Development of a New Type of Laser Protection Glasses for Aviation Crews: Results of Combining Absorptive and Reflective Filters

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Abstract. Dazzling attacks on aircrafts with lasers are a serious problem regarding aviation security. Although a broad variety of laser protection devices are commercially available for usage in research laboratories and industrial settings, the requirements for police and military missions are highly different. These requirements are not addressed in current standards. Therefore, a unique type of laser protection glasses for the usage in aircrafts was developed in close cooperation with the operational user. The concept is premised on an absorptive dyed polymer base body to provide protection against three discrete laser lines in the visible spectrum in combination with an interference coating to filter off laser radiation in spectral bands in the near infrared region. The absorbing dyes were balanced to maximize colour fidelity and visible light transmission and to ensure that information and warning lights of the cockpit as well as the helmet displays can be seen correctly by the pilot. The coating was optimized to have no discernible impact in the visible spectrum. The performance was evaluated in laboratory, ground and flight tests and was approved for flight by the Bundeswehr Federal Office of Equipment, Information Technology an In-Service Support (BAAINBw) as well as by the German AirForce Center of Aerospace Medicine. The presented results demonstrate the feasibility of designing laser protection glasses with simultaneous high-level protection in five spectral regions in the UV/VIS/NIR range without adverse effect on the user's flight safety with respect to colour vision.

1. INTRODUCTION

There is little doubt that the way in which future military conflicts may be decided will be completely different from the way recent wars have been waged. Apart from changed strategical concepts and political doctrines, this will primarily be the result of newly developed technologies such as drones, hypersonic missiles, cyber campaigns, and directed energy weapons including lasers. The overall tendency is clearly diverging from uncontrolled mass destruction and kinetic weaponry towards an integrated concept of faster, more precise, longer range, and interconnected 'smart' weapon systems. [1] In conjunction with improved sensors, autonomous robotics, and artificial intelligence, these systems will dominate the battlefields of the future.

Future combat lasers will be operating at very high energies up to several hundreds of kilowatts in the near-infrared range of the electromagnetic spectrum which is invisible to the human eye. [2] Although operationally not yet available, a number of demonstrators have been developed and successfully tested by different nations including the United States [3–5], the UK, [6] and Germany. [7] Besides these high energy lasers (HEL) that will be deployed within the next decade, a multitude of low energy laser (LEL) applications have already been available for a long time, including laser jammers, laser range finders (LRF), laser radars, and laser target designators. [8] Other devices such as beam riders are used to precisely direct laser guided weapons (LGWs) against military targets. The first LRF was based on Maiman's ruby laser and introduced in 1965, just four years after successful demonstration of the first operational laser by the inventor himself. [9–11]

Visible lasers are utilized as laser pointers, target designators mounted on ballistic weapons, and military laser dazzlers. Notably, the most trivial of these applications, the common laser pointer, has captured the highest level of attention in the past. Once considered a childish prank, misuse of laser pointers in the public for illumination of man and materials has reached epidemic dimensions which is particularly true for aircraft illumination. As of 2022, a cumulative rate of 100,000 events worldwide since 2004 has been exceeded, with increasing incidences despite of reduced air traffic due to the COVID-19 lockdowns. [12] Military aircraft are affected on home bases as well as on duty abroad, as has been confirmed by numerous official reports and press releases. [13–16] The continuously increasing emissive power of devices, the worldwide availability, and the diversification of wavelengths make it difficult to officially control this contemporary phenomenon by effective public health intervention.

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Military laser dazzlers, on the other hand, are the logical derivatives of handheld dazzling devices, optimized for strategical purposes and operating at another order of magnitude. Based on the same diode technologies, they have been used, for instance, in the Falkland War by the British and at Operation Desert Storm by the US military. [17,18]

As laser technologies emerge, engaged soldiers, police officers, and particularly aviators are calling for eye protective devices. Unfortunately, however, these safety technologies did not keep pace with the diversification and proliferation of lasers in the modern world. Most laser protection glasses (LPG) available are blocking single wavelengths of the electromagnetic spectrum, which is sufficient under laboratory conditions, but raises two major problems: The first problem is that unlike laser protection in scientific or industrial environments, the wavelength possibly impacting the human eye is not known under military conditions. Even when green lasers are considered the most frequently used emitters, as is confirmed by nearly all civil and military aviation authorities, there will always remain a certain possibility that other wavelengths are used for illumination. [19] Of particular concern in this context are blue lasers that according to the respective FAA statistics have continuously been increasing from 2 – 3 % to nearly 10 % during the last decade. [20] The traditional red laser pointer, for unknown reasons, nowadays appears to be of lower public interest. The second problem is that filtering a single wavelength or sequence out of the visible light spectrum will considerably change individual colour perception resulting in an LPG-induced deuter- or protanomalous colour shift. This problem mainly affects pilots, for instance through reduced perception of external airfield lightings such as PAPI[18] systems, or internal colour displays, both requiring normal trichromatic colour discrimination.

