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Facilitating the transition from bright to dim environments

Morris R. Lattimore* **and James Q. Truong**
U.S. Army Aeromedical Research Laboratory, Warfighter Performance Group, Fort Rucker, Alabama, United States

Abstract. High on the list of desired capabilities for warfighters noted at the 2008 Fort Benning "Lab Day" was the development of combat protective eyewear with lenses that would instantly change the amount of light they transmit, based on incident lighting conditions. We reviewed the investigation regarding the effect of four different protective spectacle lens designs [clear, standard sunglass, step filter (SF), and electro-optical (EO)] on a soldier's ability to rapidly transition from bright to dim environments. The dependent measures were selected to specifically permit the findings to be evaluated in both clinical and operational terms. A multifactorial analysis of variance revealed global statistically significant interactive effects regarding the viewing lenses, subject marksmanship, and subject visual acuity. The subjective preference ratings indicated a clear preference for the SF and the EO eyewear over no eyewear, the Authorized Protective Eyewear List (APEL) clear eyewear, and the APEL sun eyewear. Operational performance results while wearing either of these two optical devices (the SF eyewear and the electronic eyewear) are equally effective. Consequently, the fielding of either transition strategy provides equal acceptance and utility by the soldiers using this transitional gear. [DOI: 10.1117/1.OE.58.5.051803]

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1 Introduction

The purpose of this study was to determine how best to facilitate soldier transition from bright to dim environments using generally available technology, which addresses one of the operational gaps frequently identified by infantry warfighters serving in Iraq and Afghanistan. During the 2008 Infantry Lab Day at Fort Benning, Georgia, then Major General Walter Wojdakowski briefed the current gaps in technology that need to be addressed to improve soldier survivability in the contemporary combat environment. High among the list of desired capabilities for warfighters was combat protective eyewear with lenses that would instantly change the amount of light they transmit [instantaneously varied optical density (OD)] based on changing or altered lighting conditions. It was noted that although currently authorized Military Combat Eye Protection (MCEP) have interchangeable clear and tinted (i.e., sunglass) lenses, soldiers may have to remove their MCEP to manually exchange the lenses. Worse than that, soldiers may even have to remove their helmet to get access to the MCEP, to then swap out the lenses. Overall, this series of steps makes soldiers openly vulnerable to combat-induced, life-threatening injuries for a period of time. At best, the entire process is a time-consuming event that might be difficult or even impossible to accomplish at all, depending on the operational situation. Given these choices, many soldiers opt not to wear their combat eye protection to preserve their visual sensitivity under variously encountered lighting conditions. The immediate goals of the project were to identify the strengths and weaknesses of the most promising candidate procedures, strategies, and technologies generally available that have the potential for facilitating the transition from light to dark environs. The extended objectives of this research initiative were to identify, evaluate, quantify, and refine technology and/or procedures to enhance the ability of our military personnel to efficiently and rapidly transition from light to dark environments, a common task when functioning in an urban combat environment. Lastly, the characterization of these methods should not merely lead to technological improvements but also to recommended modifications to existing policies and procedures. This study was the evaluation of the effect of four different existing protective spectacle lens designs [clear, standard sunglass, step filter (SF), and electro-optical (EO)] on a representative soldier's ability to rapidly transition from bright to dim environments. The dependent measures were selected to allow the findings to be evaluated in both clinical and operational terms. In bright environments, the visual system is capable of its best resolving capacity (or acuity) and is most sensitive to optical defects; preselected tasks that reflected this were based on logarithmic-scaled minimum angle of resolution (logMAR) acuity data, in addition to soldier marksmanship scoring. The effect of the different lens filters on volunteers' ability to adapt to a dim environment following exposure to a bright environment was measured by clinical dark-adaptation timing measures. Further, the time required to detect and recognize certain objects (e.g., trip hazards, improvised explosive device, and weapons), as well as to identify nearby human targets (i.e., hostile, civilian, or friendly), was also logged for statistical analysis.

1.1 *Practical MCEP Utility*

Warfighters are required to wear MCEP in a deployed setting at all times [MCEP has been identified and itemized on the Authorized Protective Eyewear List (APEL)],[1] to protect their eyes from ballistic hazards, such as shrapnel, and to provide protection against primary blast effects on the eyes.[2]

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*Address all correspondence to Morris R. Lattimore, E-mail: morris.r.lattimore.civ@mail.mil

Warfighters are issued an MCEP kit that includes a frame, with reduced transmittance lenses (i.e., sunglasses), along with clear lenses. The clear and sunglass lenses can be interchanged without tools in about a minute or less. Changing the lenses does require doffing the MCEP, close focused visual attention, and the use of both hands. The lenses often are smudged during the change-out procedure, requiring cleaning prior to their use. Donning the MCEP may require doffing the helmet. During the day in a brightly lit environment, such as in the Middle East and Southwest Asia, the sunglass lenses can be used to provide protection from glare, and to provide relative comfort. As slightly touched-upon earlier, the primary operational task that remains problematic with MCEP use is the occasion when the warfighter is required to transition from a brightly lit outdoor environment to a dark interior space (e.g., in buildings, caves, and other possible hiding places). Currently, warfighters have four options, none of which are satisfactory because they all put warfighters at risk to one degree or another:

i. Remove their MCEP sunglasses, leaving their eyes unprotected from ballistic injury.
ii. Switch from MCEP sunglasses to clear lenses. As mentioned earlier, this requires that the operator pause, take their hands off their weapon, remove the sunglass lenses, and install the clear lenses; this is operationally very problematic.
iii. Simply leave the MCEP sunglasses on, which would make the dark interior even darker, limiting visual capability even more, thus giving the enemy an even greater tactical advantage.
iv. Use only clear lenses in the MCEP. This last approach also reduces visual capability in the dark interior spaces. In this case, the reduction in visual performance is due to the bright exterior illumination’s detrimental effects, serving to delay dark adaptation.

This effect is described in detail later.

