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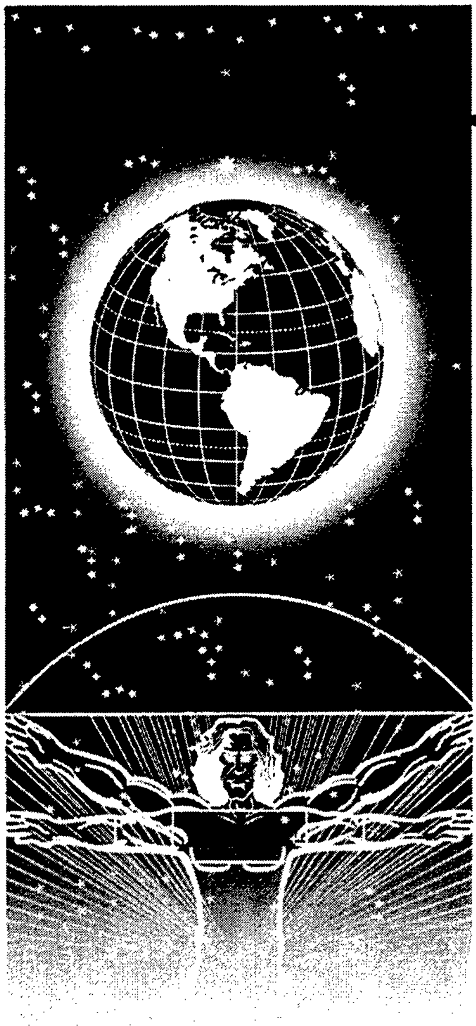

UNITED STATES AIR FORCE
RESEARCH LABORATORY

THE EFFECT OF EYEPIECE FOCUS ON VISUAL ACUITY THROUGH ANVIS NIGHT VISION GOGGLES DURING SHORT- AND LONG-TERM WEAR

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FINAL REPORT FOR THE PERIOD JULY 1996 TO AUGUST 2000

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

MARIS M. VIKMANIS
Chief, Crew System Interface Division
Air Force Research Laboratory

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13. ABSTRACT *(Maximum 200 words)*

The eyepiece lenses of ANVIS night vision goggle are ostensibly adjusted for optimum visual acuity (VA). Many users however do not adjust the eyepieces competently. This paper examines whether a single-focus eyepiece is capable of producing satisfactory VA while maintaining comfortable vision over extended periods. In a short-term ANVIS wear study, a range of eyepiece focus produced comparable VA independent of luminance and contrast. The single best-overall eyepiece focus produced vision equal to, or better than, that of subject-adjusted eyepieces, producing VA within 2% of optimal. However, zero diopter eyepieces reduced VA by 10%. In a long-term ANVIS wear study, -1.5 diopter eyepieces caused half of the subjects to complain of blurred or uncomfortable vision. These studies indicate -0.75 diopter eyepieces provide optically-corrected ANVIS users with near optimal binocular VA and satisfactory visual comfort during extended ANVIS use.

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THE EFFECT OF EYEPIECE FOCUS ON VISUAL ACUITY THROUGH ANVIS NIGHT VISION GOGGLES DURING SHORT- AND LONG-TERM WEAR

INTRODUCTION

The AN/AVS-6 Aviator Night Vision Imaging System (ANVIS) is a helmet-mounted binocular night vision goggle used by military aviators. ANVIS is similar to unity magnification binoculars in that it has two parallel eye tubes to view through (Figure 1). Each eye tube has three rudimentary parts: objective lens, image intensifier tube, and eyepiece lens. The objective lens collects and focuses light on the image intensifier tube. The image intensifier tube amplifies and transduces near-infrared light into visible light. The eyepiece acts as a simple magnifier to view the image produced by the image intensifier tube.

The objective and eyepiece lenses are focused monocularly. These lenses are independent of each other in that one cannot compensate for blur caused by the other. The objective lens focuses ANVIS to different distances, changing image clarity without changing the stimulus to visual accommodation. The eyepiece lens determines the optical distance of the image seen by the eye, and thereby regulates the accommodative stimulus. During eyepiece focusing, the eyepiece is moved closer to, or further from, the image intensifier tube, thereby, changing the optical distance of the eyepiece image. Eyepiece focus (EF) is equal to the reciprocal of the image distance and is expressed in terms of diopters (or reciprocal meters). Negative EFs produce optical images that are closer than optical infinity. For example, an eyepiece with a –2 diopter EF (i.e., -2 diopter eyepiece) produces an optical image that is (2^{-1} =) 0.5 meters away. A zero diopter eyepiece produces an image at optical infinity. Inceptive night vision goggles required adjustable eyepieces to compensate for refractive error because their short eye relief precluded concurrent spectacle wear. Modern night vision goggles have adequate eye relief; yet, adjustable eyepieces remain in the designs of future night vision goggles.

