Journal of Biomedical Optics 10(3), 034003 (May/June 2005)

Comparison of violet versus red laser exposures on visual search performance in humans

Fred H. Previc
Leon N. McLin
Brenda J. Novar
William Kosnik
Northrop Grumman Information Technology
4241 Woodcock Drive Suite B-100
San Antonio, Texas 78228

Abstract. Previous research suggests that the visual impairment of a violet laser is not highly localized on the retina, because the lens absorbs most short-wavelength visible light and partly retransmits it as a diffuse fluorescence at ~500 nm. The present study investigated whether a 405 nm violet diode laser more greatly impairs visual search performance in humans than does a 670 nm red diode laser, depending on target eccentricity. Participants had to locate a square among 15 diamonds spread throughout a visual search display while being exposed to a violet or red laser beam that was either continuous or flickering and presented either on-axis or 33° off-axis. Whereas the continuous on-axis violet and red lasers had comparable effects on search performance when the target was located near the center of the beam, the violet laser disrupted processing of eccentric targets more than did the red laser. The search decrements were reduced for both lasers when the beams were flickered or presented off-axis. Both the bluish appearance and greater spatial spread of effect of the violet laser suggest that the unique impairment caused by a violet laser beam derives from its induced lens fluorescence. [DOI: 10.1117/1.1925207]

Keywords: ultraviolet; visual search; laser; lens fluorescence.

Paper 04111RR received Jun. 25, 2004; revised manuscript received Jan. 8, 2005; accepted for publication Jan. 11, 2005; published online May 26, 2005.

1 Introduction

Eye-safe diode lasers are used in a variety of applications in government and industry, including as laser ‘‘dazzlers’’ in police and military applications. The only laser dazzlers that have actually have been deployed or are currently commercially available use diode sources in the red and green range.[1] One disadvantage of a collimated longer-wavelength laser dazzler is that its beam is focused to a point source on the retina and the extent of the glare field around the laser is limited to a few degrees for eyesafe exposures.[2] By contrast, there is evidence that more recently developed violet diode lasers centered around 405 nm create a more diffuse disabling glare than do longer-wavelength lasers.[3]

Violet (400–425 nm) and near-ultraviolet (UV) light (350–400 nm) are largely absorbed and scattered by the lens, which excites fluorophores in a phenomenon known as lens fluorescence (LF). For a relatively narrow excitation beam, longer wavelengths from the more spatially diffuse LF are transmitted to the retina along with the direct transmission of short-wavelength laser light. For violet and near-UV, the excitation peak of the LF is predominantly in the blue-green range (480–520 nm),[3] which is much closer to the peak of human spectral sensitivity than the UV or violet excitation beam. Previous data indicate that the veiling glare created by LF can disrupt visual function, especially in the elderly population where the magnitude of LF has been estimated at 12% of the background luminance[4] due to an increase in lens absorption and scatter. Zuclich et al.[3] reported a ~25% decrement in the amplitude of the visual evoked potential in monkeys to high-contrast stimuli at 60 cd/m^2 when a 413 nm laser stimulated the lens at 45° off-axis; however, the estimated LF for a 60 μW exposure was less than 1 cd/m^2.[3] Elliott et al.,[5] using a broadband incoherent UV source with a peak at 365 nm, showed a visual acuity decrement for targets of high luminance (100 cd/m^2) but low contrast (11%) in middle-aged and elderly persons. In a more recent study involving isolated human lenses,[6] the off-axis LF luminance was estimated at ~30 cd/m^2 for a 1 mW laser exposure at wavelengths from 360 to 450 nm, with an increasing ratio of LF relative to the direct beam luminance in the elderly lenses. Assuming a linear LF effect,[3] this would translate to ~1.8 cd/m^2 for a 60 μW source, approximately double the LF estimate for the monkey.[3]

The major purpose of the present study was to investigate how a 405 nm violet diode-laser exposure compares, in terms of functional visual decrements, to a typical red laser dazzler output (670 nm) of the same irradiance. The effects of the two different lasers were assessed by means of a visual search task similar to that used by Reddix et al. in studying the effects of a 532 nm exposure.[7] Visual search tasks in which participants are free to make eye movements are not as tightly controlled as typical psychophysical studies. However, search tasks offer