Since most commercial laser pointers are operating either in the red, green, or blue wavelength range, a trichromatic approach would be useful which can be technically achieved by application of dye filters absorbing the wavelengths desired. Under these conditions, however, another problem will occur: the more pigment is present in the polycarbonate LPG layers, the lower the visible light transmission (VLT) will be, resulting in a functional degradation of visual acuity and contrast sensitivity. The effect is further enhanced by increasing optical density (OD) which defines the LPG protection level and is inversely log-related to transmission. [21] Hence, a cut-off decision between OD and VLT has to be made. Most LPGs are available in optical densities between 1 and 3 meaning that the incoming light is attenuated by a factor of 10 (OD1), 100 (OD2), or 1000 (OD3).

Such attenuation factors are sufficient for visible glare reduction, for the purpose of blocking invisible laser irradiation, however, much higher attenuation factors are needed. Considering the enormous infrared emission of a 100 kW laser weapon, at least OD6 is needed, even if only the part of radiation that is reflected by an encountered target is taken into account. A promising approach to fulfilling this requirement could be the implementation of a dichroic or interference filter consisting of multiple layers of dielectric materials with different refractive indices that reflects one or more spectral bands and transmits others, while maintaining a nearly zero coefficient of absorption for the wavelengths needed for visual field perception. [22] The conceptual result of such a device would be a physical composite of laser glare protection (LGP) and laser eye protection (LEP).

Here, we describe the technological concept of a combined approach of visible and invisible light attenuation including the extent of visual degradation induced by realization of this concept. The first completed visAIRion LPGs were already delivered in 2022.

2. TECHNICAL ASPECTS

From a technical point of view, the main challenge was the development of a filter technology tasked with the blocking of about 99 % of the statistically ascertained laser attacks on aircraft by attenuating the three most common visible wavelengths and blocking the three main invisible wavelengths in the UV-A, UV-B and NIR spectral region. As a result, the filter technology is based on a combination of a dyed absorptive polymer coated with a reflective interference filter. The basics of the according technologies are briefly resumed in the following. Please note that detailed information on the filter construction and performance data are subjects to confidentiality.

2.1 Dye Filters

The working principle of dye filters is primarily based on the attenuation of light by absorption in the filter material itself while the reflection amount is basically limited by Fresnel reflection at interfaces. The spectral transmission factor $\tau(\lambda)$ of a filter with an absorption coefficient $\chi(\lambda)$, refraction index $n(\lambda)$,

[18] Precision Approach Path Indicator

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thickness d, and dye concentration c is described in good approximation by the product of the reflection factor $P(\lambda)$ and the internal transmission $\tau_i(\lambda)$ following Lambert-Beer's law:

$$\tau(\lambda) = \underbrace{\frac{2 \cdot n(\lambda)}{n^2(\lambda)+1}}_{P(\lambda)} \cdot \underbrace{10^{-\chi(\lambda) \cdot c \cdot d}}_{\tau_i(\lambda)} \tag{1}$$

Contrary to coloured glass filters where heavy metal or rare earth ions are utilized, the absorption of the presented filter system in the UV/VIS region is implemented by organic dyes. The corresponding absorption mechanism is based on wavelength specific excitation of valence π-electron systems. [23] In modern design of synthetic dyes the affinity to the substrate as well as the energy gap between ground and excited states can be individually adjusted by direct molecular modeling of the π-electron system. For example, increasing the degree of conjugation as well as the introduction of auxochromes like hydroxyl, amino or aldehyde functional groups (electron donors) induces a shift of the absorption maximum to longer wavelength, whereas anti-auxochromes like carbonyl, nitro or carboxyl groups (electron acceptors) cause an inverse effect. [24–26]

Furthermore, a large quantity of existing dyes with either more or less selective absorption features is already available. Dye filters are an attractive option for their simplicity in manufacturing from a technical point of view but typically suffer from an adverse effect on the VLT due to relatively broad absorptions with unfavorable transition steepness when used for the blocking of discrete laser lines in the visible spectral range. [27]

2.2 Interference Filters

The operating principle of interference coatings is based on wavelength selective constructive and destructive superposition of coherent light by reflection and transmission at interfaces of dielectric layers. Considering the simplest case of one layer with plane parallel surfaces and thickness d (Figure 1), an incident beam of coherent light I with an incident angle θ is partially reflected and refracted at the surface according to the Fresnel-formula and Fermat's principle, respectively. [28]