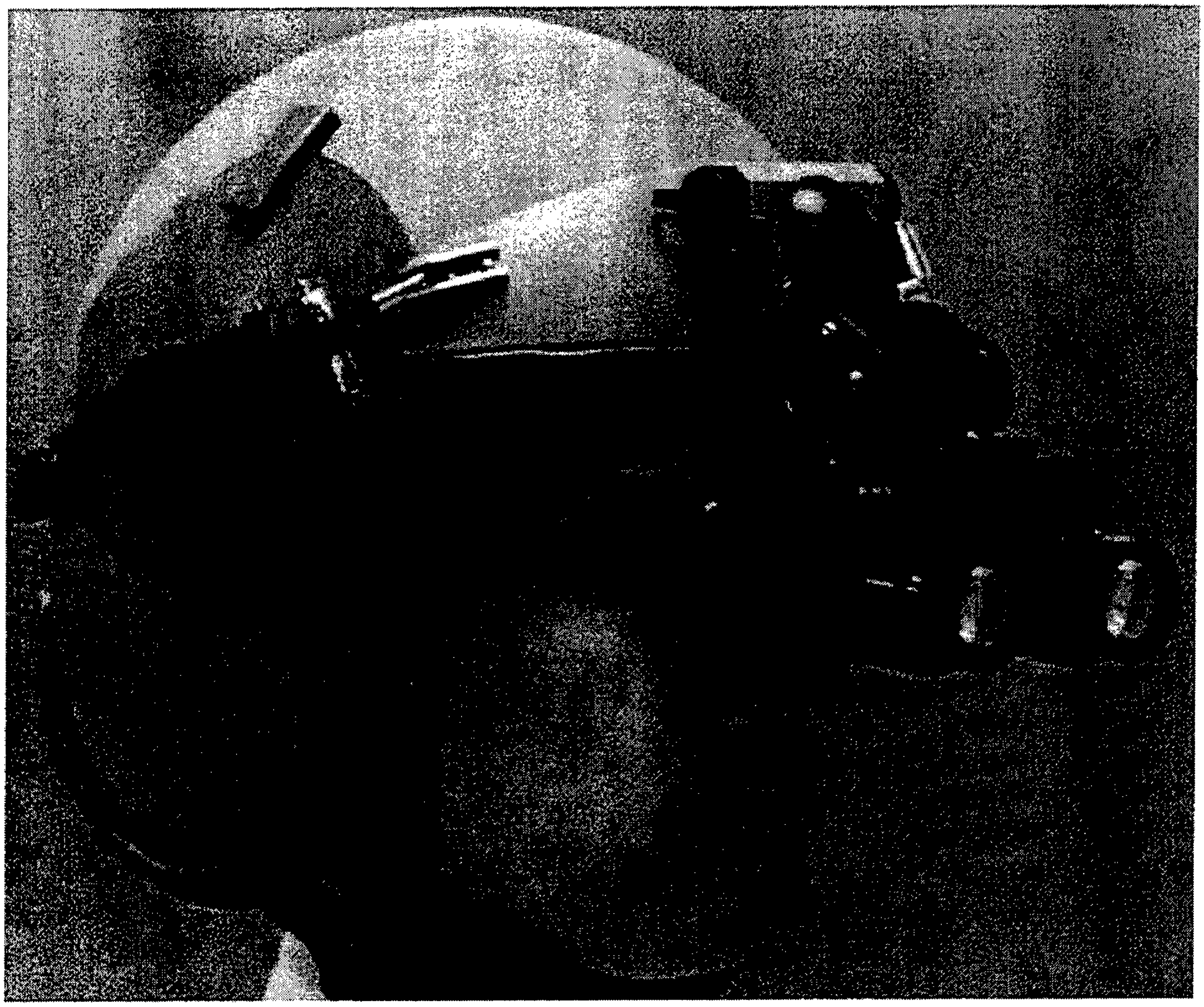


Figure 1. The Aviator's Night Vision Imaging System.

Adjustable eyepieces seem necessary for ANVIS users to "optimize" vision, and to re-focus for changing visual requirements. There is much scientific evidence (Leibowitz and Owens, 1975a,b, 1978; Hennessy, 1975; Johnson, 1976; Smith, 1983; Owens 1984) suggesting that visual accommodation is biased towards intermediate distances (0.5 to 2 meters), blurring distant objects particularly under a variety of conditions relevant to ANVIS. These conditions include instrument-viewing, low luminance, and featureless environments (Smith, 1983; Owens, 1984); the respective resulting over-accommodations are called instrument myopia, night myopia, and empty-field myopia. This accommodative bias is thought to fully manifest in the dark and is therefore often called (the eye's) "dark focus." Johnson (1976) reported that monocular vision is best for objects located near dark focus. Since dark focus is idiosyncratic (Leibowitz and Owens, 1975a, 1978), adjustable eyepieces seem necessary to satisfy all ANVIS users. Indeed, Kotulak and Morse (1994a, c) reported visual acuity (VA) through ANVIS improved 23% when the eyepieces were subject-adjusted than when set to zero diopters.

Kotulak and Morse (1994a,b) also measured eye focus while subjects viewed a distant chart unaided, and then through ANVIS with zero diopter eyepieces. Eye focus averaged 0.35 diopters for both conditions, indicating no instrument myopia occurred. However, their subjects over-focused the eyepieces (-1.13 diopters) despite the absence of instrument myopia. And, the eyepieces were not adjusted for dark focus (+0.45 diopters) either. (Note, negative EF corresponds with positive eye focus similar to how negative spectacle lenses compensate for myopic eye focus, or nearsightedness.) So, eyepiece adjustment did not depend on dark focus nor instrument myopia. This raises the possibilities that the eyepieces were not adjusted for optimum VA and consequently that single-focus eyepieces may perform as well.

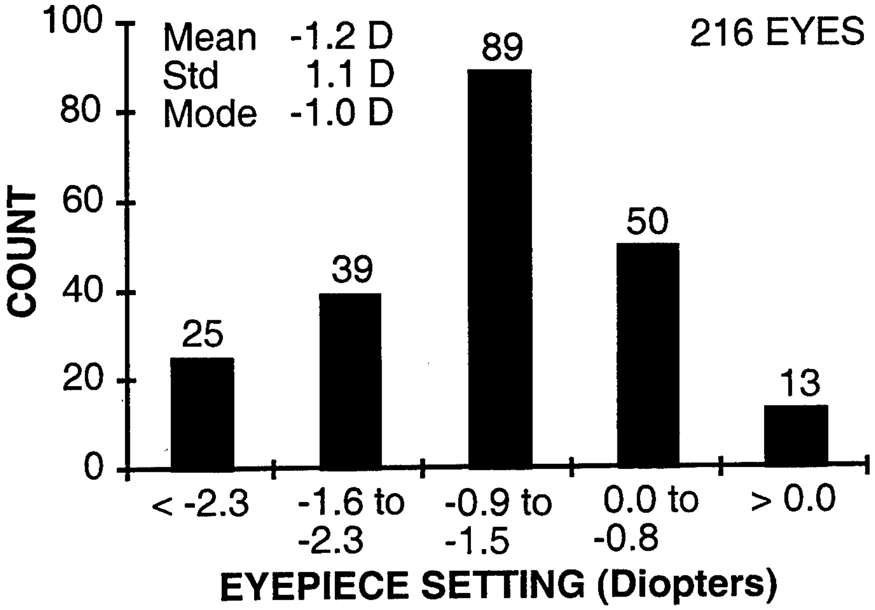
Single-focus eyepieces have distinct advantages over adjustable eyepieces. Single-focus eyepieces are simpler, lighter, and cheaper because focus mechanisms are not needed. Shorter single-focus eyepieces would reduce ANVIS's overall length, bringing the center-of-gravity closer to the head while maintaining eye relief. Adjustable eyepieces require a telecentric optical design to minimize changes in image size and brightness as the eyepiece is adjusted (Keating, 1988). Single-focus eyepieces lack this requirement and therefore can be better optimized for optical aberrations such as curvature-of-field and astigmatism. Finally, single-focus eyepieces would eliminate a precarious adjustment along with its requisite training.

