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Factors That Determine Visual Acuity Through Night Vision Goggles for Emmetropes

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The purpose of this study was to investigate factors which could affect the visual acuity of emmetropes (individuals without clinically significant refractive error) while viewing through night vision goggles, namely unaided visual acuity, clinically insignificant refractive error, and experience as a visual observer. We found that night vision goggle visual acuity is related to unaided visual acuity for emmetropes when the night vision goggle eyepieces are focused to infinity, and that this relationship is robust with respect to changes in target contrast. We also found that both the unaided and night vision goggle (infinity focus eyepiece) visual acuity of nominal emmetropes is related to uncorrected refractive error, and that experience as a visual observer is significantly related to night vision goggle visual acuity. The implication of these results is that many aviators who are medically cleared to fly without glasses will suffer from reduced vision through any night vision device with a fixed infinity focus eyepiece. Similarly, ground vehicle operators who have astigmatism and who must use spectacle incompatible night vision goggles will also suffer from reduced visual acuity.

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Introduction

Many factors which could affect visual acuity (VA) with night vision goggles (NVGs) already have been studied, e.g., night sky condition and target contrast (Levine and Rash, 1989a and 1989b; Wiley, 1989; Kotulak and Rash, 1992), NVG generation (Miller et al., 1984; Kotulak and Rash, 1992), nuclear flashblindness protection (Levine and Rash, 1989a and 1989b), chemical protective masks (Miller et al., 1989; Donohue-Perry, Riegler, and Hausman, 1990), signal-to-noise ratio (Riegler et al., 1991), interpupillary distance misadjustment (King and Morse, 1992), and instrument myopia (Kotulak and Morse, 1992, 1994a, and 1994b; Kotulak, Morse, and Wiley, 1993). Another factor which could influence NVG VA is decreased unaided VA, i.e., VA without NVGs; however, relatively little is known about it.

Kim (1982) investigated the influence of astigmatism on NVG VA; however, he did not report the unaided VA of his subjects. Hoover (1983) measured both unaided and aided VA; however, most of Hoover's subjects suffered from vision loss due to eye disease. Therefore, it is not certain whether Hoover's results are relevant to healthy populations.

In the current report, we present measurements of both unaided and aided VA on healthy, emmetropic subjects in order to determine whether there is a correlation between the two. The theoretical basis for such an association comes from the following: When two optical systems of unequal resolving power are combined, the resolution of the combined system can be predicted by the equation below, in which R_H and R_L represent the resolving powers of the high and low resolution elements respectively, and R_C represents the resolving power of the combined system (Farrell and Booth, 1984).

$$\frac{1}{R_C^{1.7}} = \frac{1}{R_H^{1.7}} + \frac{1}{R_L^{1.7}}$$

An observer viewing through NVGs can be thought of as such a system, in which the eye is the high resolution element when the observer is emmetropic. Figure 1 is derived from the above equation by holding R_L constant at 20 cycles/degree (cpd), the approximate resolution limit of current NVGs (Figure 2), and varying R_H over a wide range. The equation predicts that the resolving power of the combined system is affected by changes in R_H, especially in the region at and below the eye's maximum resolution, which is approximately 40 cpd.