The research challenge is to find another, better option for the warfighters to overcome this challenge. To this end, the following discussion establishes a biological basis to define some of the considerations and limitations for facilitating the warfighter’s transition from bright daylight to a poorly lit interior or even dark environment. Subsequent to that review will be a discussion on characteristic visual performance at varied light levels, as a function of various task requirements as quantified by the expected visual environments. Four independent technological approaches to a solution were then presented. Reasonable expectations were developed based on the task, ocular anatomy/physiology, and the available technology.

1.2 *Neural Aspects of Dark Adaptation*

It has been clearly established that the light-sensitive part of the human eye is the neural retina, which contains a class of specialized cells sensitive to light, termed photoreceptors.

Each of these photoreceptors contains a characteristic photopigment, which catches quantum-scaled packets of light imaged on the retina. The photoreceptors transform the absorbed quantal light energy into electrochemical neural responses, which are then conveyed throughout the retina and to the brain.[3,4] It would seem intuitively obvious that enough light could simply burn out the tissue, which is represented as the high-end exposure limit. However, it is not intuitively obvious where the low-end limit can be delineated. Classic studies have demonstrated that a single photon of quantal light energy absorbed by a photoreceptor’s photopigment is sufficient to trigger an electrochemical neural response in the human retina in an absolutely dark environment.[5] A small number of such neural responses within a lighter environment, occurring at essentially the same time, is sufficient to produce the visual perception of light. Thus, the retina is capable of achieving the theoretical physical limit, counting individual photon quantal events. Therefore, the minimum amount of light necessary for detection is limited by the statistical fluctuations in the number of quanta absorbed by the photoreceptors.[5] However, to achieve the ability to function over a dynamic range of 14 orders of magnitude, the eye makes several compromises that contribute to the difficulty inherent in the intended transitioning from brightly lit to dimly lit environments. One of the most important of these compromises is a basic design feature of the human retina. The retina is made up of two distinctly different classes of photoreceptors, and these two classes have very different functional characteristics.[6,7] With two classes of cells, neither class is thus required to function over the entire dynamic luminance range of sensitivity; they can be specialized for a narrower but still wide range of luminance. This specialization results in these two cell classes possessing many different functional characteristics, imposing trade-offs that limit the kinds of visual capabilities each cell class may provide.[8,9] One class is specialized for bright or daytime vision, while the other class is specialized for dim or night vision. These are referred to as cones and rods, respectively, names based on the typical anatomical shape of these two cell types. The cones utilize the brighter light to provide detail, color, and processing speed. On the other hand, the rods sacrifice everything to be able to detect shapes in the dimmest of light. These two cell classes are so different functionally that it is not unusual to encounter descriptions of the retina as being made of up two subretinas, one specialized for day vision and one specialized for night vision. These two “colocated retinas” theoretically function completely independently, separated solely by the light levels that activate them. The differences in the quality of vision between day and night come directly from these two different retinal systems. Thus, during the day, normal vision is characterized by color, precise visual discriminations, high resolution, and the ability to read text. Night vision is characterized by shades of gray, colorlessness, and flat grainy images with poor resolution.[8,9] The real challenge is that the transition from day to night vision takes an appreciable period of time, a challenge that Fig. 1 helps to illustrate. The basic problem is that prior exposure to light within the previous 15 to 20 min makes it harder to immediately see clearly in the dark.[3] The varied duration and intensity of preadapting light will affect the dark-adaptation curve in a number of areas. With increasing levels of preadapting illumination, the cone branch becomes longer, while the rod branch is active much later and appears relatively shorter. At low levels of preadapting illumination, rod sensitivity quickly reaches its absolute threshold.[10] The shorter the preadapting duration and the weaker the illumination of the preadapting light,

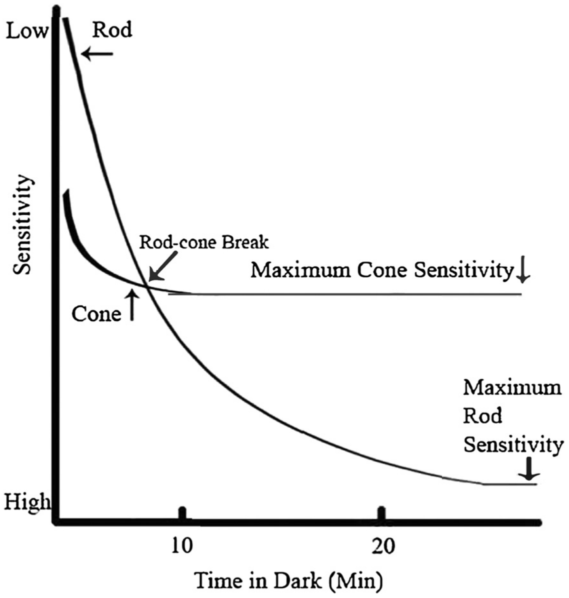

Fig. 1 The time course of dark adaptation. Dark-adaptation's time course is illustrated, following exposure to a preadaption light, whose luminance is identified as the "adapting intensity." The abscissa is time in the dark following preadaptation exposure; the ordinate is the threshold luminance of a violet test flash. Reprinted from Psychophysical Measurement of Visual Function, Norton et al., Adaptation to Light and Dark.[3,11]

the less dark-adaptation time required. For extremely short preadaptation periods, only a single rod curve is obtained. It is only after longer and brighter preadaptation that biphasic cone and rod branches are obtained. This biphasic range from brightest sensitivity to the dimmest sensitivity covers ∼14 orders of magnitude, numerically from 1 to 100,000,000,000,000 (or 1.00×10^{14}). The importance of the light level before dark adaptation (the preadaptation light exposure) and the characteristics and contribution of the different types of photoreceptors characterize the typical dark-adaptation curve as shown in Fig. 1.[3,11]

1.3 *Dark-Adaptation Variability*

In Fig. 2, the x axis indicates the dark-adaptation process in seconds, while the y axis plots the $\log_{10}$ retinal illuminance, with the faintest point noting subject detection of a 2-deg test light at 0.002 foot-Lamberts (fL). The dark-adaptation curve analyses of the two separate 24 subject runs indicate the presence of a clear between-subjects variability in their dark-adaptation time requirement. Figure 2 shows the dark-adaptation runs for each of the 24 subjects under the test control (i.e., a no-lens condition). These dark-adaptational between-subject differences emerge primarily through anatomically associated retinal influences (e.g., rod and cone physical spread, convergence of photoreceptor signaling, and postreceptoral retinal mechanisms). Previously demonstrated individual variation in visual resolution emerges via combined cortically and anatomically associated relationships that occur much higher within the visual processing hierarchy.[12] The individual influences on dark-adaptation performance variance are centered solely at the retina.[7] Furthermore, regardless of individual variation, dark-adaptation responses were generally unchanged, when retested under the clear lens condition, as noted in the upper chart within Fig. 2.