An unpublished 1993 in-house survey reported that most Air Force users considered focusing to be the most frequent and difficult of all ANVIS adjustments. This result is not surprising for at least two reasons. First, ANVIS's compact fast optics makes focusing a sensitive task. The objective and eyepiece lenses (focal length = 27 mm) produce a 1.4 diopter change in EF for each millimeter of lens translation, making smooth precise changes in optical power difficult to accomplish. Also, the objective lenses (f-number = 1.2) produce tiny depths-of-field. Assuming ANVIS's resolution is limited by the image intensifier tube (i.e., 17.5 cycles per degree, or about 20/35 Snellen), ANVIS's depth-of-field is calculated to be ±0.022 diopters. So, a 35 micron translation of the objective lens can traverse ANVIS's entire depth-of-field. Such a small tolerance makes it unlikely that the objective lenses are precisely focused, making the best image seen during eyepiece adjustment less than optimum. How eyepiece adjustment interacts with objective lens-induced blur is unknown. Second, there is no anchor for accommodation during eyepiece adjustment. Eyepiece adjustment manipulates the accommodative stimulus; however, accommodation is free to respond to the changing stimulus. Covariance of the accommodative stimulus and response during eyepiece adjustment, and its impact on the final eyepiece setting, has not been studied. But, it likely results in a wide range of eyepiece settings yielding "best VA", leading to an uncertain endpoint. The focus endpoint is influenced by the starting EF and the focusing strategy employed (Schober, 1970; Wesner and Miller, 1986); this variability in endpoint suggests accommodation is active during eyepiece adjustment.

Normally, accommodative and vergence stimuli are synchronous. (Vergence eye movements shift binocular fixation to different distances by moving the eyes horizontally in opposite directions.) Our eyes must increase accommodation and converge binocular fixation for near targets, and lessen accommodation and diverge binocular fixation for distant targets. Accommodation and vergence eye movements are neurologically linked (Fincham and Walton, 1957; Hung and Semmlow, 1980; Schor and Kotulak, 1986); stimulating one stimulates the other. This synkinetic relationship increases the responsiveness of both ocular motor systems (Schor and Kotulak, 1986; Leibowitz et al., 1988; Jiang et al, 1991).

With ANVIS, accommodative and vergence stimuli are dissociated. Eyepiece adjustment changes the accommodative stimulus without changing the vergence stimulus. ANVIS eyepieces are typically adjusted when viewing monocularly; so, vergence is not stimulated. Monocular eyepiece adjustment results in a more minus endpoint than binocular adjustment (Schober, 1970; Wesner and Miller; 1986), presumably, because vergence helps control accommodation during binocular viewing. Therefore, EFs resulting from monocular eyepiece adjustment may not be appropriate for extended binocular viewing because accommodation and vergence eye movements have limited ability to respond differentially (Borish, 1975a). During the aforementioned Air Force survey, 133 users focused an ANVIS (with a laboratory-calibrated eyepiece scale) in their usual way while wearing habitual optical corrections. Twenty-four users merely set the eyepieces to zero diopters by using the eyepiece scale; this was an occasionally taught strategy at the time of the survey. Of the remaining 108 subjects, 30% adjusted the eyepieces to exceed -1.5 diopters (Figure 2a). These high minus eyepieces are likely to cause blur and/or discomfort because it creates a significant mismatch between accommodative and vergence stimuli. To see distant objects, these users must accommodate to an image located closer than 59 cm to see clearly, yet must maintain parallel visual axes to see singly.

The two eyepieces may also be adjusted unequally since they are adjusted at different times. Half of the surveyed adjusted the two eyepieces unequally by more than 0.9 diopters (Figure 2b). Accommodation does not respond adequately to differential stimuli greater than 0.5 diopters (Stoddard and Morgan, 1942; Ball, 1950; Spencer and Wilson, 1954; Campbell, 1960). And, since the eye's depth of field is about ±0.43 diopters (Campbell, 1957), only one eye sees clearly at a time.



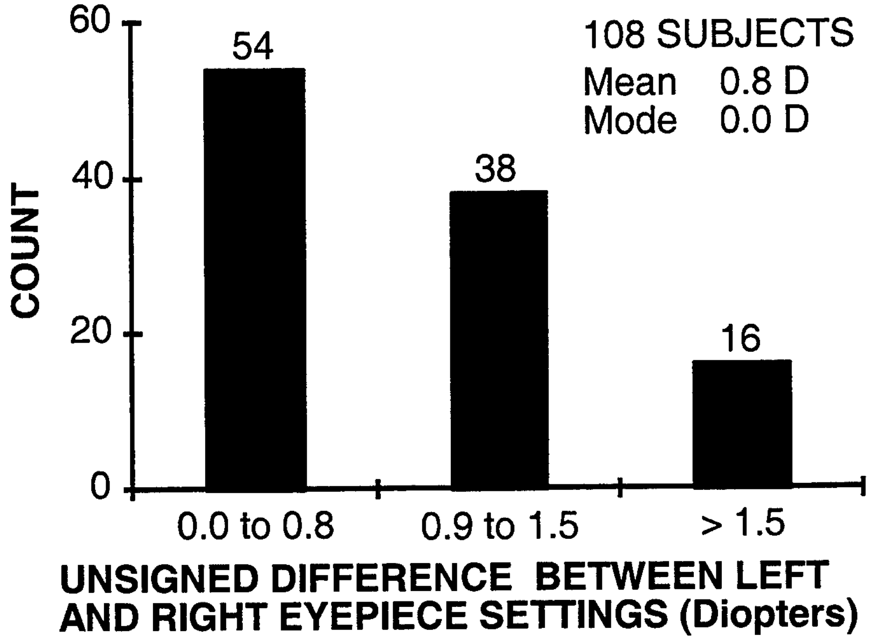


Figure 2b.