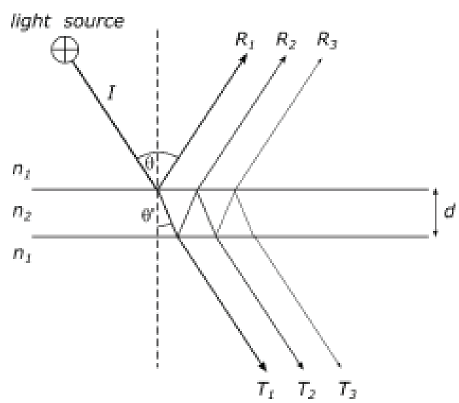

Figure 1. Interference caused by transmission and reflection at plane parallel surfaces.

This process is repeated several times at each interface generating parallel beams of transmitted (T_1, T_2, T_3) and reflected (R_1, R_2, R_3) light. In case of dielectric materials, the absorption can be neglected and d is usually in the range of nanometers, causing interference between adjacent rays of light. The nature of the interference for a transmitted coherent light beam with a specific wavelength λ depends on the layer thickness d, the difference of the complex refraction indices of the two materials (n_1 is usually considered as the refraction index of air/vacuum) and the incident angel θ. Destructive interference is induced by accordance with Formula 2, where m represents integral numbers:

$$2 \cdot d\sqrt{n_2^2 - n_1^2 \cdot sin^2(\theta)} = \left(m + \frac{1}{2}\right) \cdot \lambda \tag{2}$$

This principle can be extended to filters blocking whole spectral bands by multi-layer systems of alternating dielectric materials with high and low refractive indices and defined thicknesses calculated by software employing matrices methods. Thus, extremely effective filters can be constructed featuring transmission values close to 100 % in the passband region with simultaneous values of OD6+ in the blocking region accompanied by an outstanding transition steepness. Furthermore, the damage threshold regarding laser radiation is extremely high compared to dye filters because the intrinsic minimal absorption leads to a minor conversion of the incident light to thermal energy. Unfortunately, the dependence of the interfering wavelength on varying travelling distances of light inside the dielectric material due to different incident angles θ (see Figure 1) limits the applicability to eyewear in the visible spectral range because of angular dependent colour distortions. [29]

Interference coatings are usually applied by physical vapor deposition (PVD) methods like ion beam sputtering or thermal/plasma enhanced chemical vapor deposition (CVD) methods and are among other aspects limited to the coating complexity, substrate geometries and the minimal layer-thickness regarding the error propagation in sequences with up to several hundreds of layers. [30]

2.3 Filter Design and Spectral Properties

The filter concept of the presented LPG is based on a combination of both filter technologies. Blocking of spectral bands in the UV-A (315 - 400 nm) and UV-B region (280 - 315 nm), as well as attenuation of three major laser lines in the visible spectral range is realized by a specially developed dye-combination. The crucial advantage regarding the choice of absorption filters in the VIS range is the low sensitivity on the incident angle of light compared to interference coatings ensuring the prevention of colour distortions. Conversely, a relatively low VLT of typically 32 % was accepted leading to a visual perception comparable to that of moderate sunglasses. Proceeding from this prototype, the protection level can be tuned by changing the concentration of the dye-mixture (formula 1). Moreover, the proportions of the individual dyes were deliberately balanced in order to achieve an optimum in colour fidelity. Typical values of attenuation coefficients relative to the global VLT for red, yellow, green and blue standardized signal lights are 0.86; 1.22; 0.82 and 0.85, respectively. [31] Additionally, compatibility with night vision goggles availing low-light amplification by green or white emission of phosphorus compounds is considered by transmission values of >32 % at the emission maximum frequencies.

Dyes are directly incorporated into the blank by mixing with the polycarbonate precursor prior to injection molding. The result and functionality are shown in Figure 2:

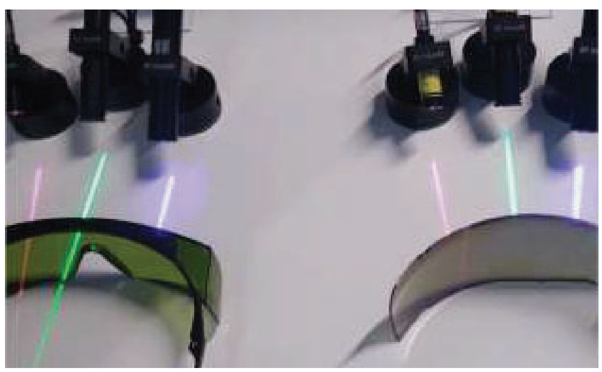

Figure 2. Experimental evidence of successful RGB blocking by the blank (right, absorption filter) as compared to conventional laser protection glasses for usage in a laboratory environment (left).