1.4 *Pertinent Facts Associated with Dark Sensitivity Recovery*

The above discussion of dark adaptation (Figs. 1 and 2) helps define some of the considerations and limitations for facilitating the warfighter's transition from an outdoor daylight to a poorly lit interior or even dark environment. The following five facts suggest that one of the best ways to facilitate the transition from the light to the dark environment is to control the ambient lighting conditions prior to entering the dark environment.

1. The rate of early dark adaptation (the first two log units) strongly slows nonlinearly, with brighter preadapting light levels.
2. A brighter preadapting environment requires more time to recover visual sensitivity. This is evident in Fig. 1, which shows it may take well over 10 min before rods become more sensitive than cones.
3. Cone sensitivity can return far more quickly than rod function, for moderate levels of light exposures.
4. Maximum rod sensitivity can take well over 20 min to return.
5. The transition between rod and cone vision is rather continuous and there is a region in which both types of vision seem to be operative simultaneously. This region of simultaneous photoreceptor function is where research seeking to maximize visual performance within degraded visual environments (DVE) needs to be concentrated. The quality of the vision provided by the cones and rods is another consideration. This visual field performance test involved the ability to detect shades of darkness against the illuminated background. The kind of vision that the rods provide is extremely limited and of very poor quality, hardly worth the perceptual delay, if the cones can get going quickly, which is all the more reason for controlling the lighting conditions during the period of preadaptation. Effective combat vision variously requires the application of detection, recognition, and identification functions across the battlefield. Mere detection tasks or even some recognition functions require only rods providing just enough information to aim a rifle. Identifying friendly civilians or specific enemy threats requires cones. In conditions so dark that cones do not function, night vision devices are a more effective strategy, although these are vulnerable to electromagnetic pulse disruption. This is the reason why individual sensitivity to dim stimuli is a key lethality issue, which is well worth developing a complete understanding of the physiological processes involved.

1.5 *Luminance Levels*

The region of Table 1 between the cone sensitivity threshold and the rod saturation point is the region ideally open to adaptational human visual performance research regarding military operations and activities under DVE conditions.

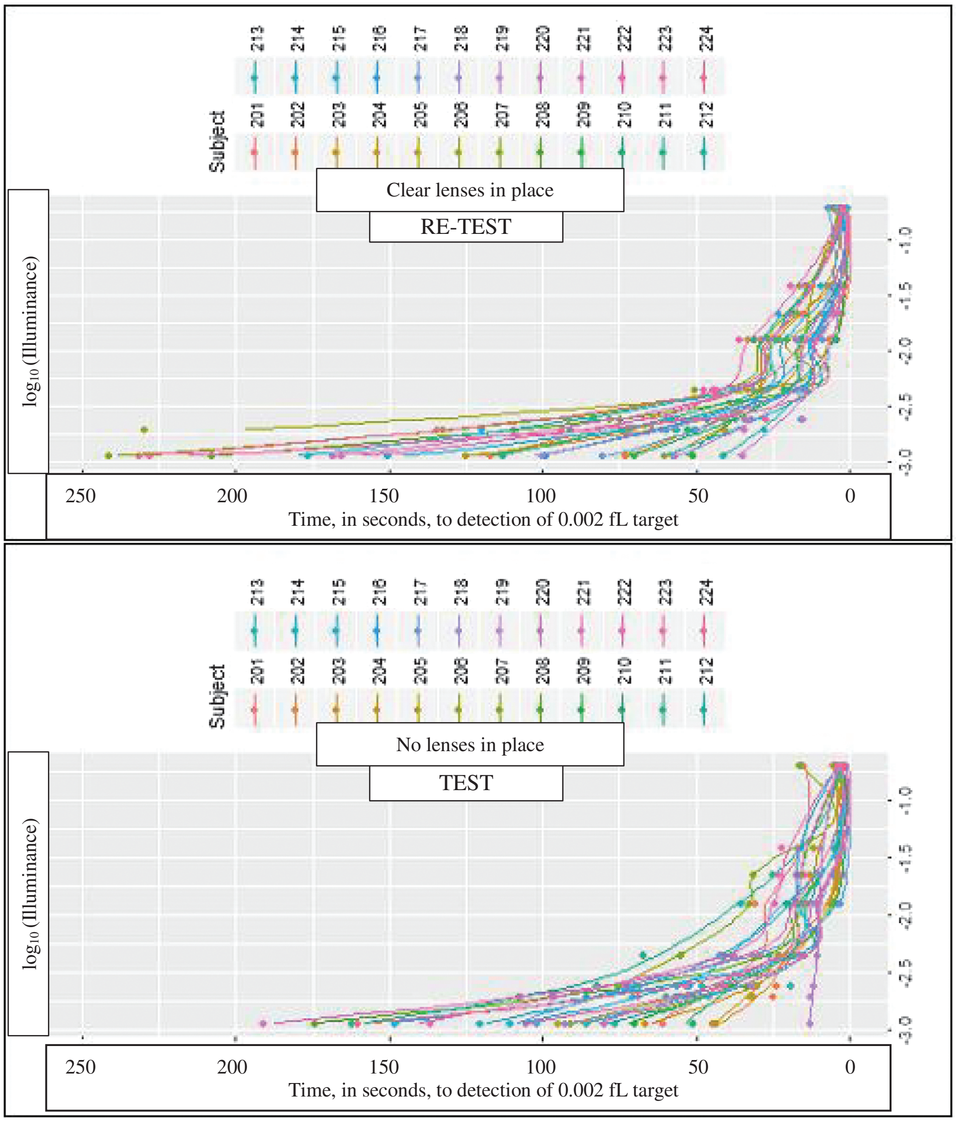

Fig. 2 Individual dark-adaptation variability. The disparate individual response curves demonstrate a measurable time difference in the visual sensitivity response; while the subject responses are categorically similar, there is a clear individual variability in amount of time needed to become fully dark adapted, ranging from 12 to 190 s.