Figure 2. Frequency count of eyepiece settings by 108 Air Force ANVIS users as a function of **a)** eyepiece setting and **b)** unsigned difference between left and right eyepiece settings.

To be a viable solution to the problems of adjustable eyepieces, single-focus eyepieces must provide satisfactory vision and visual comfort over a range of appropriate luminances and contrasts for extended periods of time. To this end, this two-part study measures binocular VA through ANVIS 1) as a function of EF, luminance, and contrast in a short-term ANVIS wear study, and 2) as a function of the EF used during a four-hour ANVIS wear period.

Note, the accommodative stimulus depends not only on object distance (which is determined by the ANVIS eyepiece), but also uncorrected refractive error (Miller, 1990). Individuals with unaided 20/20 vision may vary in refractive error from slightly myopic (near-sighted) to greater than two diopters hyperopic (far-sighted) (Borish, 1975b). Hyperopes must accommodate to see distant objects clearly, and even more so to see close objects. Myopes cannot focus on far objects, and accommodate less than normal to see close objects. For example, a young 1.5 diopter hyperope and a 0.5 diopter myope are both capable of 20/20 unaided distant vision, but when looking into a -0.5 diopter eyepiece, the respective accommodative stimuli are two and zero diopters. So, each must accommodate a different amount to see clearly. In our studies, all subjects were optically-corrected to equate the accommodative stimulus across subjects.

SHORT-TERM WEAR STUDY

Method

Subjects

Twelve subjects (24 years ± 6) participated; each demonstrated 20/20 VA in each eye and 40 arc-seconds of stereopsis. Only one subject wore habitual optical correction (-2 diopters); however, with that correction in place, this subject was considered the same as the others. Subjects were optically refracted to a "most plus lens power for best binocular VA" endpoint using standard clinical techniques (Borish, 1975c; Michaels, 1975). Due to the eye's depth-of-field and accommodation, there is a range of lens powers producing best VA during clinical refraction. The clinical endpoint is the most plus (or least minus) lens power producing best VA. In this way, at least conceptually, the visual near point is maximized while maintaining best distant VA. All subjects had less than 0.5 diopters of anisometropia and astigmatism; any astigmatic correction was subsequently ignored.

Visual Acuity Task

The visual stimulus was a square "E" randomly presented in one of four orientations (Figure 3) for one-second exposures on a super VGA monitor located twenty feet away. The version of ANVIS used by the Air Force is not sensitive to visible light because visible light is filtered out by the objective lens to make ANVIS more compatible with aircraft cockpit lighting. Only the monitor's blue phosphor was used so that the monitor would not be too bright for ANVIS. The subject's task was to push a four-way thumb switch in the direction that the presented "E" pointed. Eight presentations were made at each "E" size level. A one-second delay separated responses from ensuing presentations. If six responses were correct then the "E" would shrink by 0.1 log units and another series of eight presentations was made. When the "E" was sufficiently small that less than six responses were correct, then the "E" would grow by 0.05 log units and a final series of eight presentations was made. VA was interpolated from the last three levels of tested "E" sizes by the following method. The base VA was defined as 0.05 log units greater than the largest of the three final levels. For each level, the number of correct responses was tallied. Then, three was subtracted from each tally to compensate for random guesses; the result was truncated to zero if it was less zero. Next, the three results were summed and multiplied by 0.01. VA was calculated by subtracting this number from the base value and expressed as the log of the minimum angle of resolution (log MAR) in arc-minutes. MAR pertains to the angular size of the "E" stroke width.

Figure 3. The target was a square E in one of four orientations.

Design

The statistical design was a four-way total within ANOVA with Greenhouse-Geisser (1959) correction. VA was the dependent variable. Data met the statistical assumption of equal variance. EF, luminance, contrast, and repetition were the independent variables. Five EF (0.0, -0.5, -1.0, -1.5 diopters, and subject-adjusted), three luminance (0.045, 0.319, and 2.24 fL), and three contrast (30%, 47%, and 64%) levels were used. Luminance and contrast were measured from the left ANVIS eyepiece. Each experimental condition was tested three times.

Procedures

On a training day, subjects were familiarized with experimental methods, and carefully trained to focus ANVIS eyepieces to a "most plus lens power for best VA" endpoint. During the focusing procedure, subjects viewed a high contrast square-wave chart located 20 feet away. The chart, known as the 3x3 NVG Resolution Chart , has nine four-inch-square grating patches varying in bar width from 1.75 to 5.0 arc-minutes. The chart's background luminance was approximately 2.2 fL as measured through the left ANVIS eyepiece. Left and right eyepieces were focused independently as subjects monocularly viewed the chart.

On the first of three experimental days, each subject adjusted the ANVIS eyepieces. Resultant EFs were measured with a dioptometer (Coleman, Coleman, and Fridge, 1951), and became the "subject-adjusted" EFs for the entire experiment. A set of ANVIS goggles was rigidly mounted to a heavy table. A 20° uniformly illuminated screen was placed behind the monitor; the background screen's brightness was matched to the monitor's brightness as seen through the left ANVIS eyepiece.

