deviation of heading data identified a significant main effect of Laser condition ($F(7, 298)=18.8$, $p<.001$). The lowest SD error mean was recorded in the baseline condition. The greatest SD error mean was recorded in the strobing condition in which the 50% duty cycle was combined with the 7.2-Hz pulse repetition frequency. The second-greatest SD error mean was recorded in the continuous exposure condition, with means from the remaining strobing conditions falling between the continuous-exposure and baseline means.

Pairwise comparisons were performed (LSD, alpha=.05) to identify significant differences between SD heading cell means in the various Laser conditions. The distribution of pairwise contrasts resembled closely the distribution obtained with the RMS error means. Significant SD heading differences were identified between the baseline (no glare) condition and the continuous-exposure condition, the 7.2-Hz strobing conditions with both duty-cycle values, and the 2.4-Hz strobing condition with the 50% duty cycle. The SD error differences separating the baseline condition and the two strobing conditions with the 0.8-Hz pulse repetition frequency, and the difference between baseline and the 2.4-Hz, 10%-duty-cycle condition, were not identified as significant. The SD error mean in the continuous-exposure condition was significantly greater than those observed in all other conditions except the strobing condition combining the 50% duty cycle with 7.2-Hz repetition, which showed an even higher mean. The SD mean in this 50%-duty-cycle, 7.2-Hz condition was significantly higher than means from all the other conditions. SD error means differed significantly between the 2.4-Hz strobing conditions with the 10% vs. 50% duty cycle, but not between the 0.8-Hz strobing conditions with the two duty cycles. Notably, the SD mean in the 10% strobing condition with 7.2-Hz repetition was significantly greater than the two other 10% strobing conditions with slower pulse repetition.

Neither a main effect of Session on SD heading error nor an interaction between Glare and Session was identified.

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cycle strobing conditions with 0.8-Hz vs. 7.2-Hz pulse frequencies was identified as significant; the difference between 50%-duty-cycle strobing conditions with 2.4-Hz vs. 7.2-Hz pulse frequencies was not identified as significant; and the mean RMS error was not found to be significantly greater in the continuous exposure condition than in the strobing condition combining 50% duty cycle and 2.4-Hz repetition. No adverse physical effects or changes in visual function were identified in either subject's post-experimental eye exam.

DISCUSSION

Continuous vs. strobing laser exposure

Can a strobing laser glare source equal or exceed a continuous source of the same power in its capacity to impede visual flight control? Among strobing sources with a particular wavelength, is there an optimal temporal configuration for disrupting flight control? To the extent that both continuous and strobing laser sources disrupt flight control, does the disruption depend solely on the visibility of the elements in the visual environment (which would imply that the operator can exercise some control, as long as some elements remain above threshold some of the time), or can it also stem from interrupting or interfering with the visual motion signal? In this simulated flight environment and within the pulse repetition frequency domain considered in this experiment, our RMS and SD heading data yield straightforward empirical answers to the first two questions, and begin to answer the third question, which is more complex and far-reaching.

Striking increases in both control error measures demonstrate that the continuous exposure condition impaired visual performance significantly relative to the baseline condition, creating a large glare pattern in the central visual field that obscured visibility of the terrain, runway, and HUD symbols. Since exposures in this condition lasted ten seconds, this disruption represents an example of steady-state glare disability.

A single strobing condition, combining a 50% duty cycle with 7.2-Hz pulse repetition, was identified that rivaled and in some flights exceeded continuous laser exposure in its capacity to disrupt visual control. While the difference in error measures did not equal the large margin observed in the Beer & Gallaway (1999) study, data from this condition indicated that allowing intermittent, 69-ms glimpses of the out-the-window scene and HUD afforded no advantage relative to continuous presentation, and might have aggravated disruption by inserting spatio-temporal discontinuity. Consistent with this, one of the subjects, a Flight Surgeon with hours in civilian aircraft as well as the F-16, remarked first that "I can see what's happening to the plane, but I can't necessarily fix or control it, even though I can see the runway and HUD symbols", next, commented that "I can see the runway but not really motion … it is almost like a 'Giant Hand' situation", and finally, characterized the display as "annoying", this last uttered with a gerund modifier based on a four-lettered root.

This finding, even when considered in conjunction with the lesser visual disruption that

was observed in the other strobing conditions, indicates an affirmative answer to our first empirical question: With this visual task, at this laser wavelength, and with a certain temporal configuration, a strobing laser exposure can rival or exceed a continuous laser exposure of the same power in its capacity to disrupt visual flight control. The answer to our second question follows from the first. Within the domain of duty cycle and pulse repetition frequency values we have considered to date (up to 50% and 8 Hz, respectively), the optimal configuration for disrupting visual vehicle control combines high values for both parameters.