---

Address all correspondence to Fred H. Previc, Information Technology, Northrop Grumman, 4241 Woodcock Dr. Ste B100, San Antonio, TX 78228. Tel: 210-487-2919; Fax: 210-734-0990; E-mail: fred.previc@ngc.com

several advantages in assessing laser effects on vision because (1) they are more analogous to the natural scanning behavior of humans, (2) they generally require less time (usually one second or less) to produce a perceptual decision, which limits the laser exposure, (3) the latency and accuracy of the first saccade[8] and whether it is even made at all[9] are highly sensitive to the visibility/perceptibility of the stimulus and are predictive of overall search times,[9] and (4) search tasks are additionally sensitive to higher-order effects such as attentional capture/distraction.[10] To measure the lasers' spatial spread-of-effect, the beams were presented either to the center of the visual field (on-axis) or 33° to the right of center (off-axis). [The terms "on-axis" and "off-axis" refer to the position of the laser with regard to the visual search field. The first saccadic movement (typically around 250–300 ms in visual search studies) began after the laser and search targets appeared. After the initial saccade, the position of the laser on the retina could not be specified.] Each laser beam was also presented continuously and in a 5 Hz flicker mode, because of evidence that certain types of visual functions may be more disrupted when a laser beam is chopped.[11]

For the on-axis exposures, it was predicted that the red laser would be at least as effective as the violet laser in reducing the visibility of search targets near the center of the display (up to 7° off-axis), because of its highly focused beam. However, the violet laser and its LF were predicted to be relatively more disruptive for targets located in the outer portion of the field (8°–15° off-axis). It was also predicted that the violet laser, with its spatially diffuse LF effect, would be more disruptive than the red laser for the off-axis exposure, in which the search targets were displaced by 18°–48° from the laser-beam axis (33°±15° to each side of the monitor).

2 Methods

2.1 *Participants*

A total of eight participants took part in this study, all of whom were civilian or military personnel at the Optical Radiation Branch at Brooks City-Base, Texas. All participants signed an informed consent document approved by the Brooks City-Base Institutional Review Board, and all passed an ophthalmological screening that required a normal fundus, normal Amsler grid, normal red-green and blue-yellow color vision, and an acuity requirement of 20/25 in the right eye. The age of the participants ranged from 23–53 yr, with a mean age of 37.25 yr.

2.2 *Apparatus*

2.2.1 *Visual display*

The search display contained a single square target and a total of 15 distractor diamonds. The square target appeared randomly within the 16 blocks of a 4×4 grid (four inner positions and 12 outer ones). The square had the same dimensions as the diamonds but was rotated 45°. The diagonals of the square and the diamond subtended 0.94° of arc. The high-contrast, white search targets had an average luminance of 0.45 cd/m^2 against the dark background of the monitor. The total size of the search field was 25° vertically×31° horizontally, while the outer boundary of the inner four positions was 12°×15°. The presentation of the stimuli, search interval, and other parameters of the search task were controlled by means of customized software programmed on a Gateway computer (model ATXSTF FEDPro M1000).

Participants viewed the visual search stimuli while restrained in an ophthalmic brace (including chin and forehead rests), head straps, and a bite-bar made of dental-impression compound (Kerr Mfg. Co., Romulus, MI). They viewed the video monitor (Gateway model VX700) at a distance of 58.4 cm through a beam splitter located directly in front of the right eye. The room was darkened, and the left eye was occluded.