Before each experimental session, the experimenter focused the objective and eyepiece lenses while looking through ANVIS with an afocal 8x telescope at the "3 by 3" chart. Each experimental session featured a single luminance level. EF was varied by placing thin lenses immediately behind the ANVIS eyepieces. Luminance was controlled with neutral density filters placed in front of the ANVIS objective lenses. Contrast ($\Delta L/L$) was controlled through software. Subjects began each session with 15 minutes of dark adaptation. Subjects adapted to the display luminance for one minute before each trial. Luminance was counterbalanced across subjects. Contrast and EF were randomized over each set of fifteen trials. Three sets of fifteen trials were performed each day. After each session, the experimenter again looked through ANVIS with the afocal 8x telescope to ensure that neither the objective nor the eyepiece lenses had changed focus. Head movements were minimized with a chin cup and headrest. Experimental sessions were typically eighty minutes long.

Results

Table 1 summarizes refractive error and eyepiece adjustment measurements. Although the average refractive error (n = 24 eyes) was slightly hyperopic (+0.23 diopters ± 0.38), the eyepieces were adjusted myopically (-1.05 diopters ± 0.34), resulting in an average accommodative stimulus of 1.28 diopters (± 0.55) with a range of +0.5 to +2.5 diopters. The average unsigned EF difference between the two eyes was +0.40 diopters (±0.29) with a maximum difference of +0.75 diopters. Table 2 lists the average subject-adjusted EF and unsigned interocular difference in subject-adjusted EF for the aforementioned Air Force Survey, Kotulak and Morse study (1994a), and this study. Values from the two laboratory studies agree well. The most striking difference is that the survey reported twice the inter-subject variability as the two laboratory studies. The survey also reported a greater disparity between right and left eyepiece settings. Differences from the survey likely reflect the recent detailed training of subjects in the two laboratory studies.

	Average	Std Dev	Range
Refractive Error	+0.23	0.38	-0.25, +1.00
Eyepiece Focus	-1.05	0.34	-1.75, -0.25
Accommodative Stimulus	+1.28	0.55	+0.50, +2.50
|Δ| Refractive Error	0.08	0.12	0.00, +0.25
|Δ| Eyepiece Focus	0.40	0.29	0.00, +0.75
|Δ| Accommodative Stimulus	0.48	0.25	0.00, +0.75

Table 1. Summary of subject refractive error, user-adjusted ANVIS eyepiece focus, and resulting accommodative stimulus. |Δ| represents unsigned differences between right and left eyes (or eyepieces). Units are diopters

	Average EF (Std Dev)	|Δ| EF (Std Dev)
Air Force Survey	-1.17 (1.13)	0.83 (0.99)
Kotulak and Morse	-1.13 (0.63)	0.57 (0.47)
Current Study	-1.05 (0.34)	0.40 (0.29)

Table 2. Average user-adjusted ANVIS eyepiece focuses are listed with standard deviations for an unpublished Air Force survey, Kotulak and Morse (1994a), and the current study. |Δ| represents unsigned differences between right and left eyepieces. Units are diopters.

Figure 4 plots VA as a function of luminance, contrast and EF. The effects of luminance and contrast on VA are well known (van Meeteren and Vos, 1972; Richards, 1977). VA improves with increasing luminance ($F_{2,22} = 326$, $p < 0.0001$) and contrast ($F_{2,22} = 913$, $p < 0.0001$). Contrast influences VA more when luminance is low ($F_{4,44} = 25$, $p < 0.0001$). More interestingly, EF ($F_{4,44} = 8.4$, $p < 0.01$) affects VA without interacting with luminance or contrast. Specific comparisons between EFs (Table 3) were made using a pooled two-tailed t-test where the error term was calculated by pooling the variance of the three repetitions across luminance, contrast, and EF. Zero diopter eyepieces reduced VA by nearly 10%; other specific comparisons were not significant. Other main effects and interactions were not significant.