It should be emphasized, however, that apart from this 50%, 7.2-Hz temporal configuration, strobing laser exposure was less disruptive than continuous laser exposure at the same power. All of the other strobing conditions including the 10%, 7.2-Hz condition gave rise to significantly lower error means than the continuous exposure condition, in both measures of control performance, and at the other end of the performance spectrum from the two most disruptive conditions, there were three conditions that were only marginally disruptive, namely the two 0.8-Hz strobing conditions and the 10%, 2.4-Hz condition, which failed to push control error measures significantly above baseline levels.

In particular, disruption of the control task was negligible in the 0.8-Hz conditions, both with a 10% duty cycle, which offered a 1125-ms inter-pulse recovery period following each 125-ms pulse, and with a 50% duty cycle, in which exposure pulses and the inter-pulse intervals both lasted 625 ms. This indicates that an inter-pulse duration of 625 ms offered sufficient time to recover from residual threshold elevation (flashblindness) and reestablish and maintain a stable flight path, while a pulse width of the same 625 ms (during which the pilot's control corrections were presumably impaired) was not enough time for the vehicle platform to slide far from a stable, neutral dynamic state. It is in the comparisons among the strobing conditions whose effects on control error were intermediate to these marginally disruptive conditions on the one hand and the two severely disruptive conditions on the other, that we can begin to infer the multidimensional interaction of laser irradiance (power) and temporal factors, which determines how the strobing laser stimulus will impede flight control.

Interaction between pulse width and inter-flash duration

This interaction is complex for a number of reasons. Even if we consider only the visibility of

the outside scene in the presence of a laser pulse train (as opposed to the availability of a visual motion signal or the ability to execute eye movements), the source power, pulse width, and inter-pulse duration can all affect visual disruption. In the present experiment, the visibility of the HUD symbols and runway during strobing exposure depends on how much light adaptation occurs during each pulse (i.e. how high the pulses boost visual thresholds above the contrast values present in the HUD and terrain), and on how much dark adaptation (visual recovery) occurs between pulses. At the onset of a bright stimulus (be it a uniform adaptation field presented on a laboratory CRT, a light background on a cinema screen, or the glare pattern from a point laser source), light adaptation occurs, and visual thresholds rise over time at a rapid but finite rate. Thresholds typically peak shortly after the onset, and then settle to an elevated state that persists as long as the bright stimulus is illuminated (Adelson, 1982; Barraza & Colombo, 2001; Bichao et al., 1995; Crawford, 1947; Geisler, 1978; Hayhoe et al., 1987; Hood & Finkelstein, 1986). When the bright stimulus is extinguished, dark adaptation occurs, whereby visual sensitivity recovers and thresholds fall over time, typically at a slower rate than that of the initial light adaptation phase (Crawford, 1946; Hayhoe et al., 1987; Hood & Finkelstein, 1986; Miller, 1965). Light and dark adaptation are thought to involve multiple components, including multiplicative and subtractive processes and receptor persistence, but in many stimulus situations, they can be characterized generally as gain-modulation mechanisms, one of which (*viz.*, the light-adaptation or onset-response component) operates with a faster time constant (Hayhoe et al., 1987).

The extent of light adaptation from a light pulse of a given area and wavelength is determined by its energy delivery or its power (intensity, or energy per unit time), depending on temporal characteristics. According to a classical model, a stimulus' visual effect is determined by its energy delivery if the pulse width remains below a certain *critical duration* thought to be in the neighborhood of 100-150 ms, and by its intensity if the pulse width exceeds this duration (Legge, 1978; Smith et al., 2003; Watson, 1986). One corollary of this model, known as Bloch's law, is that for rectangular light pulses shorter than the critical duration, thresholds will show reciprocity between source power and pulse duration (Brindley, 1952; Crawford, 1946). Reciprocity predicts that a 1.0-$\mu W/cm^2$ source viewed for 100 ms will have the same adaptation effect as a 10-$\mu W/cm^2$ source viewed for 10 ms, and (in the present experiment) that a 60-

$\mu W/cm^2$ pulse presented for 14 ms will have a lesser effect than the same 60-$\mu W/cm^2$ pulse presented for 69 ms.