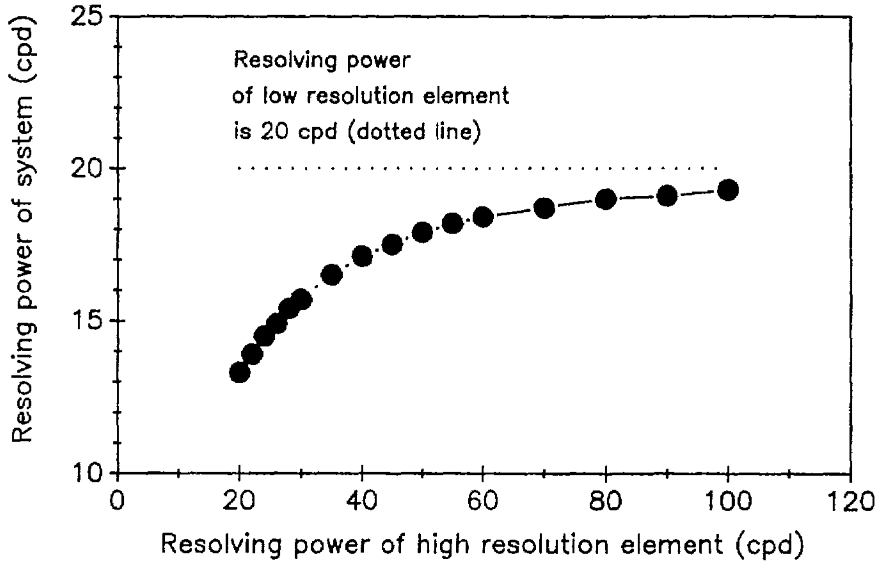

Figure 1. The relationship between the resolving power of the high resolution element and the combined system, given that the resolving power of the low resolution element is held constant. This model was derived from experiments with photographic systems (Farrell and Booth, 1984).

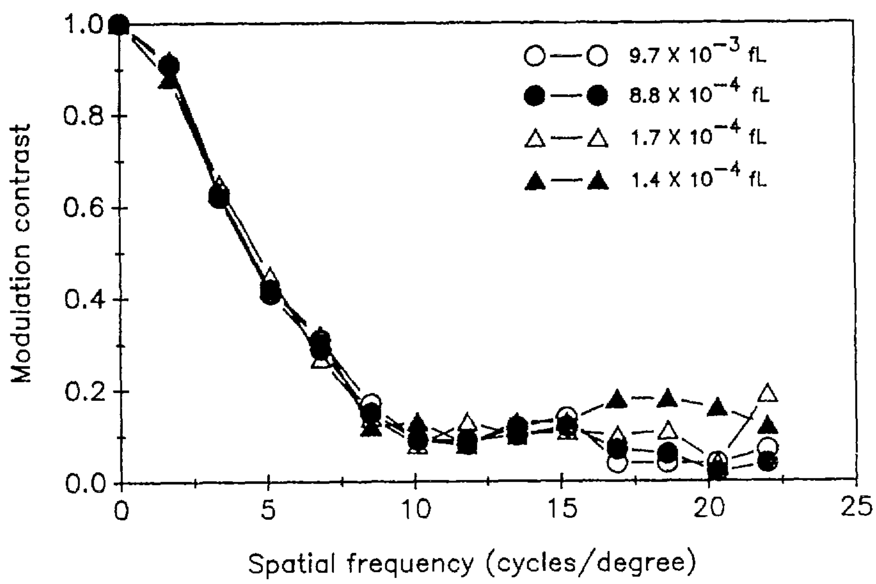

Figure 2. The ANVIS spatial modulation transfer function under varying levels of ambient luminance (Kotulak and Morse, 1994).

In this report, we also explore other factors which could influence NVG VA among emmetropes, namely refractive error and experience as a visual observer (flight experience and NVG experience). In the strictest sense, refractive error and emmetropia are mutually exclusive. However, emmetropes are commonly defined clinically as persons who have a distance VA of at least 20/20 in each eye, a condition which does not preclude small refractive errors (Hirsch, 1945).

Methods

Subjects

Sixteen volunteer subjects, who were either U.S. Army aviators (n = 12) or flight school students (n = 4), were recruited for the experiment. All subjects had unaided visual acuities of at least 20/20 in each eye, and were free from eye disease and other ocular anomalies. All of the subjects were cleared to fly without spectacles. Table 1 gives descriptive statistics regarding age, flight and NVG experience, and refractive error for the subjects. The refractive error data probably overestimate the degree of myopia by about 0.25 diopters (D) due to instrument myopia elicited by the autorefractor (Miwa, 1992).

Table 1.
Descriptive statistics of subjects.