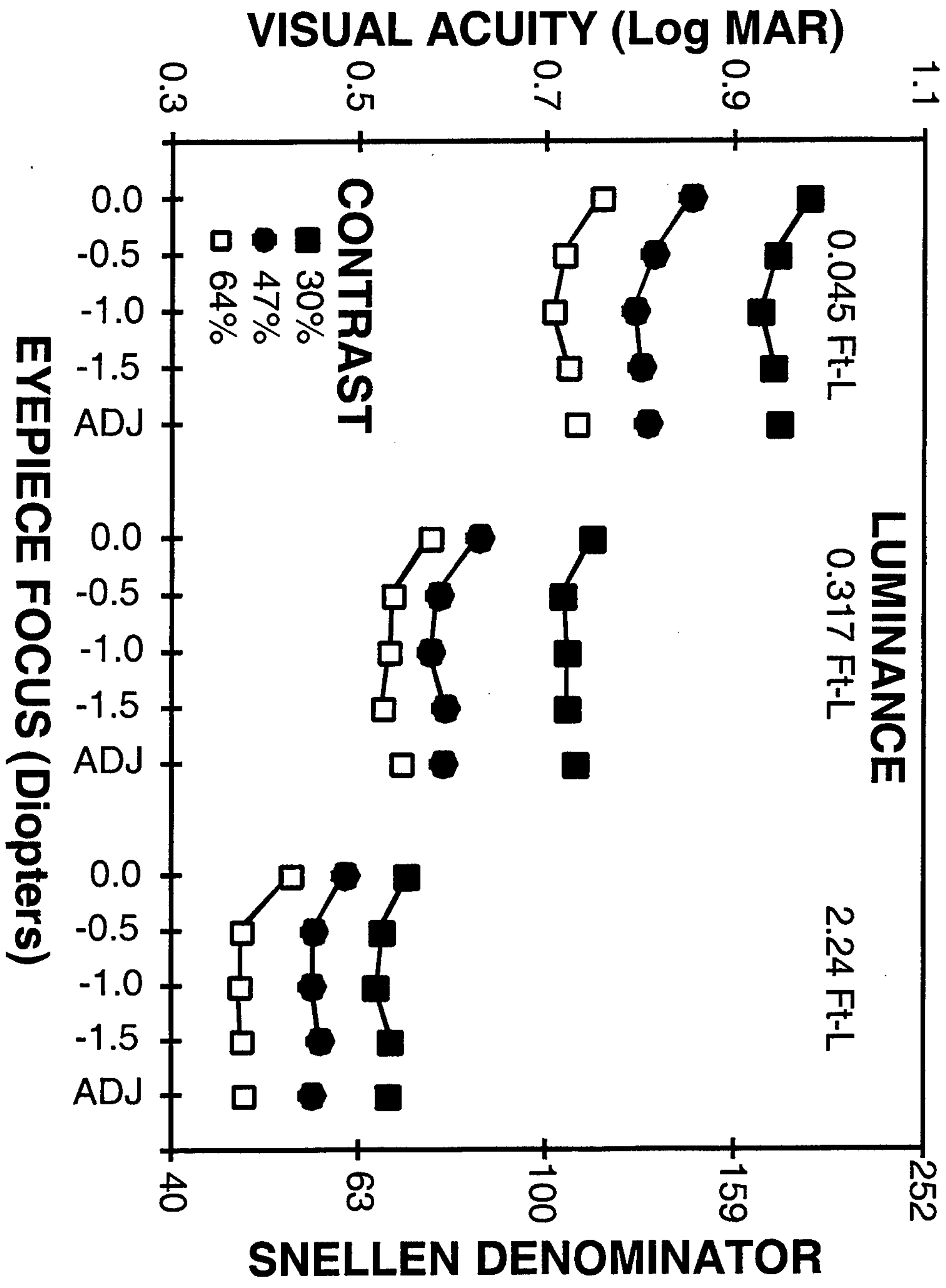


Figure 4. Group-averaged visual acuity through ANVIS is plotted as a function of luminance, contrast (ΔL/L) and eyepiece focus. Note, since subjects were optically corrected, the accommodative stimulus equals eyepiece focus.

Specific Comparisons	Change in Log MAR	Visual Acuity Improvement	Pooled t-Test df = 44
0.0D to -0.5D	-0.038	9.1%	p < 0.0001 *
0.0D to -1.0D	-0.045	10.9%	p < 0.0001 *
0.0D to -1.5D	-0.038	9.1%	p < 0.0001 *
0.0D to Adjusted	-0.033	7.9%	p < 0.0005 *
-0.5D to -1.0D	-0.007	1.6%	p > 0.4
-0.5D to -1.5D	0.001	-0.2%	p > 0.9
-0.5D to Adjusted	0.005	-1.2%	p > 0.5
-1.0D to -1.5D	0.007	-1.6%	p > 0.4
-1.0D to Adjusted	0.012	-2.8%	p > 0.2
-1.5D to Adjusted	0.005	-1.2%	p > 0.6

Table 3. Specific comparisons of eyepiece focus in short-term ANVIS wear study. Asterisks indicate statistical significance (p = 0.05).

Subsequent analyses were conducted separately for each subject to determine whether EF requirements for best VA were idiosyncratic. For each subject, specific comparisons were made between the subject-adjusted, best-overall, and optimum EFs using two-tailed t-tests where the error terms were calculated by pooling the variance of the three repetitions across luminance, contrast, and EF. The best-overall EF was -1.0 diopters, producing the best average VA across all conditions and subjects. Each subject's optimum EF produced the best average VA across all conditions. EFs of -0.5 and -1.0 diopters were each optimum for five subjects. Zero diopter eyepieces were not optimum for any subjects. Table 4 lists each subject's optimum EF, and VA for subject-adjusted, best-overall, and optimum EFs.

		Eyepiece Focus		
Subject	Optimum EF	Optimum	Best-Overall	Subject-Adjusted
1	0.5	0.560	0.561	0.558
2	0.5	0.629	0.643	0.633
3	0.5	0.602	0.614	0.607
4	0.5	0.587	0.601 *	0.610 *
5	0.5	0.654	0.670 *	0.706 *†
6	1.0	0.602	0.602	0.621
7	1.0	0.654	0.654	0.678
8	1.0	0.616	0.616	0.640 *†
9	1.0	0.622	0.622	0.647 *†
10	1.0	0.620	0.620	0.645 *†
11	1.5	0.597	0.604	0.608
12	1.5	0.616	0.655 *	0.654 *
AVERAGES				
Log MAR		0.613	0.622	0.634
Snellen Acuity (20/)		82.1	83.7	86.1
Visual Acuity Loss			2.0%	4.9%

Table 4. Average visual acuities (VA) through optimum, best-overall, and subject-adjusted ANVIS eyepiece focus (EF) are listed by subject. Asterisks and obelisks indicate a statistical difference (df = 36, p = 0.05) from optimum and best-overall EFs, respectively. Group-averaged VA are listed below as log MAR and Snellen equivalent along with per cent VA loss from optimum.

Subject-adjusted and optimum EFs were compared to determine whether subjects indeed optimized VA through eyepiece adjustment. At a 0.05 per-comparison probability level, subject-adjusted eyepieces produced optimal VA for half of the subjects. VA was reduced by 7.5% for the remaining subjects. Overall, subject-adjusted eyepieces reduced VA by 5%. Only one comparison was significant at a 0.05 procedure-wise error level.

Similarly, best-overall and optimum EFs were compared except that a statistically more powerful 1-tailed t-test was used because, by definition, the best-overall EF could not surpass the optimum EF. At a 0.05 per-comparison probability level, the best-overall EF produced optimal VA for 75% of the subjects. VA was reduced by 5.5% for the remaining subjects. Overall, the best-overall EF reduced VA by 2%. No comparisons were significant at a 0.05 procedure-wise error level.

Subject-adjusted and best-overall EFs were compared to determine whether single-focus eyepieces could produce VA comparable to subject-adjusted eyepieces. At a 0.05 per-comparison probability level, the best-overall EF produced (up to 5%) better vision for 25% of the subjects. Only one comparison was significant at a 0.05 procedure-wise error level. No subject saw better with subject-adjusted eyepieces.

LONG-TERM WEAR STUDY

Method

Subjects

Twelve subjects (23 years ± 4) participated; each demonstrated 20/20 VA in each eye and 40 arc-seconds of stereopsis; six participated in the above short-term wear study. None wore habitual optical correction. Subjects were optically refracted to a "most plus lens power for best binocular VA" endpoint. All subjects had less than 0.5 diopters of anisometropia and astigmatism; any astigmatic correction was subsequently ignored. Refractive errors ranged from -0.25 to +1.00 diopters with an average of +0.33 diopters (±0.4).