Blocking in the NIR spectral region, where incident angle dependent colour distortions play a minor role on the visual cognition of the protected person was achieved by an interference coating of 120 layers with an overall thickness of approximately 14.5 µm applied by a magnetron sputtering PVD-process. In this way high protection levels in the NIR region of OD6+ could be realized.

For the application of PVD coatings some crucial factors have to be considered in terms of the overall stability of the filter against thermal or mechanical stress. [32] Potentially, low adhesion of the PVD coating to the substrate or internal strain may cause delamination. [33] This is usually accomplished by choosing substrates and dielectric materials with similar mechanical properties like hardness or thermal expansion coefficients. [34] Since polycarbonate and the dielectric materials used for filter construction exhibit significantly different properties, a hard coat based on polysiloxanes was applied to the blank by dip coating as an adhesion promoter prior to the PVD process. Additionally, a special anti-fog coating is applied on the inner side of the lenses to prevent mist formation in environments with high atmospheric humidity.

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2.4 Spectacle Design

Usually, commercially available laser protection glasses can be purchased in a single configuration, or a filter system is offered with different spectacle frames and lens geometries. In the current case a different approach was chosen because of the complexity of the coating process and its dependency on the lens geometry. Therefore, one type of spectacles was developed offering numerous options for the customization like different frame and nose bridge sizes, as well as length, shape, and material of the temple stems. Altogether, 96 modifications are available to cover almost all personal requirements and facial contours. A prototype of visAIRion LPG is depicted in Figure 3. Shape and design consider occupational safety requirements such as aviation related operational aspects. The field of view was enlarged as compared to usual commercial design, and the curvature was manufactured to prevent lateral intrusion of laser irradiation underneath of protection. Low weight, temperature resistance and shatter protection are guaranteed by the polycarbonate composites of the base body.

Figure 3. Prototype of the visAIRion laser protection glasses.

Special attention was dedicated to the fit. The temple joint areas are positioned inward in order to narrow the frame ensuring compatibility with visor systems as being used in the German Air Force. The temples were designed as flat as possible to avoid inconvenient pressure in the contact area when wearing them in combination with ear protectors of the integrated helmet system. Moreover, the temples are much shorter compared to conventional LPGs and the typical side curvature was removed to simplify sliding them underneath the headphones or the inner lining of the helmet. Nose bridges are attached and exchangeable per clip mechanism and can be optionally equipped with correction lenses without modifying the basic protection device.

3. MEDICAL TEST RESULTS

The development of the final prototype of the visAIRion LPG presented in this paper took a total of five years to meet requirements like compatibility with the helmet system and to figure out the ideal compromise between visible light transmission (VLT) and the protection level. For the latter task, a set of 6 prototypes with incrementally graded transmission properties was developed in collaboration with various eyewear manufacturers and independent research institutes and was provided to the AirForce Center of Aerospace Medicine for visual testing and fine tuning. The final cut-off settled in a 30 - 40 % VLT range. Experimental increase of transmission resulted in a decrease of optical density to values below the targeted minimum. Conversely, experimental increase of optical density introduced a disturbing image obscuration, which, as a result of reduced contrast vision, was rated operationally unsatisfactory by test pilots, especially under twilight conditions. The finally achieved VLT has to be regarded the maximum of glare protection currently feasible with the technology described in this paper.

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3.1 Visual Acuity

Central visual acuity was tested in non-spectacle or contact lens wearing persons only using standard Landolt's C-projection[19] at a distance of 5 m. Tests were performed under mesopic ambient light conditions with room lights turned off. There were $n = 20$ male persons tested, with a mean age of 31,3 years and an age range between 18 and 39 years. All participants were tested with and without the laser protection device.