Variable	Mean	SD	Median	Range
Age (years)	27.1	4.9	27.0	22 to 37
Total flight hours	988.1	1347.2	300.0	68 to 4000
Flight hours with NVGs	84.7	139.1	21.0	0 to 500
Equivalent sphere (D)	-0.35	0.37	-0.44	-0.88 to 0.50
Sphere (D)	-0.16	0.39	-0.25	-0.63 to 0.63
Cylinder (D)	-0.39	0.26	-0.25	-0.13 to -1.00

Apparatus

The NVG used in the study was the AN/AVS-6 Aviator Night Vision Imaging System {ANVIS} (Jenkins and Efkeman, 1980). ANVIS is a unity-magnification pair of binoculars which electronically amplify ambient light and thus provide photopic vision under night sky conditions. ANVIS consists of two identical monoculars, the main components of which are an objective, a third-generation image intensifier, and an eyepiece. The ANVIS modulation transfer function (Figure 2) demonstrates that the phosphor image is spatially lowpass filtered. As a result, VA with ANVIS under optimum conditions is only 20/35, and it gets worse with decreasing night sky luminance (Kotulak and Rash, 1992). The output luminance of ANVIS falls off steadily with decreases in input luminance when the latter is less than quarter moon, the lower limit of the ANVIS automatic gain control. This allows the ANVIS display luminance to be manipulated as an experimental variable.

The visual stimuli were high (Bailey and Lovie, 1976) and low (Bailey, 1982) contrast Bailey-Lovie acuity charts. Two versions of the chart, differing only in letter sequence, were used at each level of contrast. These charts were chosen because their scale is five times finer than that of Snellen-like charts, and their test-retest reliability is twice as great (Bailey et al., 1991). In addition, Bailey-Lovie charts incorporate an equal-interval scale that permits the use of parametric statistics (Lovie-Kitchin, 1988).

The contrast of the Bailey-Lovie optotypes was calculated from the equation below, in which L_B and L_L represent background and letter luminance respectively.

$$C = \frac{100\,(L_B - L_L)}{L_B}$$

Photometrically-measured luminance was used to calculate target contrast, both on the NVG phosphor screen under simulated night sky conditions (labelled "Aided" on Table 2), and on the charts themselves under photopic conditions (labelled "Unaided" on Table 2). Table 2 also gives the background luminance (i.e., the luminance of the white portion of the chart) for the aided and unaided conditions.

Table 2.
Target parameters.

Parameter	Aided		Unaided	
	High	Low	High	Low
Contrast (percent)	62	12	98	21
Luminance (cd/m^2)	6.5		6.5	

Procedures

VA always was measured under binocular conditions. The same charts were used for aided and unaided viewing. VA thresholds, which were defined as the common logarithm of the minimum angle of resolution {log MAR} (Bailey and Lovie, 1976), were recorded using Bailey-Lovie scoring procedures (Bailey and Lovie, 1976), without a time limit, and without reinforcement. Contrast changes were made by switching between charts. The order of presentation of the stimuli was randomized.

Prior to making focus adjustments, the subjects were trained to reach a most-plus endpoint, i.e., use the most plus (or least minus) dioptric power that was required for best vision. This is consistent with established clinical technique for refraction. Eyepiece power was verified with a dioptometer. Refractive error was measured objectively with an autorefractor.

Design and statistical analysis

The dependent variables were high and low contrast aided VA measured with the NVG eyepieces focused at infinity, and high and low contrast aided VA measured with the NVG eyepieces focused by the users for best vision. The design was within subjects. The correlation of the dependent variables with various candidate independent variables was tested by simple and multiple linear regression. The independent variables were high and low contrast unaided VA, total flight hours, NVG flight hours, and refractive error. Three refractive error components were considered separately, i.e., sphere, cylinder, and equivalent sphere (one-half the cylinder power plus the sphere power).