It should be noted that a number of factors qualify and limit the generality of a critical duration principle. First, the principle of reciprocity has been considered in several contexts, including the determination of thresholds and perceived brightness for the stimulus itself, and also the stimulus' capacity to induce light adaptation and delay dark adaptation (i.e. to elevate thresholds for detecting other stimuli) for a significant period. These contexts might not always be functionally equivalent. In addition, it has been reported that under some conditions, the transition from reciprocity to a power-dependent threshold state (in which thresholds and light adaptation are determined by steady-state intensity) is incomplete and comprises merely a change in the slope of the threshold-duration function (Barlow, 1958; Crawford, 1946; Legge, 1978; Watson, 1986).[11]

	Exposure	Inter-Pulse		Exposure	Inter-Pulse
10% 0.8	125	1125	**50% 0.8**	625	625
10% 2.4	41.7	375	**50% 2.4**	208	208
10% 7.2	13.9	125	**50% 7.2**	69	69

Table 1. Pulse width and inter-pulse duration in ms for the six strobing conditions.

Whether or not strict principles of reciprocity and of a critical duration boundary hold throughout the temporal domain, there appears to be sufficient evidence to expect that for short flashes of light, narrowing pulse-width without changing intensity will reduce the ensuing visual effect (Brindley, 1952; Legge, 1978; Watson, 1986). This predicts that a 7.2-Hz pulse train will elevate thresholds (and thereby disrupt performance) more with a 50% duty cycle than a 10% duty cycle. This prediction is consistent with the distribution of performance that was observed in the present experiment. While the same reasoning can be applied to the 2.4-Hz pulse trains,

[11] In addition, Smith et al. (2003), in an assessment of visual effects from laser pulse trains, reported a number of presentation conditions under which reciprocity appeared to hold, but also reported an apparent threshold elevation for 1- and 10-ms pulses presented at 10 Hz. While this apparent enhancement was localized and calls for replication, it suggests an additional configuration in which reciprocity might not apply strictly.

the 50%, 2.4-Hz pulse probably lies outside the reciprocity domain.

Dark adaptation resumes at the beginning of each inter-pulse interval; the visual system begins to recover sensitivity, and the extent of this recovery depends on the time elapsed from the extinction of the source. At a given pulse repetition frequency, this favors the observer in low- as opposed to high-duty-cycle conditions, because narrowing the pulse affords a longer duration for thresholds to subside below the contrast values found in the HUD and scene (Table 1). Among the four exposure conditions assigned 2.4-Hz or 7.2-Hz repetition frequencies, the 10%, 2.4-Hz condition offers the longest inter-pulse recovery time, and the 50%, 7.2-Hz condition, the shortest. These two conditions induced, respectively, the least and the greatest disruption effect on the control error measures; indeed, since the difference in the conditions' pulse width was relatively small, it seems likely that their considerable difference in control performance resulted from the disparity in inter-pulse interval.

It is also meaningful to compare the 50%, 2.4-Hz condition and the 7.2-Hz, 10% condition, which were roughly equivalent in their effects on control error, but appear to have achieved this disruption via different mechanisms. In the 50%, 2.4-Hz condition, the 208-ms pulse width probably lies outside the reciprocity domain; it is reasonable to propose that each light pulse at its extinction yielded thresholds lower than the peak thresholds immediately following onset (Crawford, 1947), but higher than thresholds resulting from continuous exposure (Hood & Finkelstein, 1986). This condition gives up some of its capacity to impede visibility by affording 208 ms of recovery time in the inter-pulse interval. Each light pulse in the 10%, 7.2-Hz condition, by comparison, affords a shorter 125 ms of recovery time, but because of its shorter, 13.9-ms pulse width, acts as the photic equivalent of a small-caliber round, incapable of raising thresholds as far as the higher-duty-cycle pulses in either the 2.4-Hz or the 7.2-Hz repetition frequencies.

When we consider these findings in conjunction with earlier studies (Beer & Gallaway, 1999; Stamper et al., 1997b), the titration of pulse width and inter-pulse interval can be observed across a greater temporal range. Considered in sum, this existing body of findings is varied but not inconsistent. Stamper et al. considered two discontinuous exposure configurations, including 20-Hz trains of 280-μsec (.28-ms) laser pulses and 30-Hz trains of 245-μsec (.245-ms) pulses, and observed that these configurations impeded the visual control task less than continuous

exposure. If the account proposed above is correct, these shorter pulse widths, which translate to very low duty cycles of 0.6% and 0.7% respectively, reduced the pulses' capacity to elevate thresholds, even though their peak irradiance exceeded the continuous-exposure irradiance.