Table 1 Summarizing luminance, retinal illuminance, and visual function.[11] The highlighted bold area represents the range of mesopic conditions, which enables both rods and cones to function in an inversely concurrent manner.

Luminance (log cd/m^2)	Pupil diameter (mm)	Retinal illuminance (log trolands)	Luminance of a white sheet of paper	Visual functions	
−6	7.1	−4.4	—	Scotopic	Absolute threshold
−4	6.6	−2.5	—		No color vision
−2	**5.5**	**−0.62**	**Starlight**	**Mesopic**	**Cone threshold**
0	**4**	**1.1**	**Moonlight**		
2	**2.4**	**2.6**	**Indoor lighting**		**Rod saturation**
4	2	4.5	Sunlight	Photopic	Best acuity and good color vision

Table 1 relates 0 log trolands to be roughly equivalent to moonlight, which is in the middle of the range of light exposures open to cone visual functioning. Normal indoor lighting is identified as about 2.6 log trolands, sufficient light to provide normal supra-threshold acuity and color vision, while saturating the rod system's ability to respond establishing functional rod incapacitation. One solution to the problem of facilitating the rapid transition from a light to a dark environment is to limit or control the amount of light falling on the retina before entering into the darkened space. One of the standard techniques for this in the past has been the use of sunglasses.

1.6 *Sunglasses and Other Optical Filters*

Dain[13] credits James Ayscough with the use of specially tinted lenses, designed specifically to protect against sun glare, advertising for spectacles with tinted lenses and double-hinged sides in 1752. By 1912, the American Optical Company listed several tinted lenses, some for use with automobile goggles; but none of these were referred to as "sunglasses." By the 1920s, tinted lenses had become an over-the-counter product and the ophthalmic profession did not become involved with the topic of sunglasses for a number of years. By 1940, the Sun Glass Institute, Inc. initiated the first of the Commercial Standards for Sunglasses in coordination with the National Bureau of Standards. This had been initiated in response to a suddenly large increase in commercial market sunglass sales, which had spurred a further rush of products, most of very poor quality.[14] By 1948, pioneering works on recommendations for military sunglass design were published.[15,16] Synthesizing a variety of sources of information, Dean Farnsworth recommended sunglasses for military purposes with a percent transmittance (%T) from 10% to 16%. A lower transmittance (3%) was suggested for work in snow fields, but 8% transmittance is the minimum sunglass correction allowed by several nations for driving.

1.7 *Transmission and Optical Density*

Sunglasses are designed to absorb a defined percentage of light that is incident on the sunglass and to transmit the remainder. Thus, sunglasses are often described in terms of the percent transmittance (%T). They commonly are also described in terms of their OD, which is the log of the reciprocal of the fraction of transmittance. These relationships are shown in Fig. 3 for common %T and OD. One of the advantages of converting %T to OD is that OD simplifies the interpretation of Farnsworth's recommendation for 10% to 16% transmittance, which from Fig. 3 show these two levels of transmittance have an OD of 1.0 and 0.8, respectively.[14–16] These ODs can be interpreted easily by referring to Table 1 when attempting to relate sunglass-based exposures to retinal light exposure, because both OD and retinal exposures are established on logarithmic scales. It may be noted, for comparison purposes, that consumers generally purchase sunglasses with much higher %T than recommended for military use, often in the neighborhood of 30% to 50% transmittance, which, in terms of the above discussion, suggests that these sunglasses would have minimal effects on the dark-adaptation function and the recovery of visual sensitivity. One explanation for this propensity for sunglasses with such high %T is that most purchases are made indoors, where the background lighting can be as much as 4 orders of magnitude less than the outdoors.[17] From the preceding discussion, it can be concluded that the effectiveness of sunglasses for preserving visual sensitivity, thereby facilitating the transition from a bright to a dim environment, depends critically on the luminance levels involved. They may have little if any effect in bright environments but may be more effective in dimmer environments. It can be noted that the 10%T to 16%T recommended by Farnsworth, which produced an attenuation of from 0.8 to 1.0 log units, includes the currently authorized military sunglasses, which have a 15%T (although currently supplied military sunglasses possess 21%T). Most importantly, when warfighters go from outdoors to a dark interior, they currently must remove their military combat eye protection system; otherwise, the tinted lenses simply hamper the process of visual dark adaptation.

1.8 *Sunglasses and Glare*

For military as well as for civilian purposes, sunglasses are more commonly thought of as reducing or controlling the

Optical Density (OD value)	Transmittance	Attenuation Rate	Protective Function
0	100%	0	Weak
1	10%	1/10	
2	1%	1/100	
3	0.1%	1/1000	
4	0.01%	1/10000	
5	0.001%	1/100000	
6	0.0001%	1/1000000	
7	0.00001%	1/10000000	
8	0.000001%	1/100000000	
9	0.0000001%	1/1000000000	
10	0.00000001%	1/10000000000	High

Fig. 3 OD, transmittance, and protective factor. The table demonstrates the inverse functional relationship between OD and percent transmittance.

magnitude of glare, or protecting the eye from bright or annoying lights rather than facilitating the transition from a light to a dark environment. This begs some clarification about the nature of glare. Studies of glare have found it useful to distinguish among three types of glare: disability, reflected, and discomfort.[18] Disability glare refers to scattered light, either outside the eye or in the eye that reduces the image contrast of the object regarded or seen. Thus, light can be scattered by particles in the atmosphere itself, as well as on the optical surfaces of spectacle lenses, goggles, windshields, or windscreens, including sunglasses. Intraocular light scatter can be due to any or all of the optical components of the eye itself, ranging from the cornea to the lens, and the aqueous and vitreous, as well as from the different layers of the retina. In general, tinted filters, such as sunglasses, cannot really control such disability glare because they reduce the overall amount of light. A filter operates equally on the scattered and the imaged light. The second type of glare comes from the specular reflection off shiny surfaces, e.g., metals, glossy papers, water surfaces, anything whose surface can glint with reflected light. These are frequently horizontal surfaces, which may impart some polarization to the reflected light so that polarized sunglasses may help reduce the reflected glare, particularly if metallic surfaces are involved. The third type of glare is discomfort glare, the sensation of pain or discomfort from bright lights. As a subjective category, any mitigation of discomfort by sunglasses will be strictly presumptive in nature, varying from person to person.