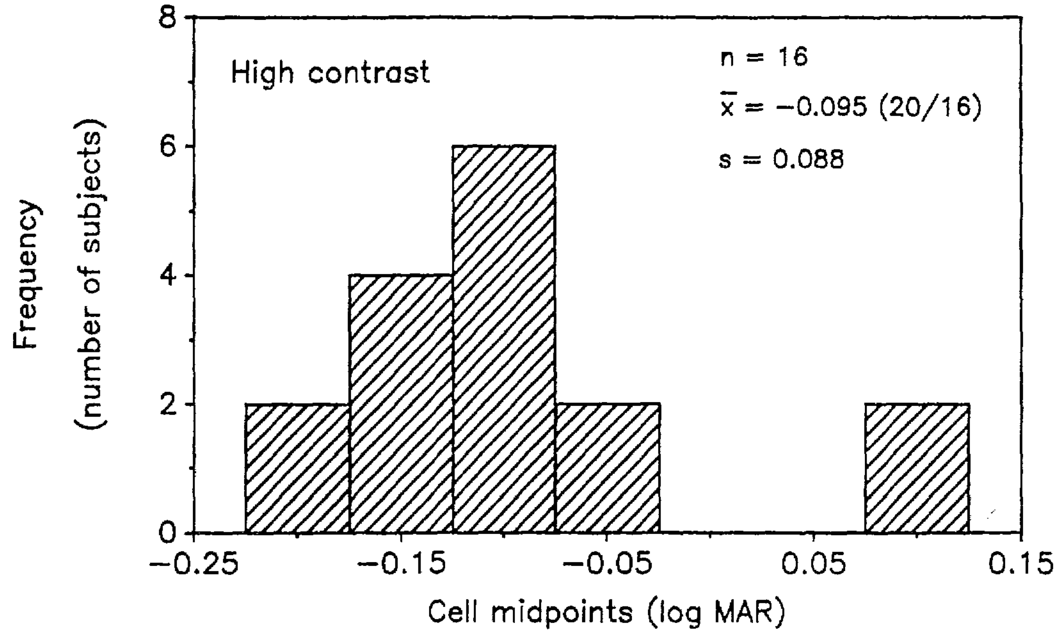

Figure 3. The distribution of uncorrected unaided visual acuities to high contrast letters for nominal emmetropes.

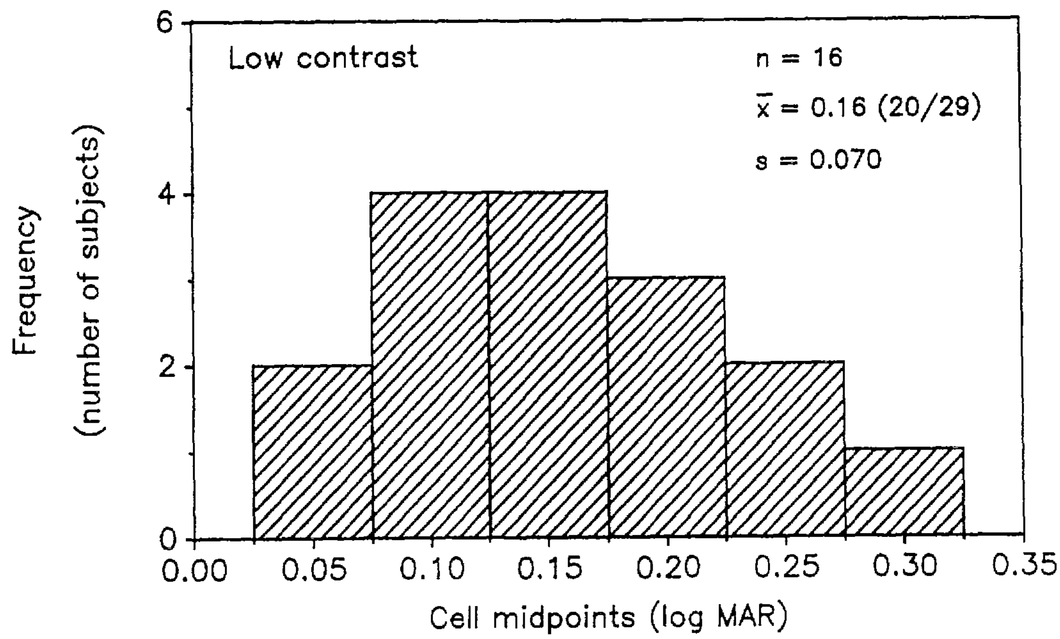

Figure 4. The distribution of uncorrected unaided visual acuities to low contrast letters for nominal emmetropes.