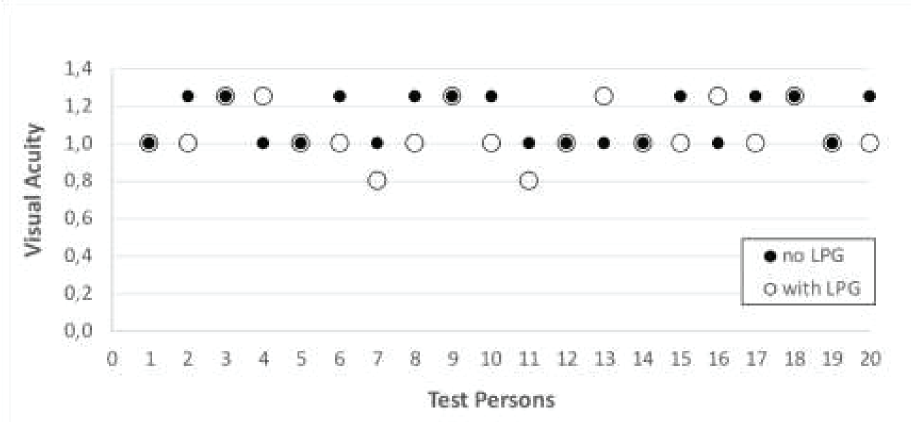

Figure 4. Visual acuity with and without laser protection glasses (right eyes only)

There was no significant difference between both groups using Mann-Whitney U-Test (1.125 ± 0.128 vs. 1.055 ± 0.144; $p = 0.781$). In two cases, a visual acuity impairment was noted while LPG wearing (VA = 0,8 or 20/25), whereas all remaining cases coincidentally scattered between 1,0 (20/20) and 1,25 (25/20).

3.2 Contrast Sensitivity

For measuring contrast sensitivity (CS), Pelly-Robson Charts were used under photopic (lights on) and mesopic (lights off) conditions. Under mesopic conditions, all objects within the test room were fairly visible including details such as door handles or name badges. All volunteers ($n = 8$) were measured binocularly with and without LPG at a distance of 2 m. The test measures optotype visibility using a single large letter size optotype with continuously decreasing grayscales across groups of letters. To determine contrast sensitivity, the letter-by-letter scoring system as indicated on the referring scoring sheets was used, whereby each letter correctly identified was scored as 0.05 log units. A Pelli-Robson score of 2.0 indicates normal contrast sensitivity of 100 %, whereas scores less than 2.0 indicates reduced contrast sensitivity. Scores of less than 1.5 are considered visual impairment. Importantly, there were no light boxes used in this test as we were interested in the differentiation of photopic and mesopic visual environments.

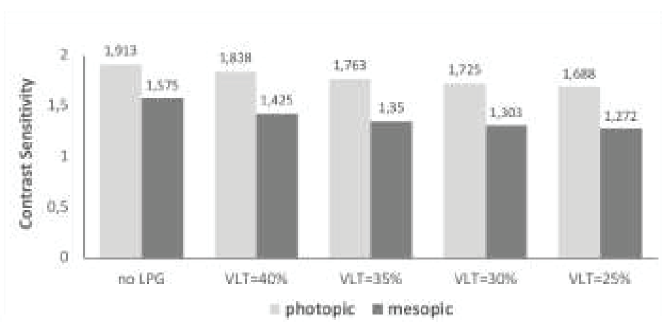

Figure 5: Contrast sensitivity with and without laser protection glasses (mean values from binocular testing in 8 test subjects)

[19] The Landolt C is an optotype defined as a ring with a gap at varying positions (left, right, bottom, top and the 45° positions in between). The size of this optotype is reduced until the tested persons makes a specified rate of errors.

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Under photopic conditions, use of LPG did not impair vision even when VLT was reduced to 25 %; all scores were evaluated with a mean CS > 1.5. Under mesopic conditions, all scores except the one without wearing any LPG resulted in values < 1.5 indicating significantly reduced contrast sensitivity. Backward calculation revealed an LPG-induced reduction of contrast sensitivity by 11.8 % under photopic, and 19.2 % under mesopic conditions.

3.3 Colour Perception

Colour vision was approached by anomaloscopy. The test procedure has been described first by Nagel in 1917 and relies on subjective comparison of two separated hemicycles. In the upper part a mixed colour of green and red (548 and 666 nm) is offered, while in the lower part an orange to yellow colour (589 nm) is set. The colouring of the upper part can be varied by the examiner and matched by the tested person through operating a red-green screw. [35] The purpose is to determine the anomalous quotient (*AQ*) i.e., the subjectively required ratio of green and red colour shares. Calculations were performed using the Rayleigh equation [36], where *P* corresponds to the study participant and *N* to the (normal-sighted) examiner:

$$AQ = \frac{(73-P)/P}{(73-N)/N} \tag{3}$$

This corresponds to the relationship:

$$\frac{Green(P)\cdot Red(N)}{Red(P)\cdot Green(N)} \tag{4}$$

where 73 is the scale value of the mixed colour for green-free presentation, and 0 that for red-free presentation. A colour normal subject will perceive the two half-fields as equal if the mean standard equation 40/15 (i.e., mixture = 40 and brightness = 15) is set. Since colour discrimination is subject to a certain degree of variance (range of adjustment), ratios between 0.65 and 1.32 are considered normal. A deuteranomalous subject will match with too much green ($P < 40$; $AQ > 1.32$), a protanomalous one with too much red ($P > 40$; $AQ < 0.65$). Tests were performed in 10 volunteers.