2.2.2 *Laser exposures*

Both the violet (405 nm) and red (670 nm) diode lasers were PPMT models supplied by Power Technology, Inc. Each laser was rated as having a maximum output of 4 mW at its exit aperture, although the actual laser power at the eye was 15 μW as measured by a Newport Corp. 883-SL detector and power meter (model 1815-C) tuned to each laser wavelength. For 32 trials at 1.5 s (the number of trials in each laser condition in a given session times the maximum duration of the search interval during which the laser beam was presented), the 15 μW continuous-wave (cw) exposure represented 19% of the maximum permissible exposure (MPE) limit for humans at 405 nm and 4% at 670 nm. Because the *American National Standard for Safe Use of Lasers*[12] assumes a fully dilated, 7 mm pupil (pupil area of 0.38 cm^2) in calculating the MPE, the 15 μW continuous exposure would correspond to an ocular irradiance of 40 μW/cm^2. For a block of thirty-two 1.5 s trials in the 405 nm range, 40 μW/cm^2 represented 19% of the MPE value of 208 μW/cm^2 for a cumulative exposure of 48 s (10 mJ/cm^2). The same exposure over 48 s represented only 4% of the MPE for 670 nm, because the MPE does not reflect a cumulative effect for that wavelength.

The outputs of the two lasers were combined by a beam splitter, sent through a 2 mm aperture and then passed through a Uniblitz electronic shutter (model T132), which limited their presentation to only the search-field interval. The two beams then passed through a variable-transmission neutral-density filter that was used to adjust the final output power at the eye. By means of a second beam splitter, one beam was sent directly to the fovea in line with the center of the search display, while the other beam was sent to a mirror located to the right of the video monitor that reflected the beam into the eye from 33° off-axis (see laboratory illustration in Fig. 1). Measurement of the on-axis and off-axis 405 and 670 nm beam profiles by means of a Cohu solid-state camera (model 4812–7000) showed them to be approximately Gaussian, with an average beam diameter of 1.85 mm (range of 1.13–2.33 mm) that was well within the minimum diameter of the human pupil under low-to-moderate illumination.[13]

The laser beam was presented either in a cw mode or was flickered at 5 Hz by means of a Systron-Donner pulse generator (model 100A). In the flicker mode, the peak laser power remained at 15 μW but the beam was chopped with a 50% duty cycle (100 ms on; 100 ms off), so that average power of the beam was half that of the cw exposure.

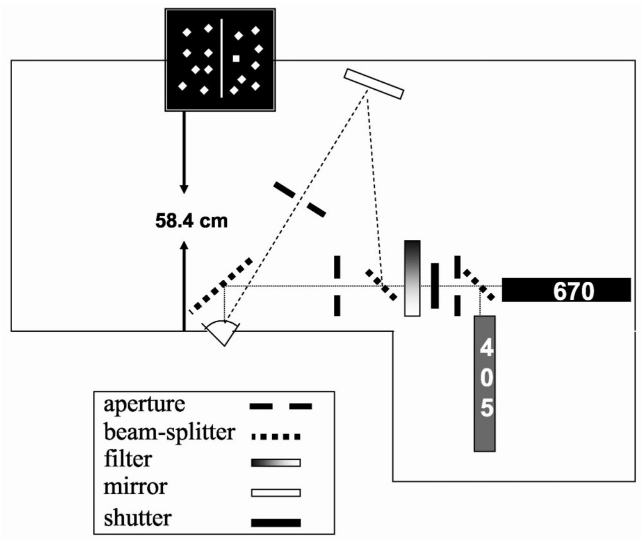

Fig. 1 An illustration of the laboratory setup for the experiment.

2.2.3 *Procedures*

Prior to the first trial of each laser condition, the beam power was adjusted to the desired power level at the eye. The beam was then attenuated to less than 1 μW by means of a 1.5 log optical density filter, so that participants could align their right eye with the beam. In aligning the beam, participants were instructed to maximize the beam's glare image by moving their heads slightly in all directions while holding tightly to the bite bar. In independent observations, the LF appeared to be approximately centered on the eye when the participant reported being aligned using this procedure.

The search task that participants performed was a two-alternative forced-choice discrimination task. They had to report, using the left or right key of a computer mouse controlled by their left hand, whether the square target appeared to the left or right of the search field. Each trial in the self-initiated block of 16 trials began with a 500 ms presentation of the square target superimposed on a fixation cross. Participants were directed to fixate the center of the cross until the search field was presented, after which they were allowed to move their eyes to locate the target. The search field was then presented for as long as it took to find the target and respond with the mouse, up to a maximum of 1.5 s. If the participant responded with the opposite key or did not respond within the 1.5 s interval, the response was categorized as an error. In the laser conditions, either the violet or red laser was on for the entire search-field interval, whereas the search field was viewed unobstructed in the ''no-laser'' condition. The inter-trial interval was 1 s. In each trial block, the target appeared in each of the 16 locations in the search field using a ''sampling-without-replacement'' procedure. A second block of 16 trials was run immediately thereafter for each laser condition, so that a total of 32 trials were run per laser condition per session.