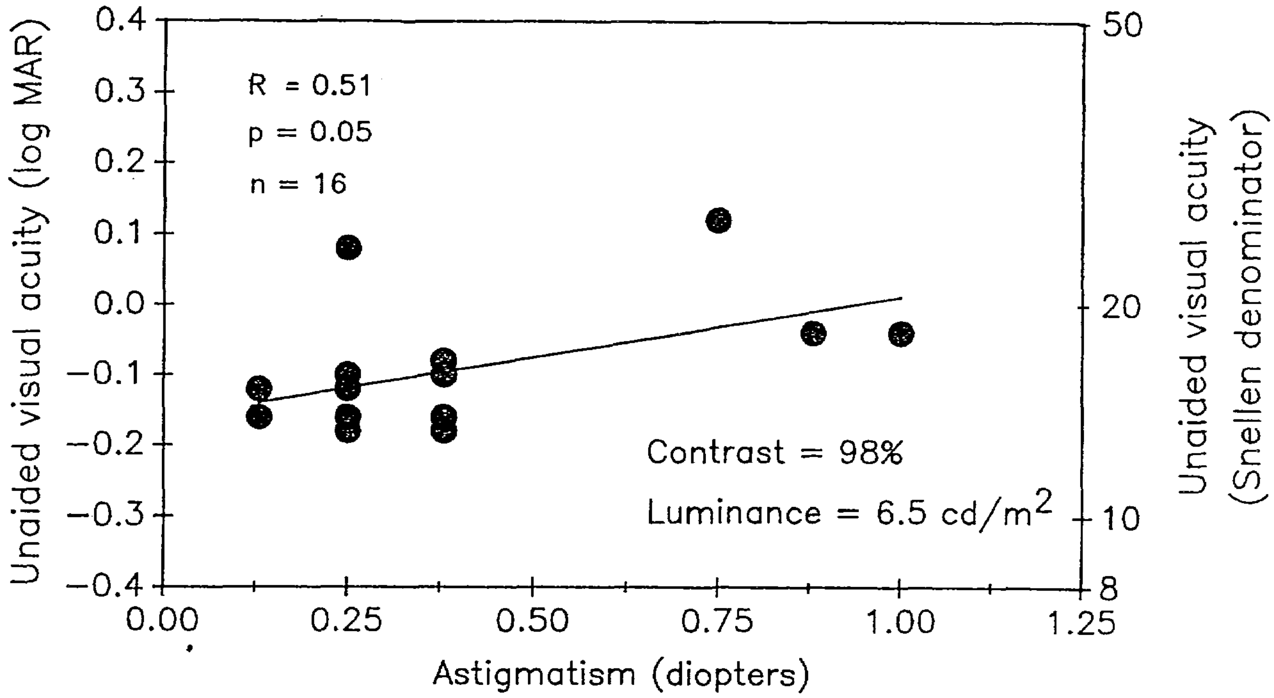

Figure 5. The relationship between uncorrected unaided VA and the absolute value of the astigmatic component of the refractive error for nominal emmetropes. The relatively low chart luminance, which was intended to match that of the NVG display, resulted in elevated acuity thresholds.

Results

Bivariate relationships

Figures 3 and 4 give the distributions of unaided VAs for our nominally emmetropic subjects at high and low target contrasts, respectively. Note that in Figure 3, two subjects had VAs less than 20/20. This was most likely due to the test luminance of 6.5 cd/m^2 (Sheedy, Bailey, and Raasch, 1984), which is considerably lower than the 85 cd/m^2 that is recommended for the clinical measurement of VA (National Research Council, 1979). The luminance of 6.5 cd/m^2 was selected because it matched the ANVIS display luminance (Table 2).