2 Research Design

2.1 *Organization of the Study*

The study was commissioned by the U.S. Army Program Executive Office for Soldier Systems (PEO-Soldier), with the sole purpose of seeking a determination of the optimal method (within the reach of current technological limitations) to permit soldiers to transition from one level of luminance to another, with a minimum of distracting glare or blur. This was a standard, within subject, repeated-measures, experimental design with a control, plus four different independent variables or optical filters for wear when transitioning from a bright to a dim lighting condition [control condition (CC), clear protective lenses (CL), sunglass protective lenses (SL), SF, and EO lens]. Each subject was exposed to a CC, plus all four levels of the independent variable.

The study assessed the impact on vision of the following four filter approaches/technologies for accelerating the effective transition from a light to a dark environment.

1. A CC, in which no corrective lens or filter is used, to serve as the basic performance level against which all other filter conditions were assessed.
2. CL, in which one of the MCEP included in the APEL were worn with its clear lenses in place.
3. SL, i.e., with a standard 15%T, in which the same MCEP selected for the CL condition, were worn with the SL condition.
4. An SF or gradient lens, in which the lens OD that will be worn is not constant (as in the SL condition) but an abrupt step function such that the top half of the sunglass or filter has an OD as close as possible to 1.0, while the bottom half of the sunglass or filter has an OD of 0.0. The SF condition also used an MCEP but was fitted with the custom-made SF bigradient lenses outlined previously.
5. A newly available EO lens of proprietary nature was also tested at the request of PEO-Soldier Systems. The optical transmittance of the lenses could be changed at the push of a button, which was mounted on one of the spectacle temples or side pieces. The production source of the EO lenses was not evidenced or visibly provided. The power source was a very small battery. Otherwise, no technical or operational details were provided.

There were four segments to the study, which evaluated the effect of these four different protective spectacle lens designs (in Fig. 4). The CC was without any lenses, followed by CL, SL, SF, and EO lenses. This control and these four experimental conditions determine their effect on a representative soldier's ability to rapidly transition from bright to dim environments. This report constitutes our specified investigation, as requested by the PEO-Soldier regarding the effect of a no-lens control and four different protective spectacle lens designs (CL, SL, SF, and EO lenses) on a soldier's ability to rapidly transition from bright to dim environments. Since these protective lenses will be worn in-theatre at all times, their effect on the visual performance of the volunteer subjects was evaluated in both bright and dim environments.

The dependent measures were selected to specifically permit the findings to be evaluated in both clinical and operational terms. The responses through five different conditions were measured: (1) no-eyewear control, (2) APEL clear

Fig. 4 Eyewear used in the study. At the top is the EO lens, mid-right is the SF lens, mid-left is the standard sunglass, and the bottom is the clear lens. The spectacles in the lower half of the figure are the Transition Combat Eye Protection system lenses, a developmental, proprietary initiative of PEO-Soldier. The protective eyewear provides ballistic fragmentation protection as well as UV protection. The lenses can adjust to varying light conditions with a 1-s response time.

eyewear, (3) APEL sun eyewear, (4) APEL SF eyewear, and (5) EO eyewear. For each spectacle condition, visual acuity and precision marksmanship were measured under bright conditions (50.7 fL). Following the precision marksmanship task, each subject was light adapted for 4 min by viewing a brightly illuminated white board (378 fL). Subsequent to light adaptation, the flood lights were turned off, creating a condition of dim illumination. The adaptation time to identify objects [heads (2.57×10^{-3} fL), torsos (19.1×10^{-4} to 0.73×10^{-4} fL), and rifles (1.03×10^{-4} fL)] and lights (from 0.199 to 0.0005 fL) was recorded. Subjects ranked their preferences for the control and the four types of eyewear in terms of overall practical utility. The reverse process of adapting to a sudden brightly lit environment occurs in mere moments, resulting from the pupillary light reflex and the cone's ability to overcome the sudden glare by almost instantly adapting to the brighter condition.

2.2 *Study Participants*

All 24 volunteer subjects signed an informed consent, with the protocol having been approved by the laboratory, in-house Scientific Review Committee, administratively processed by the in-house Research Compliance Office, the Laboratory Commander, and the Medical Research and Materiel Command Institutional Review Board. The target population of our study sample consisted of volunteer warfighters of either available gender who would be required to function in-theatre. Study volunteers were from the population of active duty Army personnel in the local area that are above the age of consent in Alabama (19 years) and less than 41 (above the age of 40, rates of dark adaptation may be adversely affected by aging processes). This age range reflected the major aspect of the operational population, in which we were most interested. Civilians that met Army personnel vision standards were also selectively permitted to participate. Exclusion criteria were exclusively based on the volunteer's vision, in that a volunteer must have a best-corrected visual acuity of at least 20/25 in the eye used for sighting a rifle, a conditional requirement of the funding agency.

2.3 *Objective and Type of Study*

The objectives of this research were to identify, evaluate, quantify, and refine procedures that improved the ability of our military personnel to efficiently and rapidly transition from light to dark environments and then to function effectively. The specific aims of the project were to identify the strengths and weaknesses of the most promising candidate procedures, strategies, and technologies that have the potential for facilitating the transition from light to dark environments. There were several underlying principles supporting this study:

1. There exist techniques, technologies, and procedures that facilitate the transient from light to dark.
2. Some of these techniques are more effective than other techniques.
3. These techniques all have liabilities in that they can unintentionally degrade visual performance.