Participants received a total of eight laser conditions in an orthogonal combination of three factors (405 nm versus 670 nm; on-axis versus off-axis; and cw versus flicker mode). They received four laser conditions (32 trials each) in one session and the other four in a second session. A Latin-square procedure was used to counterbalance the order of the eight conditions across participants. The order of presentation of the eight laser conditions was reversed for each participant during a second replication conducted during the third and fourth sessions. In addition to the laser conditions, a block of 16 no-laser trials was run at the beginning or end of each of the four sessions, in an alternating procedure across sessions and participants. (The total of 128 trials in the no-laser condition was the same as for each of the laser conditions.) Each laser session was run with 72 h separation, to avoid cumulative laser exposure effects.

In addition to the experimental sessions, participants received three training sessions. During the last training session, a single block of trials was presented with the full laser exposures to prepare participants for what would be experienced during the experiment.

3 Results

After averaging across the two replications, the data were analyzed in terms of the speed in finding the target—i.e., mean search time, in milliseconds (ms)—and the accuracy of the search (% errors, which included all trials in which an incorrect response was made or no response was made within the 1.5 s interval). To measure the spatial ''spread-of-effect'' for the two different lasers, the on-axis and off-axis conditions were analyzed separately and with different groupings for the location variable. In the on-axis conditions, the laser wavelength and flicker mode (cw or flicker) effects were analyzed for the inner versus outer eccentricities. In the off-axis condition, in which the laser exposure always was presented to the right of the search field, the same analyses were carried out when the locations were divided into the right versus left portions of the search field. All analyses-of-variance (ANOVAs) were performed using *SPSS* (Chicago, IL).

3.1 *On-Axis Data*

The speed and accuracy data for the on-axis condition are shown in the top and bottom panels, respectively, of Fig. 2. The data for the violet versus red laser exposure (light versus dark gray bars), cw versus 5 Hz mode (solid versus stippled bars), and inner versus outer locations are depicted, along with the respective means for these measures in the no-laser condition (depicted by black lines). Figure 2 reveals that the cw exposures disrupted visual search more than did the flickering exposures and that the 405 and 670 nm exposures had comparable effects on the inner targets whereas the violet exposure was much more effective for the outer eccentricities. The mean search time in finding the outer target was $\sim$120 ms longer when the violet cw beam was presented. Similarly, the percentage of errors for the outer targets was nearly doubled (21.9% versus 12% for the 405 and 670 nm cw laser exposures, respectively).

Because the no-laser means for the inner and outer targets were substantially different, each participant's no-laser mean at each eccentricity was substracted from the mean in each laser conditions prior to performing the repeated-measures ANOVA. The ANOVA for on-axis search times revealed significant main effects of flicker mode ($F[1,7]=6.73$, $p<0.05$) and location ($F[1,7]=7.26$, $p<0.05$), as well as a significant wavelength×location interaction effect ($F[1,7]$

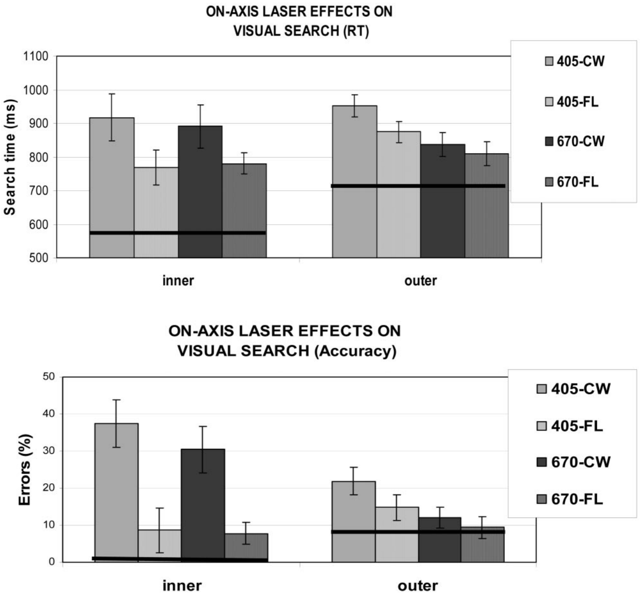

Fig. 2 The effects of 405 nm versus 670 nm cw (solid bars) and flickering (stippled bars) on-axis exposures on search times (top panel) and errors (bottom panel) for locating inner and outer targets. No-laser means are depicted by black lines.