Results indicate that monochromatic as well as dichromatic filters had a stronger effect on colour perception than trichromatic filters. Commercially available LPGs tested for comparison (Figure 6) introduced a significant impairment of colour discrimination, which apparently resulted less from filter types used than from specific wavelengths selectively or cumulatively blocked. With simultaneous blue and green blocking, colour perception shifted into the deuteranomal range (average adjustment range 1.08 - 1.46), whereas under red and green blockade, a shift into the protanomal range (average adjustment range 0.39 - 0.48) resulted. This corresponds to a deutan shift between + 31.6 and + 39.1 % (A) and a protan shift between -52.4 and -54.7 % (B), respectively. In contrast, with triple RGB blocking (C), colour perception remained approximately normal (average adjustment range 0.77 - 0.94) with relative shifts between -10.2 and -12.4%. On the behalf of these results, subjective colour perception of a pilot in duty can be simulated as shown in Figure 7.

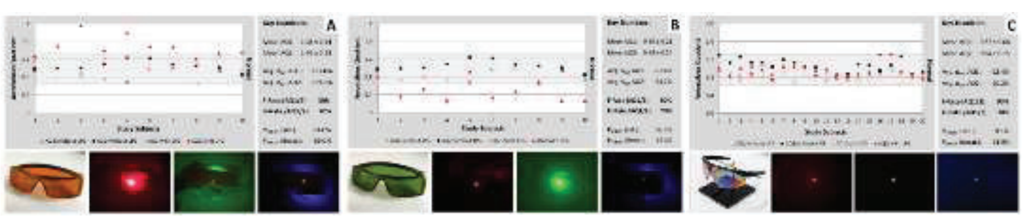

Figure 6. Results of colour vision testing. The diagrams show the anomalous quotients (red dots) of the respective glasses imaged underneath, as compared to the individual reference values without glasses (black dots). The transillumination images display the filter capacities of test glasses in a dark room. The residual dot remaining at effective attenuation levels is intentional in order to enable the pilot to realize and to report the respective laser event. **Mean**: Mean plus/minus standard deviation. **Avg. Δ_{Ref} AQ1/2**: Mean deviation from reference value (= AQ without LSB). **F-Rate (AQ1/2)**: Medical fitness rate considering AQ1 and AQ2. **U-Rate (AQ1/2)**: Medical unfitness rate, inverse function of T-rate. **P_{ERROR} (sat.)**: Error probability 15-Hue saturated.. **P_{ERROR} (desat)**: Error probability 15-Hue desaturated. Test results of monochromatic filters have been omitted in this depiction.

In order to evaluate the best cut-off between VLT and OD, 6 VLT variants of the developed prototype were tested for their colour fidelity and image quality. The tests were performed blinded, i.e., the respective transmission of the provided test glasses was not known at time of testing. Examinations were performed on 20 male study subjects, with each subject evaluating all glasses according to the same proceeding and order. Participants were asked to sort the glasses based on their quality of vision in order from 1 to 6. For evaluation, an inversely proportional score from 6 to 1 was assigned. From this, a total ranking score was calculated for each of the 6 glasses. After unblinding and assignment of transmission levels, an almost perfect correlation between both parameters was found ($R^2 = 0.98$), i.e., the higher the light transmission, the better the subjective visual impression was rated by the subjects (Figure 8). There was remarkably low variance in this result.