The characterization of these methods and their interaction with the experimental lenses can lead to technological improvements, as well as recommendations on policies, procedures, and biomedically based, empirically validated standards. The base hypothesis was that one of the lens-based dark-adaptation conditions was visually superior to all the others.

2.4 *Human Performance Measurements*

The human subjects evaluated the effects of these optical devices on their visual performance. These human performance measurements were grouped as follows: (1) clinical measurements under bright lighting conditions, (2) operational performance measurements under bright lighting conditions, (3) clinical measurements of dark adaptation, and (4) operational performance measurements transitioning from light to dark conditions.

2.4.1 *Clinical measurements in bright lighting conditions*

These measurements assessed best-corrected visual acuity using standard clinical optometric procedures, whereby the subjects were seated behind a phoropter in a 20 foot-long eye lane, with standard luminance levels, typically between 1 and 10 $\mathrm{cd/m^2}$. These measurements were obtained using objective practitioner retinoscopy, followed by subjective lens choice preferences, basically a forced-choice patterning, measuring refractive error, and visual acuity (Fig. 5).

2.4.2 *Operational performance measurements*

The specific criterion for operational performance was precision marksmanship (Fig. 6), measured with Olympic competition-quality air rifles. Safety procedures for air rifles established by Army JROTC for their high school marksmanship program were followed at all times. The primary investigator successfully completed the JROTC Marksmanship Instructor Course. These air rifles have been calibrated to levels of repeat reliability and precision

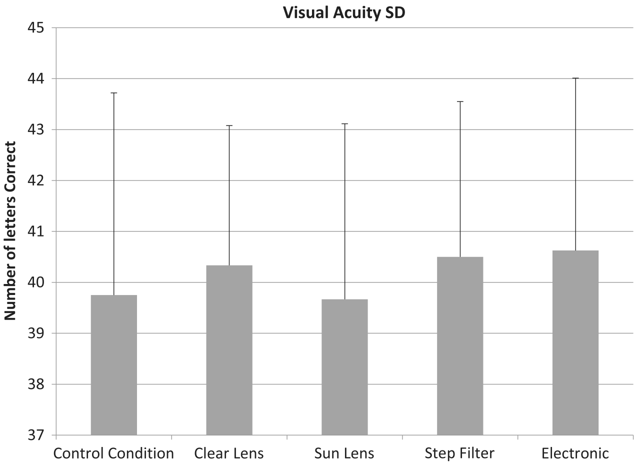

Fig. 5 Mean acuity function via letter-counting. The combined data are labelled in number of letters correctly identified, which can be converted to logMAR acuity under each viewing condition, with the error bars displaying the standard error of the mean (SEM). A longer or higher bar indicates better visual resolution.

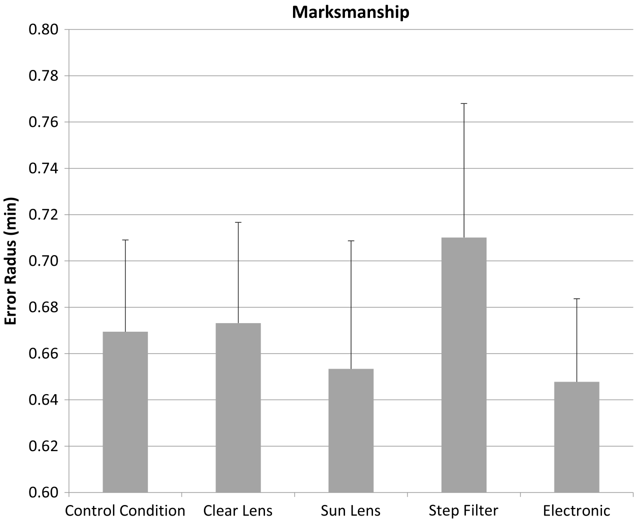

Fig. 6 Individual marksmanship performance. The combined marksmanship data results for each lens/filter condition, scored by error radius. The error bars display the SEM.

that exceeds the optical limits of the human eye. Thus, the performance limit of the task should be the optical resolution capabilities of the human eye rather than the measurement device.[19–21] The human eye's angular resolution limit is 1 arc min, or 20/20 acuity; the rifles are manufactured to such precision that they are capable of shooting a series of pellets into a tight pattern of <1 arc min. The marksmanship scoring was based on an angular optical measurement, meaning the error is based on seconds of arc, not merely a vertical or a horizontal offset from the bull's eye, but an angular, radius-based error. The rifles were mounted into a rigid test fixture and the subject adjusted sight alignment via control knobs on the fixture, thus insuring the results are due to visual factors, with occasional results adversely affected by optical aberrations. Additional tests could have been conducted, where the rifle is fired from either a supported (sandbag) or nonsupported (off hand/standing) position, if the need arose. The measurements were made with lighting conditions comparable to those used in the optometric eye lane, that is, between 1 and 10 $\mathrm{cd/m^2}$. These marksmanship measurements were made with all four filter types (plus the control), to assess the impact of these devices on a critically important operational task that can be degraded by imperfections in the optical elements.

2.4.3 *Light to dark adaptation—clinical measurements*

Adapting from light to dark began by exposing subjects to a bright preadapting field (50.7 fL) for 4-min viewing of a white board of 378 fL to reduce their photoreceptor sensitivity. In our study, the brightness of the preadapting field simulated normal daylight conditions. The preadapting field was turned off, with the room illumination reduced so that the subjects were immediately transitioned into a dark environment. Their task was to report, at different times during the dark-adaptational period, how many of the dark adaptometer lights were visible. The dark adaptometer used in this study was a purpose-built instrument, whose design was modeled on classic procedures of measuring dark adaptation so that the results obtained with it were comparable to results using standard clinical instrumentation.[22] The 10 lights on the adaptometer varied in brightness by a total of 3.3 log units, decreasing in brightness by 1/3 of a log unit from one light to the next. The brightest was immediately visible at the start of the test period and the dimmest (set at the light level that marks the transition from cone to rod vision, or about 4.5 log trolands) was set to just be visible at the end of the darkened period. The control box allowed any combination of the lights to be on at any given time. As the volunteers dark adapted, they could sequentially detect dimmer and dimmer lights. The dark-adaptation measurement (Fig. 7) was done in conjunction with the operational task, as described in Sec. 2.4.4.