Design

The statistical design was a four-way total within ANOVA with Greenhouse-Geisser (1959) correction. VA was the dependent variable, and was measured as log MAR. The method for measuring VA is described above. The independent variables were EF (0.0, -0.75, -1.5 diopters), luminance (0.32 and 0.05 fL), time (pre- and post-extended wear), and EF worn during the extended-wear period (0.0, -0.75, -1.5 diopters). Each experimental condition was tested twice, and these results were averaged.

Procedures

On a training day, subjects were familiarized with experimental procedures. Equipment and general methods are described above. Three experimental sessions were performed on separate days; each featuring a single EF level worn during a four-hour ANVIS wear period. VA was measured through a table-mounted ANVIS as a function of EF and luminance. Target contrast ($\Delta L/L$) was 46%. The order of luminance and EF was randomized within each of two sets of six trials.

After initial VA measurements, the subject wore a second head-mounted ANVIS for four hours with the EFs set to one of three levels. The order of EFs worn during the extended-wear period was counterbalanced across subjects. ANVIS was held to the subject's head with a Litton hair net harness. Peripheral vision was blocked to restrict vision to ANVIS's 40° field-of-view. Small apertures and neutral density filters were placed before ANVIS's objective lenses to increase the depth-of-field and to make the ANVIS display luminance approximately two foot-lamberts. Subjects were free to wander around the room, but they mostly played video games or watched video-taped movies on a large projection screen. An experimenter stayed with the subject to ensure the subject's safety, and that the subject remained alert and attentive to the video game or movie.

After the extended wear period, VA was re-measured with the table-mounted ANVIS. Subjects were not allowed to look away from the table-mounted ANVIS during VA tasks. Care was taken to prevent subjects from looking around the room when switching from the head-mounted ANVIS to the table-mounted ANVIS. Pre- and post-extended wear VA measurements required twenty minutes each. Experimental sessions were five hours long.

In addition to measuring ANVIS VA, each experimental session began and ended with two sets of unaided VA measurements. Unaided VA was measured using the monitor's green phosphor. Each experimental condition was tested twice, and the results were averaged. Target luminance was 2.7 fL and contrast was 46%. A separate two-way total within ANOVA was performed. Independent variables were time (pre- and post-extended wear) and extended-wear EF (0.0, -0.75, -1.5 diopters).

Results

Unaided VA was not affected by time ($F_{1,11} = 0.42$, $p > 0.6$) or by EF used during the extended wear period ($F_{2,22} = 0.22$, $p > 0.6$). There were no significant interactions.

Figure 5 depicts all main effects for ANVIS VA. As in the short-term study, VA was significantly affected by luminance ($F_{1,11} = 4602$, $p < 0.0001$) and EF ($F_{2,22} = 18.3$, $p < 0.001$). Specific comparisons (Table 5) were made for EF using a two-tailed t-test where the error term was calculated by pooling the variance of the two trials across extended-wear EF, time, and luminance. Subjects saw 13% better with -0.75 diopter eyepieces than with zero diopter eyepieces. VA was not affected by extended-wear EF ($F_{2,22} = 0.13$, $p > 0.8$) or time ($F_{1,11} = 2.97$, $p > 0.1$). There were no significant interactions. Notably, the best EF for VA before the extended ANVIS wear remained the best afterwards, regardless of the EF used during the extended-wear period. So, eyepiece adjustment seems unnecessary for retaining good VA during extended ANVIS use.