The discontinuous exposures in the Beer & Gallaway (1999) study, which were observed to impede the visual control task more than continuous exposure, presented 650-nm laser pulse trains with a 50% duty cycle and an 8-Hz repetition frequency. In this configuration, whose temporal dimensions resembled those of the 50%, 7.2-Hz configuration in the present experiment, peak irradiance was twice as great as in the continuous condition; time-averaged power was the same for both conditions. Beer and Gallaway (1999) determined that the time-averaged power did not predict the extent of visual disruption in this time domain: Strobing exposures impeded control performance significantly more, by an approximately two-to-one margin, prompting the comparison between irradiance-matched strobing and continuous sources in the present experiment. This comparison confirmed the effectiveness of a strobing stimulus with these temporal characteristics, because the 50%, 7.2-Hz condition induced at least as much disruption as the continuous condition, from a pulse train that delivered half the time-averaged power.

These findings indicate that if inter-pulse visibility comprises the main mechanism of visual disruption from strobing laser exposure (and there might be others; see below), this disruption is achieved by delivering enough photons during the pulse to elevate thresholds above contrast values found in the scene, and then using a short inter-pulse interval to keep thresholds from subsiding and remaining below scene contrast values. Failing to do this will offer glimpses of the scene, which are necessary (though perhaps not sufficient; again, see below) for the operator to perform the control task. While it remains possible that time-averaged power will predict the extent of visual disruption if the light pulses are short and the pulse repetition frequency approaches the flicker fusion threshold, a more general characterization should probably recognize peak power, pulse-width, and inter-pulse duration.[12] The importance of peak power in elevating thresholds is obvious. The importance of pulse-width is indicated by the weak effect of Stamper et al.'s (1997b) repetitive-pulse stimuli. The importance of inter-pulse

[12] Of course, manipulating wavelength will also play an important role in determining the effects from strobing laser exposure, but we are considering temporal effects here.

duration is indicated by the weak effect of all repetitive-pulse configurations other than the 50%, 7.2-Hz condition in the present experiment.

How meaningful is the margin between the 50%, 7.2-Hz and the continuous condition?

It is noteworthy that the RMS error values measured in the 50%, 7.2-Hz condition were not significantly different from those in the continuous exposure condition, and that a *post-hoc* comparison identified the SD heading errors measured in the 50%, 7.2-Hz condition as greater than those in the continuous exposure condition. These findings support the claim that visual disruption from the 50%, 7.2-Hz exposures was greater than or equal to that from the continuous exposures. This answers a question posed in the introduction, and indicates that this strobing configuration was privileged in its capacity to disrupt performance in this flight control task.

This does not, however, demonstrate that disruption from this strobing configuration will always exceed the disruption from continuous exposure. The LSD *post-hoc* comparison, which identified greater SD heading error in the 50%, 7.2-Hz condition than in the continuous condition, is liberal in that its likelihood of allowing a Type I error (*viz.*, false rejection of the null hypothesis) is relatively high. In addition, the control performance measures were quite variable between and within conditions, and in certain flights in the 50%, 7.2-Hz condition, pilots registered lesser error values than in certain flights in the continuous condition. These findings should be replicated before we can conclude that we have identified a strobing configuration that always disrupts vision more than continuous exposure.

Visibility vs. motion

In the introduction, it was proposed that exposure to discontinuous illumination, in addition to impeding visibility of the HUD and out-the-window scene, might also interfere with the pilot's ability to process motion and make anticipatory responses to changes in aircraft state. This experiment has yielded some evidence consistent with this distinction between stimulus visibility and motion perception. As described above, one pilot commented during the flashing exposures in the 50%, 7.2-Hz condition that he could see the HUD symbols and runway, but not necessarily respond to them. This suggests that scene visibility represents only a necessary, not a sufficient condition for flight control: While intermittent glimpses of the HUD and out-the-window scene

were above-threshold some of the time in this condition, visual disruption still rivaled that from continuous exposure (during which no subject reported being able to see through the glare field.)

Barraza and Colombo (2001) compared the effects of transient and steady glare sources on the lower threshold of motion detected in grating displays, and reported that the transient source had a greater effect. The motion thresholds were observed to follow a time history resembling Crawford's (1947) characteristic brightness threshold function, peaking shortly after flash onset and then decreasing progressively to the value obtained in steady glare conditions. Barraza and Colombo attributed this to a rapid gain adjustment in retinal detectors with transient response properties; interestingly, this account invokes the same mechanism to explain an induced deficit in motion perception, as is proposed above to describe the impaired visibility of scene information between repeating laser pulses.