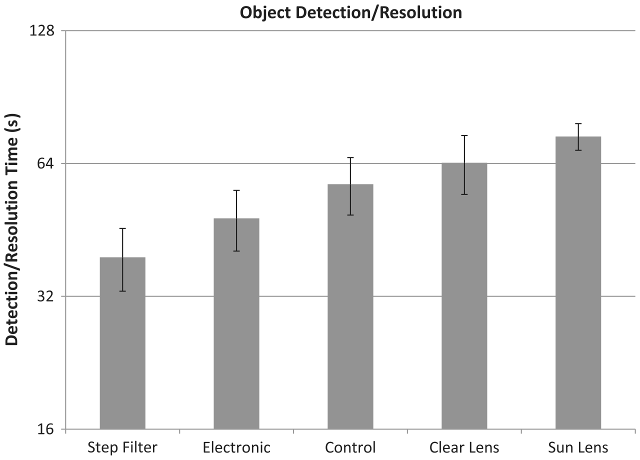

Fig. 7 Dark-adaptation time required to detect specific stimuli. Continuous variable plot of dark adaptation based on length of time required to detect a certain numeric light configuration. The error bars display the SEM.

2.4.4 *Operational performance*

Measurements transitioning from light to dark conditions also began with the subjects being exposed to a bright preadapting field for the same defined time constant (as noted in Sec. 2.4.3), to once again reduce their photoreceptor sensitivity. In this study, the brightness of the preadapting field also simulated normal daylight conditions. Then the bright preadapting field was turned off and the room illumination reduced so that the subjects were immediately transitioned into a dark environment. The task of the subject was to identify, as soon as possible, objects that had been placed on the floor in the dark room. These objects possessed defined visual characteristics of size, shape, and contrast. The subject's task was to detect object presence and then verbalize the localization of as many objects as soon as possible (Fig. 8). Second, subjects were to verbalize when object recognition and then identification was determined. Thus, scored responses (times of correct detection, recognition, and identification of each of the objects) were all measured per trial. The dependent variable was the length of time required for the subject to correctly locate and identify each of the eight objects distributed around the dark room.

2.4.5 *Mechanics of marksmanship task*

It should be emphasized that every subject was tested individually. Furthermore, for the duration of this part of the

Fig. 8 Adaptation time as a function of luminance. Dark-adaptation/object detection task of the grouped lens/filter data. Error bars represent the SEM. Time in the dark before object detection is possible.

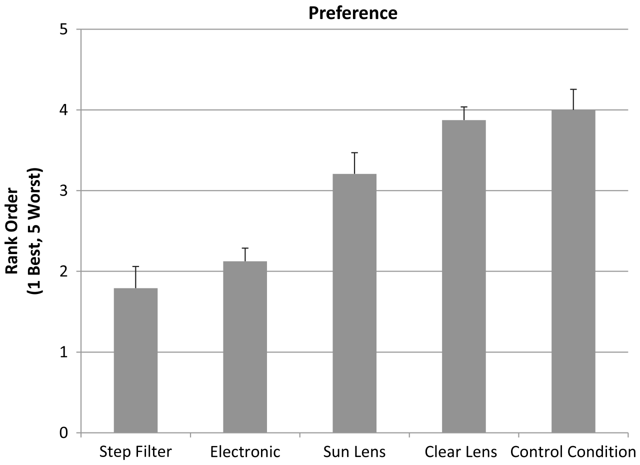

Fig. 9 Personal preference. The bar chart illustration of the combined preferential rankings by filter type, including the CC, can be seen on the left; the shorter bars represent the preferred means of facilitating bright to dim transitions. Error bars represent the SEM.

experiment, the subjects remained seated, to minimize the possibility of tripping or stumbling in the dark. Olympic grade, single shot pellet air rifles, combined with a computer-based scoring system, were used in the marksmanship section.[19,20] The scoring system reports each shot's score (to a 1/10th point), as well as *xy* position (to a 1/100th mm). The sights used in the study simulate typical M-16 iron sights, which uses the smaller long-distance rear aperture of the A2 sight system. A purpose-built, gimbaled rifle-mount table utilized the gimbaled vise aspect to rigidly secure the rifle. Yet, the shooter was able to adjust the rifle's alignment both laterally and vertically. The shooter's task is to aim the rifle vertically via one set screw for elevation, and laterally for windage compensation adjustment, and then fire the rifle. A just noticeable difference in sight alignment is produced by rotating either of the set screw adjustment knobs one third of a revolution. To reduce mechanical cues, the ambidextrous set screw control knobs are round and their action has intentional hysteresis. An orange Clear Bore Indicator cord was inserted into and through the barrel, emerging from the open chamber, as indication that the rifle was cleared and unloaded.

3 Results

3.1 *Visual Acuity Assessment*

Visual acuity was not significantly affected by any of the lens designs. Interestingly, in this brightly lit testing environment, the EO and the SF condition resulted in very slightly improved visual acuity, not enough to reach either practical or statistical significance, though. Yet, there are a number of inconsistencies within the initially obtained bright illumination visual acuity results, which suggests the presence of widely varying CC acuities, which are adversely affecting the average CC's visual response. For example, the pupil size was not controlled for when varied filters were worn, which is a classically identified factor potentially affecting the visual acuity results. The average marksmanship scores for the 24 subjects were scored by means of documenting error radius in arc sec. Interestingly, the SF marksmanship scoring was somewhat worse than all other conditions suggestive of difficulty in controlling the viewing condition. The sun and the EO lenses displayed slightly better marksmanship scoring as in Fig. 6, where a shorter bar on this graph represents a tighter error radius or better marksmanship performance.