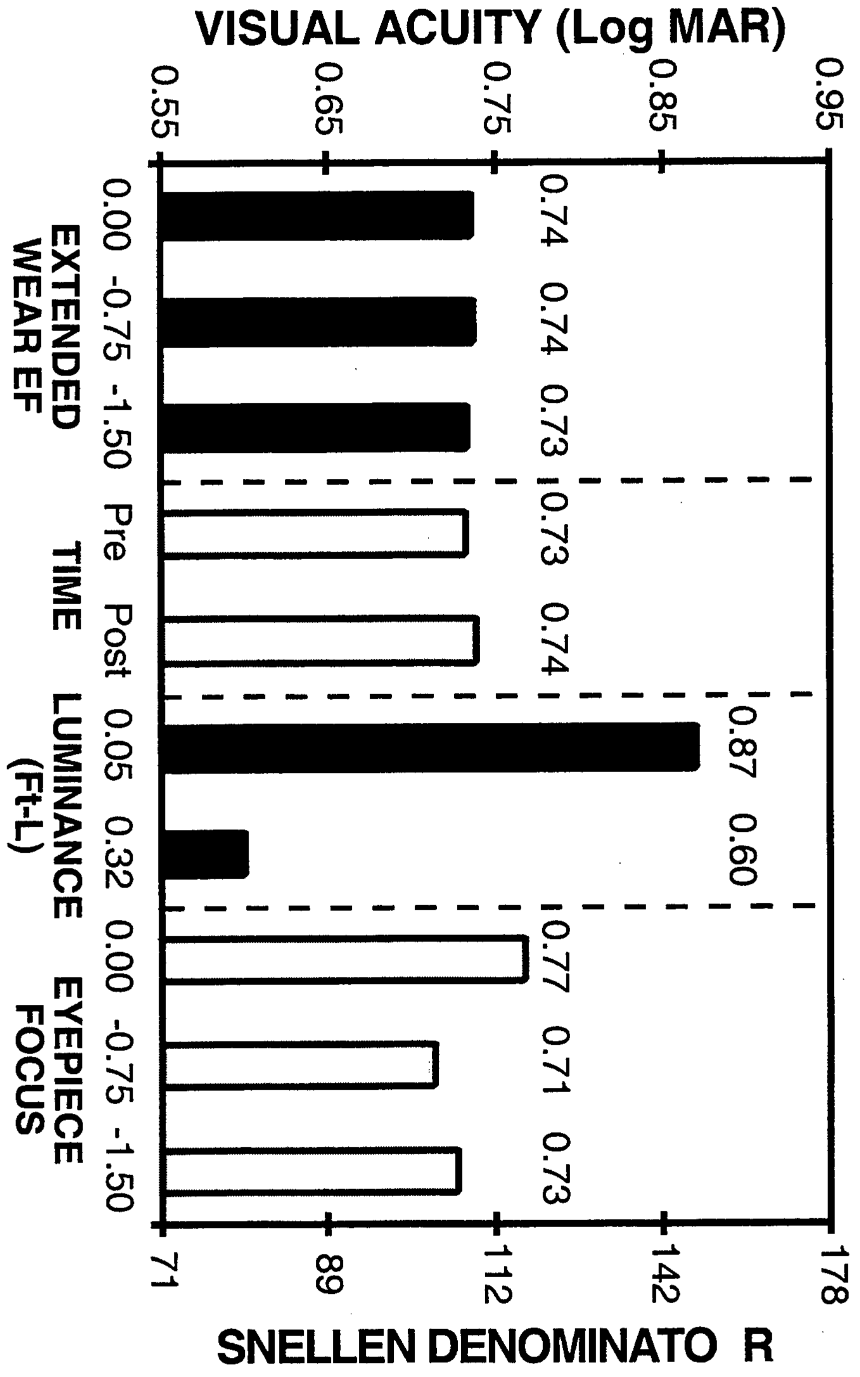


Figure 5. Group-averaged visual acuity through ANVIS is plotted for eyepiece focus (EF) used during the extended-wear period, time (pre- and post-extended wear), ANVIS display luminance, and EF. Note, since subjects were optically corrected, the accommodative stimulus equals EF.

Specific Comparisons	Change in Log MAR	Visual Acuity Improvement	Pooled t-Test df = 22
0.00D to -0.75D	-0.054	13.2%	$p < 0.001$ *
0.00D to -1.50D	-0.041	9.9%	$p < 0.005$ *
-0.75D to -1.50D	0.013	-3.0%	$p > 0.1$

Table 5. Specific Comparisons between eyepiece focus in long-term ANVIS wear study. Asterisks indicate statistical significance ($p = 0.05$).

Without solicitation, six subjects complained of uncomfortable and less than clear vision during the extended-wear period with -1.5 diopter eyepieces. Four of these subjects thought they saw poorly during post-extended wear VA tests; however, no change in VA was measured. Another subject, an ambitious ROTC cadet aspiring to be a fighter pilot, insisted on discontinuing after two hours of extended-wear due to very uncomfortable vision. Fortunately, this subject completed the entire -1.5 diopter EF extended-wear condition on another day. Diplopia was not reported by any subject. No complaints were reported for the extended-wear periods featuring zero and -0.75 diopter eyepieces.

Discussion

We confirm Kotulak and Morse (1994a) in that vision through ANVIS night vision goggles is better when the eyepieces are adjusted by the user than when set to zero diopters. But, we found less improvement with subject-adjusted eyepieces (8% versus 23%). This difference may be explained by uncorrected refractive error. Subjects were optically-corrected in this study. Subjects were uncorrected and slightly myopic (-0.1 diopters ± 0.4) in Kotulak and Morse's study. Images at optical infinity are beyond the accommodative range of myopes, and therefore cannot be seen clearly. Nonetheless, merely setting the ANVIS eyepieces to zero diopters is not an auspicious strategy.

Binocular VA improved with -0.5 diopter eyepieces, and then was insensitive to EF over a range of -0.5 to -1.5 diopters even as VA varied greatly with luminance and contrast. This suggests that accommodation was as accurate as it needed to be to achieve near optimum VA. Only half of the subjects adjusted the eyepieces for optimum VA. Therefore, the superiority of subject-adjusted over zero diopter eyepieces is likely due to the mere addition of minus EF rather than actual optimization of VA by the user. A -1.5 diopter eyepiece caused half of the subjects to complain of blur and discomfort during extended use. Presumably, these symptoms were caused by ocular motor responses to dissonant accommodative and vergence stimuli. The average accommodative stimulus after eyepiece adjustment was only slightly less (1.3 diopters); therefore, some subjects may have become symptomatic with their subject-adjusted EFs during extended use. On the other hand, -0.75 diopter eyepieces caused no symptoms. Varying luminance and contrast does not necessitate a change in EF, nor does extended ANVIS use.

Our principal finding is that, for users who are optically corrected to a "most plus lens power for best binocular VA" endpoint, -0.75 diopter eyepieces provide satisfactory comfort and near optimal binocular VA for extended ANVIS viewing. However, the accommodative stimulus is the relevant factor, and it is determined by EF and uncorrected refractive error. So, more broadly, the accommodative stimulus should be approximately 0.75 diopters for extended ANVIS use. This result may extend to other binocular visual displays.

The major impediment to implementing this knowledge is that ANVIS users without habitual optical corrections may range from slightly myopic to moderately hyperopic. This dictates a range of EFs to achieve the desired 0.75 diopter accommodative stimulus. We suggest three possible eyepiece designs for future generations of ANVIS:

1. <u>Single-focus -0.75 diopter eyepieces</u>. This is the simplest design. However, it will make uncorrected hyperopes effectively more hyperopic, increasing the chance of uncomfortable and less clear vision. <u>Single-focus -0.5 diopter eyepieces</u> may be an appropriate compromise since it provided the largest incremental improvement in VA from zero diopter eyepieces.

2. <u>Single-focus zero diopter eyepieces with modified spectacle correction</u>. Emmetropes, myopes, and the optically-corrected would wear spectacles (or contact lenses) with a -0.75 diopter over-correction. Uncorrected hyperopes do not need this over-correction since it is built in to themselves.

3. <u>Single-focus zero diopter eyepieces with thin lens inserts</u>. ANVIS would contain a holder for a thin -0.75 diopter lens to be placed immediately behind the eyepiece. Emmetropes, myopes, and the optically-corrected would use the lens; uncorrected hyperopes would not.

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