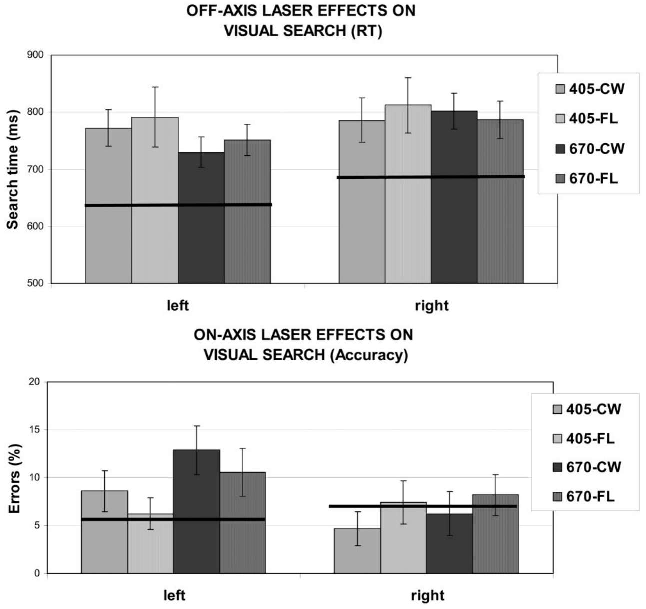

Fig. 3 The effects of 405 nm versus 670 nm cw (solid bars) and flickering (stippled bars) off-axis exposures on search times (top panel) and errors (bottom panel) for locating left-sided and right-sided targets. No-laser means are depicted by black lines.

$=13.99$, $p<0.01$). Posthoc simple main-effect analyses revealed that the wavelength×location interaction was caused by the greater effect of the 405 nm versus 670 nm laser on search times for the outer eccentricities ($F[1,7]=3.27$, $p=0.09$) than for the inner eccentricities ($F[1,7]=0.02$, $p=0.89$). The repeated-measures ANOVA for the on-axis error data yielded a mostly similar set of results, including significant main effects of flicker mode ($F[1,7]=19.07$, $p<0.01$) and location ($F[1,7]=16.14$, $p<0.01$), as well as a flicker mode×location ($F[1,7]=46.77$, $p<0.001$) interaction effect. Post-hoc simple main effects tests revealed that the flicker mode×location interaction was caused by the greater effect of the cw versus flickering exposure on the inner eccentricities ($F[1,7]=45.45$, $p<0.001$) than on the outer eccentricities ($F[1,7]=1.59$, $p=0.23$). Despite the greater number of errors for the outer targets when the violet as compared to red laser was presented, the wavelength ×location interaction proved nonsignificant. Thus, there was no speed-accuracy tradeoff that could have accounted for the significant wavelength×location interaction in the search time data.

3.2 *Off-Axis Data*

The speed and accuracy data for the off-axis condition are shown in the top and bottom panels, respectively, of Fig. 3. The increase in search times across all locations and laser conditions relative to the no-laser mean varied only slightly, from 85 to 145 ms. There were slightly more errors to targets on the left side of the display during the 670 nm versus 405 nm laser exposure, but this was offset by a slight decrease in search times on the left side during the red exposure. Because the no-laser mean search time for the left-sided targets was substantially less than the mean for the right-sided targets (perhaps because only the left hand was used in all conditions), no-laser means were subtracted from the laser means in the same hemifield prior to performing the off-axis ANOVAs for the search time and error data. In contrast to the on-axis ANOVAs, however, neither of the off-axis ANOVAs revealed even a single marginally significant main or interaction effect.