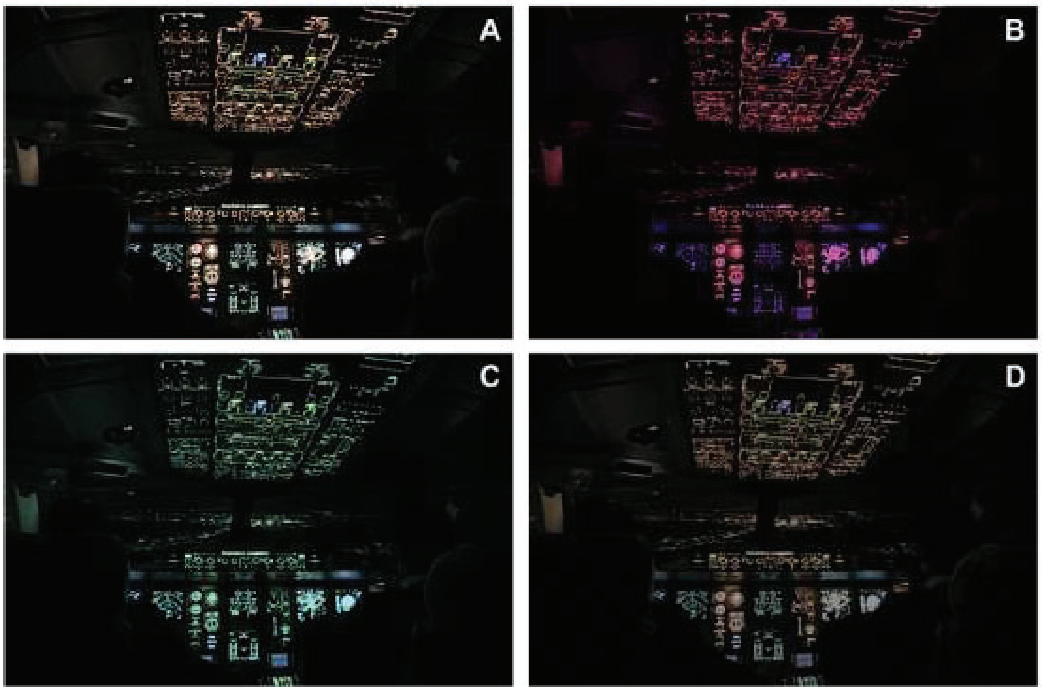

Figure 7. Simulation of colour perception with different LPG filters: (A) View at night without LPG. (B) Selective blocking of green results in over-representation of red and violet hues (deuteranomalia); reliable differentiation of cockpit displays under these conditions is not possible. (C) Selective blocking of red results in over-representation of green and blue hues (protanomalia); reliable differentiation of cockpit displays under these conditions is not possible. (D) Simultaneous blocking of red, green, and blue under equilibrated conditions results in a reduction of contrast vision and colour saturation while maintaining a normal colour perception; reliable differentiation of cockpit displays under these conditions is possible.

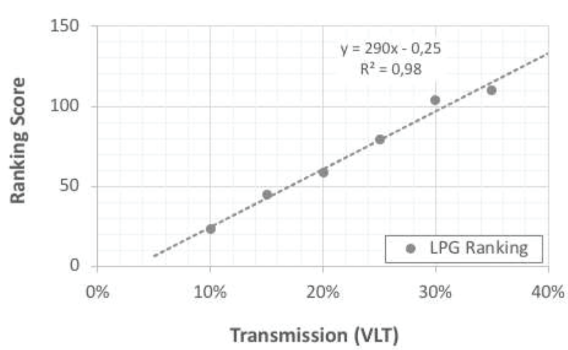

Figure 8. Subjective ranking of quality of vision at different transmission levels.

4. Discussion

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The combination of improved sensors and automated controls with advanced laser technologies will produce a generation of weapon systems that will change the appearance and strategical concepts of future battlefields. These systems will primarily be available to advanced military nations with some of them in reach of smaller state and non-state actors including asymmetric forces and terrorists. Hence, it can be predicted that safety precautions and counter measures will be major concerns in this instance.

The main hazard of laser exposure is ocular injury which makes the topic a highly sensitive issue with considerable psychological impact. Although the anti-personal use of high-energy lasers has been banned by protocol IV of the UN Declaration of Helsinki, the remote possibility of collateral eye damage by scattered or reflected laser radiation remains. Given the destructive power of a 100 kW laser in operation, the 1/millionth part of the emitted energy reaching a soldier's eye might be sufficient to cause irreversible eye injury. In contrast to the continuous radiation emitted by HELs, low energy lasers rely on pulsed emissions which makes it difficult to predict remote interaction with biological tissues. Historical experiences suggest that most cases of ocular injury in the past have been accidental due to inattentive, careless, or untrained handling of the respective devices. Taken together, the ocular hazard from future invisible lasers will be primarily coincidental and accidental, if deliberate anti-personal use is excluded.