The variability in VA among emmetropes is due, at least partially, to uncorrected refractive error, as shown in Figure 5 (see also Table 1). Figure 5 demonstrates that unaided VA to high contrast letters is correlated with the amount of astigmatism. Similarly, the ANVIS VA of emmetropes also can be related to uncorrected refractive error. For example, Figure 6

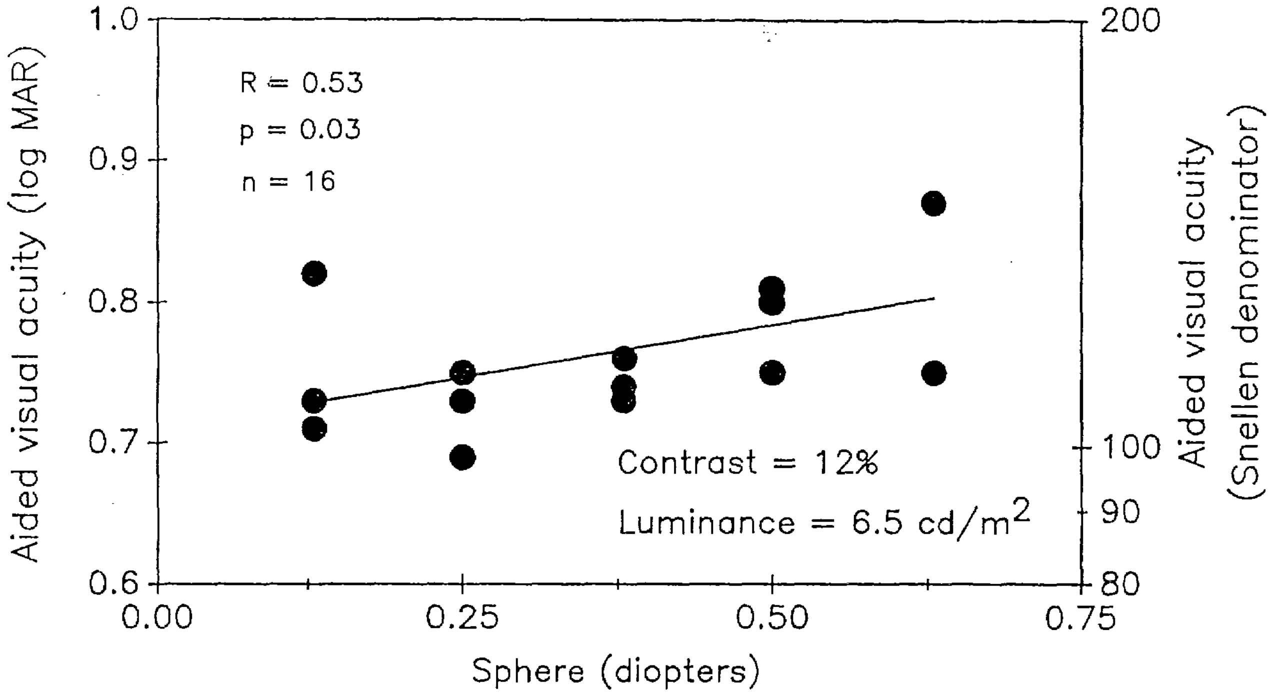

Figure 6. The relationship between uncorrected NVG VA and the absolute value of the spherical component of the refractive error for nominal emmetropes. The NVG eyepieces were focused to infinity.

reveals that aided VA is correlated with the power of the spherical component of the refractive error when target contrast is low and the instrument eyepieces are focused to infinity.

Figure 7 demonstrates that there is also a correlation between aided and unaided VA for emmetropes when the eyepieces are focused at infinity. This relationship is statistically significant at both high ($R = 0.73$, $p = 0.001$) and low ($R = 0.61$, $p = 0.01$) contrast. However, the relationship ceases to be significant when the focus is adjusted by the user for best vision ($R = 0.18$, $p = 0.5$ at high contrast; $R = 0.39$, $p = 0.13$ at low contrast).