4 Discussion

The results of the present study clearly point to the fact that a 405 nm laser exposure produces a more spatially diffuse glare than does a 670 nm exposure, presumably because of the LF induced by the short-wavelength exposure. For on-axis exposures, the greater effect of both cw and 5-Hz violet exposures on search times and errors was present only for the outer eccentricities (8°–15° off-axis). For off-axis exposures, the 405 and 670 nm beams both produced relatively weak effects that did not differ from one another, indicating that the spread of the LF was insufficient beyond 18° to disrupt visual search using the task and stimulus conditions of the present study.

Based only on the direct transmittance of the excitation beam, the comparable effectiveness of the on-axis violet laser exposures for the inner targets was somewhat surprising. The photopic sensitivity of the human visual system is about 30 times greater for 670 nm light than for 405 nm light,[14] so the red laser should have produced a greater impairment of visual search performance in the absence of LF. It is possible that the red laser beam did produce a greater impairment within a degree or two of the fovea but that this effect was not reflected in the overall effects on the inner search targets, whose average eccentricity was 4°. Also, it is possible that LF contributed to increases in search time and error rate even for the inner targets.

Despite the greater violet versus red laser effects on the outer targets, the violet laser effects on search times and errors, relative to the no-laser condition, were nevertheless substantially greater for the inner than outer targets. The falloff in the effectiveness of the 405 nm laser is consistent with recently obtained isolated-lens data in humans, which were used to estimated the combined veiling luminance of a 400 nm exciting beam and its fluorescence at the posterior surface of the lens.[6] For lenses in the 36–45 age range—which included the age of the average participant in the present study—the estimated glare luminance at 405 nm ranged from slightly greater than 100 cd/m^2 for a 1 mW beam at 2° off-axis to ~30 cd/m^2 at 14° off-axis (slightly beyond the average eccentricity of the outer targets). Assuming linearity of the LF gain,[3] the luminance of the veiling glare produced by the on-axis 405 nm, 15 μW exposure used in the present study would be expected to fall from ~1.5 to ~0.45 cd/m^2 from the center to the periphery of our display, thereby reducing the contrast of the inner and outer targets in our display to 23% and 50%, respectively. In contrast to the isolated-lens study,[6] however, the lack of a significantly greater violet laser effect in the off-axis exposure conditions indicates that LF does fall off considerably beyond 10°–15° and is definitely not homogeneous across the visual field.

Violet and red laser exposures differ in other ways besides LF, but these other differences are less likely to be the source of the differences in search performance for the outer targets. Relative to medium- and long-wavelength light, violet light requires less lens accommodation, given its refractive error of +1.5 diopters.[15] However, such a defocus could not have spread our point-source laser image as far as 5°–10° off axis. It is also possible that the on-axis violet laser may have been more distracting and thereby limited search performance more at the outer eccentricities. However, there is no evidence that violet light is more attention capturing than red light, particularly since the red light was radiometrically equal but photopically brighter. If anything, red light has generally been found to be more associated with danger.[16]

The effectiveness of both the 405 and 670 nm beams was greater when presented as a cw as compared to flickering exposure. Whether cw or chopped laser exposures are more effective has been shown to depend on the type of task, flicker frequency, and other parameters.[11] In this study, the largest differences between the cw and 5 Hz laser exposures occurred in the on-axis conditions, both for search times and errors. Thus, the cw exposure was relatively most effective in those conditions where the laser glare was greatest and where the chopping of the beam allowed for a reduced average power and increased interpulse visibility to occur.

In summary, the results of this study demonstrate a specific advantage of the 405 nm laser exposure in disrupting visual performance at moderate eccentricities beyond those covered by the glare from the direct beam but within the larger LF glare field. For a more intense beam, the shape of the LF glare field would presumably remain the same but the glare would be more potent at all eccentricities[3] and effectively extend further off-axis for a given target. However, the glare field at 405 nm—while broader than for 670 nm and other visible longer-wavelength laser beams—is not homogeneous. The results of Zuclich et al.[6] suggest that, for excitation wavelengths below 390 nm, LF may approach a more homogeneous spread because the transmission of the main beam is only ~1%.[17] Thus, future research should also be directed at the consequences of LF produced by near-UV lasers.