In addition to changing motion thresholds and response times, adding discontinuity to the display can change the perceptual characteristics of a moving pattern. In the flash-lag phenomenon, for example, a flashing target presented in spatial alignment with a continuously moving target appears to lag the continuous target's position (Nijhawan, 1994). This effect has been explained as a result of a lack of perceptual acceleration, whereby the visual representation of a continuous stimulus is facilitated by its previous appearance in an immediately adjacent location (Bachmann & Poder, 2001); it could impede performance in control tasks involving stimuli in which the intermittent masking of a pulsing laser source adds discontinuity.

Discontinuous illumination can also alter a moving pattern's perceived continuity. Under the principle of size constancy, observers perceive that the size of an approaching object remains the same in spite of its expanding retinal projection (a percept that is generally valid in the real world). Size constancy deteriorates in the presence of stroboscopic illumination, particularly at strobing frequencies of 8 Hz and when the stimulus extends into the peripheral visual field (Rogowitz, 1984).

These findings suggest interference mechanisms beyond residual flashblindness that might underlie the disruption of visual control that we observed under high-duty-cycle, high-repetition-frequency conditions. They demonstrate that adding pauses, excessive inter-frame displacements, or stroboscopic illumination to a visual display can interrupt the perceived continuity of moving objects in that display, and impede perception of those objects' motion. In

a cockpit environment, such interference could impair flight control without wholly obscuring the visibility of the instruments or external scene.

Other factors: Planned eye movements in continuous vs. strobing exposure conditions

During flight trials, the experimenter, who was seated next to the optical table at the second computer station, could watch the laser exposures illuminate the subject's face. Two subjects were observed trying to game the task occasionally, by fixating locations to the side or above the central part of the display. While the subjects never adopted this as a reliable strategy in all flights (presumably because they discovered that it did not restore the information from the central HUD symbols and runway), an interesting characteristic emerged: These attempts to fixate peripheral locations were observed only during continuous, not strobing exposure conditions. This represents only a qualitative observation, because the experiment did not include eye position recording and the pilots were not monitored in every flight, but it suggests that strobing exposure did not favor the execution of planned eye movements. One way in which discontinuous illumination might impede eye movements is via a greater transient glare effect (i.e. longer-lasting threshold elevation from transient vs. continuous glare sources) observed in the visual periphery (Bichao et al., 1995); since planned eye movements must have a suprathreshold peripheral destination, this differential increase would tend to impair the initiation and control of planned eye movements. In addition, increasing discontinuity in an apparent motion display has been reported to produce smooth-pursuit deficits in monkeys (Churchland & Lisberger, 2000), which suggests that strobing laser exposure could impair the initiation and control of pursuit eye movements as well as saccades. This possibility motivates future investigation, in which our visual flight control paradigm and laser bench apparatus can be combined with an eye position recorder to determine whether strobing exposure impairs voluntary eye movements.

CONCLUSION

A significant portion of this report has been dedicated to evaluating the significant disruption of visual flight control that is caused by a laser glare source operating in a strobing configuration with a 50% duty cycle and a 7.2-Hz repetition frequency, and comparing it to the disruption

caused by continuous laser exposure. This should not distract us from the fact that in almost all the other configurations we and other investigators have considered, strobing exposure has proven significantly less disruptive than continuous exposure.

Two adaptation processes operate during strobing exposure and affect the inter-pulse visibility of the instruments and scene. The first is light adaptation during each light pulse, which is determined by the effective "weight" of the photic stimulus and increases with peak power and (for short flashes) pulse width. The second is dark adaptation, which begins at the end of each pulse and increases with inter-pulse interval. Both processes afford the pilot an advantage when the duty cycle of a strobing exposure is reduced; the lesser pulse width reduces threshold elevation, and the greater inter-pulse interval increases recovery. Findings from the study are, furthermore, consistent with the operation of other mechanisms, including motion interference and impairment of eye movements, that might contribute to strobing lasers' disruptive capacity.

In a real-world engagement in which a shooter were to attempt to acquire and track an aircraft with a strobing laser, multiple factors would operate to attenuate the beam and reduce the time on target. This would reduce the effective duty cycle and increase post-exposure recovery times. For this reason, a stringent set of conditions must be met before a strobing laser could begin to disrupt visual flight control significantly, let alone rival the disruption from continuous exposure. Further investigation is warranted; objectives should be to fill in more gaps in the range of temporal parameters that have been explored (including pulse repetition frequencies greater than 7.2 Hz, but below the critical flicker fusion threshold), and to evaluate psychophysically the effects of strobing exposure on visual motion processing and eye movements.

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