Multivariate relationships

Multiple regression was used to predict aided VA by building a model which includes only those independent variables that add markedly to the strength of prediction. Tables 3 and 4 list the variables that were tested as potential predictors of aided VA for the fixed infinity focus condition, and Tables 5 and 6 list the variables that were tested for the adjustable focus

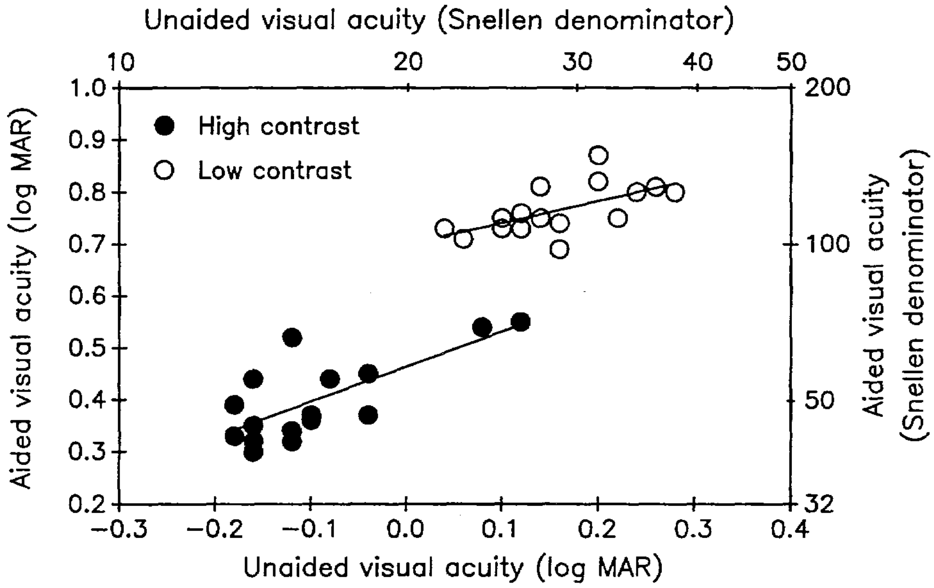

Figure 7. The relationship between uncorrected NVG VA and uncorrected unaided VA for nominal emmetropes. The NVG eyepieces were focused to infinity. Table 1 gives the values for high and low contrast for the aided and unaided VA measurements.

condition. In these tables, partial correlation is equivalent to Pearson's R in simple linear regression, and F-to-enter is the test statistic for determining whether R is significant.

Fixed infinity focus condition

Aided visual acuity for high contrast targets

The list of candidate independent variables to predict aided VA for high contrast targets is given in Table 3. The variables that were selected from this list are given by the equation below, in which A_A represents aided acuity, A_U represents unaided acuity (high contrast), and N_L represents the log of NVG flight hours (a log transform was performed because the distribution of NVG flight hours was asymmetric).

$$A_A = 0.50A_U - 0.08N_L + 0.58$$

The relative contribution of each independent variable to the model can be inferred from the percent of variance explained. Unaided VA, the most predictive variable (highest F-to-enter value in Table 3), alone explained 37 percent of the variance of aided VA, i.e., $R^2 = 0.37$. The combination of unaided VA and log NVG hours explained 60 percent of the variance of aided VA, i.e., $R^2 = 0.60$. Thus, the addition of log NVG hours to the model increased the prediction of the dependent variable by 23 percent (60 - 37 = 23).

Table 3.
List of candidate independent variables to predict aided visual acuity (high contrast) when the eyepiece is focused at infinity.

Variable	Partial correlation	F-to-enter
Unaided VA	0.61	6.50
Equivalent sphere	0.49	3.45
Sphere	0.39	1.99
Cylinder	0.41	2.16
Flight hours	-0.32	1.25
Log flight hours	-0.38	1.84
NVG hours	-0.49	3.40
Log NVG hours	-0.59	5.97

Table 4.
List of candidate independent variables to predict aided visual acuity (low contrast) when the eyepiece is focused at infinity.