3.2 *Determination of Performance Profiles*

Qualitatively, dark-adaptation responsiveness was most effective while using the SF design, followed by the electro-optic lens condition; the slowest dark-adaptation process occurred while using the sunglass or tinted filter design. Object detection/resolution processes ensued throughout the dark-adaptational period. The research subjects consistently noted that the ACU-wearing cutout had required the greatest length of time to detect and to identify under all of the various lens/filter conditions. Every object viewed was detected quickest by the SF design condition, followed closely by the electro-optic lens design. Lastly, a subjective preference task was installed in the protocol, resulting in the most consistent analytical assessment of all the conditions imposed on this investigation. The SF scored as the most preferred option but that was not consistently expressed to the point of statistical significance. The EO means of facilitating dark adaptation was a close subjective second. Subjects were asked to rate the ease of their light to dark transition for each of the experimental conditions (scoring 1 for best, and 2 to 5 for sequentially poorer performance). The preference ratings (Fig. 9) revealed that the SF and the electro-optic eyewear were preferred over the no-eyewear control, APEL clear eyewear, and APEL sun eyewear. Essentially, no significant difference in preference was found between the SF- and the electronic-eyewear conditions. However, the step-wise filter did hold a 0.5 point preferential scoring advantage over the EO system.

4 Discussion

All the obtained data could be categorized as continuous, parametric in nature, except for the last application, which obtained subjective, nonparametric data. A globally applied, full-scope multivariate analysis of variance (ANOVA) was performed in determining the systematic presence of any statistically significant performance differences within the complex variable matrix.[21,23] The multivariate ANOVA resulted in a determination of interactive significance across all dependent variables.[24] This, in turn, further prompted the performance of secondary, posthoc testing to independently assess the effects of the five independent variables (i.e., the five viewing conditions/lenses/filters) on each of the four research segment results.

4.1 *Acuity and Marksmanship as a Combined Function*

While an observational assessment of visual acuity and marksmanship performance results did not initially appear to possess any significant interactions across the five viewing conditions, an applied ANOVA using the restricted subjects from the acuity test yielded statistically significant interactive effects of both performance categories ($p < 0.0001$). Further assessment of the five best and five worst visual acuity performers revealed statistically significant interactive effects of visual acuity with marksmanship performance ($p < 0.0001$), as well as displaying a high degree of covariance, which makes sense in that the intended marksmanship ability was designed to document the presence or absence of ocular aberrations. The five individuals with the lowest visual acuity combined to provide the poorest marksmanship scores.

4.2 *Objective Dark-Adaptation Progression*

The objective portion of the dark-adaptation study, when an adaptometer was utilized to measure the documented time required to correctly identify the number of test lights presented at specific times and at specific illumination strengths, served as a comparative index for when subjects were tasked with identifying specific test objects, while undergoing dark adaptation. By inferential analysis, the dark-adaptation profiles obtained on the adaptometer's test-light identification task closely matched those profiles established in the dark-adaptation test-object-identification task, in agreement with the findings of Christoforidis and Zhang.[25] A recently published study has demonstrated a direct dark-adaptation performance difference related to macular pigmentation density, which could have been manifested as a performance difference within our data.[26] Subject-specific analyses could provide insight toward defining specific visual performance variation sources that occurred across our subject pool.[26] The PEO-Soldier task involved investigator identification of the viewing lens/filter which had been the most successful in facilitating a soldier's entrance into a dark room from a brightly lit environment. After undergoing an exhaustive analytical series of objective and subjective assessments, it was clear that of the existing technologies assessed within this protocol, there were two means of facilitating efficient transition from a bright to a dim environment. The first of the two identified means of dark-adaptation facilitation was the step/filter or gradient design, which depended on subject mastery of head position alteration, to effectively control levels of retinal light exposure. The second most effective means of facilitating adaptation in transition from a bright environment to a dark environment was utilization of the EO lens option, which applied facilitated variation to lens transmittance levels (i.e., increasing transmittance when entering a dark room, after maintaining decreased transmittance while outside in bright illumination).

5 Conclusion

Both these lens/filter methods (SF versus EO filter) were always very near optimal visual performance levels across every aspect of this research effort. Therefore, the hypothesis of one method being superior to all others was rejected (i.e., $p > 0.35$). Consequently, the technology fielding decision was reduced to selecting one of the two preferred viewing conditions over the other, based on other decision factors beyond those posed by this research effort. The two leading performance options were statistically better than the remaining three options. Visual acuity and marksmanship results did not appear on casual inspection to significantly identify any one of the five conditions; the sun and EO lenses resulted in approximately equivalent marksmanship performance at 0.65 arc min (or 39 arc sec). Similarly, logMAR visual acuity resulted in close performances by the EO lenses and the SF lenses, closely followed by the clear lens condition. Again, with no statistically clear leader, the subjective preference ratings indicated preferences for both the SF and the EO eyewear over all other conditions. No statistical difference in subjective preference was found between the SF and the EO eyewear. Operational performance results while wearing either of these two optical devices (the SF eyewear and the EO eyewear) were equally effective. If the technology fielding decision is governed by the standard acquisition matrix of cost-schedule-and-performance, then the less expensive option, with fewer secondary fielding issues (e.g., no battery requirement, no added weight, etc.) would seemingly be preferable. Therefore, the SF or gradient lens system is the suggested means of optimally facilitating dark adaptation at present. Future technological developments beyond the level of the proprietary electro-optics used in this study could alter the decision factors in another direction, reinforcing the need to continuously monitor the technologies that potentially could become available. Given the continued doubling of complexity of technology every 18 to 36 months means there is a likely improved electro-optics system now available.

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Morris R. Lattimore has both clinical and research doctoral degrees. He has worked within the U.S. Army’s medical healthcare and medical research communities for over 42 years. His service has been divided into three categories of assignment: tables of distribution and allowances health care, TO&E healthcare operations, and applied medical research. His primary research area of interest is corneal physiology and biochemistry. His recent publications are oriented toward native visual capabilities and individual variation in absolute visual sensitivity.

James Q. Truong has both clinical (OD) and research (PhD) doctoral degrees. He has served within the U.S. Army’s medical and research communities for over 20 years, during which time he has participated in a variety of operations including RSOI, Cobra Gold, Beyond the Horizon, and Operation Iraqi Freedom. He is a vision scientist with research emphasis on the visual aspects of mTBI, ocular protection, and visual performance.