Acknowledgments

The authors thank Dr. Jim Dykes for his statistical support and Javier Trevino, David Kee, Gary Noojin, and Dan Seaman for their technical support in procuring equipment, programming the search tasks, and helping set up the laboratory. This research was supported by funding from the Department of Defense Joint NonLethal Weapons Directorate (Quantico, VA).

References

1. R. J. Dennis, J. T. Harrison, W. E. Mitchell, R. J. Thomas, and S. R. Cora, *Visual Effects Assessment of the Dissuader Laser Illuminator (AFRL-HE-BE-TR-1999-0179)*, United States Air Force Research Laboratory, Brooks AFB, TX (1999).
2. J. K. Ijspeert, T. J. van den Berg, and H. Spekreijse, ‘‘An improved mathematical description of the foveal visual point spread function with parameters for age, pupil size and pigmentation,’’ *Vision Res.* **33**, 15–20 (1993).
3. J. A. Zuclich, R. D. Glickman, and A. R. Menendez, ‘‘*In situ* measurements of lens fluorescence and its interference with visual function,’’ *Invest. Ophthalmol. Visual Sci.* **33**, 410–415 (1992).
4. R. A. Weale, ‘‘Human lenticular fluorescence and transmissivity, and their effects on vision,’’ *Exp. Eye Res.* **41**, 457–473 (1985).
5. D. B. Elliott, K. C. Yang, K. Dumbleton, and A. P. Cullen, ‘‘Ultraviolet-induced lenticular fluorescence: intraocular straylight affecting visual function,’’ *Vision Res.* **33**, 1827–1833 (1993).
6. J. A. Zuclich, F. H. Previc, B. J. Novar, and P. Edsall, ‘‘Near-UV/blue light-induced fluorescence in the human lens: potential interference with visual function,’’ *J. Biomed. Opt.* (in press).
7. M. D. Reddix, T. L. DeVietti, J. C. Knepton, and J. A. D'Andrea, *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 (1990).
8. B. R. Beutter, M. P. Eckstein, and L. S. Stoen, ‘‘Saccadic and perceptual performance in visual search tasks. I. Contrast detection and discrimination,’’ *J. Opt. Soc. Am. A* **20**, 1341–1355 (2003).
9. F. H. Previc, ‘‘Attentional and oculomotor influences on visual field anisotropies in visual search performance,’’ *Visual Cognition* **3**, 277–301 (1996).
10. D. E. Irwin, A. M. Colcombe, A. F. Kramer, and S. Hahn, ‘‘Attentional and oculomotor capture by onset, luminance and color singletons,’’ *Vision Res.* **40**, 1443–1458 (2000).
11. J. M. A. Beer, *Disruption of Visual Flight Control in a Synthetic Cockpit, Resulting from Continuous vs. Discontinuous Laser Glare (NHRC 2004-080)*, Naval Health Research Center, Brooks City-Base, TX (2004).
12. *American National Standard for The Safe Use of Lasers* (ANSI Z136.1). Laser Institute of America, Orlando, FL (2000).
13. B. Winn, D. Whitaker, D. B. Elliott, and N. J. Phillips, ‘‘Factors affecting light-adapted pupil size in normal human subjects,’’ *Invest. Ophthalmol.* **35**, 1132–1137 (1994).
14. D. C. Hood and M. A. Finkelstein, ‘‘Sensitivity to light,’’ in *Handbook of Perception and Human Performance. Volume 1. Sensory Processes and Perception*, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds., pp. 5-1 to 5-66, Wiley, New York (1986).
15. L. N. Thibos, A. Bradley, and X. Zhang, ‘‘Effect of ocular chromatic aberration on monocular visual performance,’’ *Optom. Vision Sci.* **68**, 599–607 (1991).
16. A. Chapanis, ‘‘Hazards associated with three signal words and four colours on warning signs,’’ *Ergonomics* **37**, 265–275 (1994).
17. D. V. Van Norren and J. J. Vos, ‘‘Spectral transmission of the human ocular media,’’ *Vision Res.* **14**, 1237–1244 (1974).