Meanwhile, there is consent that in case of visible lasers the primary hazard is visual impairment rather than retinal injury. From a physical perspective, focused retinal injury at larger distances is nearly impossible due to atmospheric disturbances, beam divergence, target movements, and scatter effects at transmissive surfaces such as windows and visors. Although it might appear injudicious to deny the remote effects of a device that was actually designed for distant operation, the missing evidence of ocular injury in pilots illuminated in flight appears to confirm that medical incapacitation is not a primary concern of visible laser exposure, at least when evoked by traditional laser pointers. However, the remaining effects of glare and disruption may cause psychophysical impairment possibly resulting in a reduction of human performance. With respect to aviation, the main concern is the pilot's ability to maintain control during take-off and landing maneuvers when operational skills are critical. [37] According to the Federal Aviation Regulations, aircrew interactions in these phases of flight are restricted on operationally relevant communication in order to maximize attention and to minimize the potential of human error. [38] This safety principle is called the sterile cockpit environment which is agreed to be violated in any case of accidental or deliberate laser illumination, thus interfering with flight safety even if no physical injury might be expected.

Concerning the unique characteristics of lasers and their interaction with the human eye, design and construction of advanced laser-protective eyewear is a demanding task that requires multiple considerations in terms of safety and efficacy on the one, and cut-off decisions on technological feasibility on the other hand. [39] Examples include visibility of the outer world under daylight as well as twilight or night conditions, implementation of optional refractive corrections, and the customization of spectacle fit. Military considerations include anti-fog coatings, scratch resistance for operational use in desert environments, technical compatibility with integrated helmet/visor systems, and visual compatibility with helmet mounted displays, night vision goggles (NVG), and optical combiner technologies.

The prototype presented in this paper was developed by the ESG Elektroniksystem- und Logistik-GmbH, Fuerstenfeldbruck, in close collaboration with the German Air Force (GAF) Centre of Aerospace Medicine in Cologne and Fuerstenfeldbruck. Operational testing was performed by combat mission pilots of the GAF test facilities in Manching and Fritzlar, Germany. The device as pictured in Figure 3 belongs to a new generation of LPG combining laser glare protection (LGP) with laser eye protection (LEP). Glare protection is provided by visible light attenuation at three distinct wavelengths (RGB), while eye protection is provided by additional high-range attenuation of three invisible spectral bands (UV-A, UV-B, NIR). To our knowledge, this concept has not been described or realized to date for use in aviation or related tasks. Further information of attenuation factors and wavelength specifications are classified restricted according to governmental regulations.

The three key features to be considered from the ophthalmological point of view are visual acuity (VA), contrast sensitivity (CS), and colour perception. Unlike tinted sunglasses, wearing of the LPG did not introduce a significant reduction of visual acuity. In two test persons, a VA of 0,8 (20/25) resulted in one eye which, if confirmed, would not meet the VA criteria required for active aircrew. Contrast sensitivity showed a decrease ranging from 11.8 to 19.2 % depending on VLT and ambient light conditions which would reflect a very reasonable, hence acceptable grade of visual degradation. The question is whether the testing standards of routine VA and CS measurements under photopic conditions may be applied to a device that will be primarily used under mesopic and scotopic conditions. Both, VA, and CS measurements, rely on spatial resolution which is expected to considerably increase when optotypes are exposed on background-illuminated plates or light boxes as foreseen for test routines using Landolt C or Pelly-Robson Charts.

As expected, the most challenging issues to be handled were the cut-off decisions regarding colour perception. Effective attenuation of dichromatic filters induced iatrogenic colour deficiencies in every constellation tested, to an extent that was not acceptable for demanding visual tasks such as flying an aircraft. The colour shifts recorded by conventional anomaloscopy produced deuteranomalous and protanomalous results in up to 100% of cases (Figure 6) dependent on wavelengths blocked and optical densities applied. The best results were received in greyish-toned glasses indicating a role of colour equilibration with regard to simultaneous attenuation of red, green, and blue colour spaces. After multiple refinements of wavelength peaks and ranges based on this RGB equilibration principle we finally elaborated a profile that is compatible with high-end visual tasks including aircraft-related operations.

From the military point of view, not all operational interferences and limitations under diverging ambient light conditions have been tested at this point. Standard optical requirements including related regulations such as DIN EN 207, [40] DIN EN 167, [41] DIN EN 168, [42] etc. however, are met. In addition, the built-in dye and dichroic filters do not restrict the application of military image intensifiers such as night vision goggles (NVG) or forward looking infrared (FLIR) used in aviation-related as well as ground-based operations. Future developments will include optimization for different types of aircraft and special forces requirements, including colour saturation, contrast vision, and enhanced protection levels for invisible lasers. At the end, the remaining question will always be how much safety is desired, and which extent of visual degradation is acceptable for this purpose.

In conclusion, we have shown that it is possible to design laser safety eyewear that provides simultaneous protection in three visible and three invisible wavelength ranges without affecting colour vision to an extent that would be incompatible with actual flight safety requirements. The finalized product is currently being delivered after completion of operational tests and final approval by the German Ministry of Defense.

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