Variable	Partial correlation	F-to-enter
Unaided VA	0.60	6.04
Equivalent sphere	0.30	1.05
Sphere	0.42	2.14
Cylinder	0.53	4.30
Flight hours	-0.57	5.39
Log flight hours	-0.60	6.06
NVG hours	-0.36	1.60
Log NVG hours	-0.43	2.45

Table 5.
List of candidate independent variables
to predict aided visual acuity (high contrast)
when the eyepiece is focused for best vision.

Variable	Partial correlation	F-to-enter
Unaided VA	0.29	1.01
Equivalent sphere	0.17	0.33
Sphere	0.18	0.37
Cylinder	0.21	0.53
Flight hours	0.09	0.09
Log flight hours	0.06	0.04
NVG hours	-0.28	0.93
Log NVG hours	-0.32	1.26

Table 6.
List of candidate independent variables to predict
aided visual acuity (low contrast) when
the eyepiece is focused for best vision.

Variable	Partial correlation	F-to-enter
Unaided VA	0.34	1.43
Equivalent sphere	-0.09	0.08
Sphere	0.22	0.58
Cylinder	0.17	0.33
Flight hours	-0.20	0.46
Log flight hours	-0.11	0.14
NVG hours	-0.09	0.09
Log NVG hours	-0.11	0.14

Aided visual acuity for low contrast targets

The list of candidate independent variables to predict aided VA for low contrast targets is given in Table 4. The variables that were selected from this list are given by the equation below, in which A_A represents aided acuity, A_U represents unaided acuity, and F_L represents the common logarithm of total flight hours (a log transform was performed because the distribution of total flight hours was asymmetric).

$$A_A = -0.04F_L + 0.34A_U + 0.82$$

The most predictive variable was log flight hours (highest F-to-enter value in Table 4), which alone explained 36 percent of the variance of aided VA, i.e., $R^2 = 0.36$. The combination of log flight hours and unaided VA explained 53 percent of the variance of aided VA, i.e., $R^2 = 0.53$. Thus, the addition of unaided VA to the model increased the prediction of the dependent variable by 17 percent (53 - 36 = 17).

User adjusted focus aided condition

When the NVG focus was adjusted by the user for best vision, aided VA was not predictable by any of the candidate independent variables. This was true at both levels of contrast (Tables 5 and 6).

Discussion

We found that the between-subject variations in unaided VA of nominal emmetropes do manifest themselves as corresponding fluctuations in aided VA when the NVG eyepieces are focused at infinity. This effect is robust with respect to changes in target contrast. However, the effect diminishes significantly when the eyepieces are focused by the user for best vision. This suggests that the relationship between unaided and aided VA among emmetropes is mainly due to an optical factor, e.g., clinically insignificant refractive error.

Multiple regression revealed that, when the eyepieces were focused at infinity, unaided VA and experience as a visual observer (i.e., log NVG hours and log flight hours) were important determinants of NVG VA. At high contrast, unaided VA explained the greatest proportion of the variance of NVG VA. At low contrast, total flight hours explained the greatest proportion of the variance of NVG VA. This suggests that experience as a visual observer is more important under degraded stimulus conditions than it is under optimal conditions. Refractive error was not selected for any of the multiple regression models although it is related to aided VA (Figure 6). This is because refractive error does not explain any of the variability of NVG VA that is not already explained by unaided VA.

Our data on the relationship between unaided and NVG VA among emmetropes is consistent with data from other studies in which the subjects had reduced unaided VA either due to astigmatism (Kim, 1982) or to eye disease (Hoover, 1983). The data from all three studies are fit well by the same regression line (R = 0.87) (Figure 8). Since there appears to be no significant difference between Kim's data from ametropes and Hoover's data from visually impaired subjects, perhaps the source of reduced unaided VA is not important in predicting aided VA.

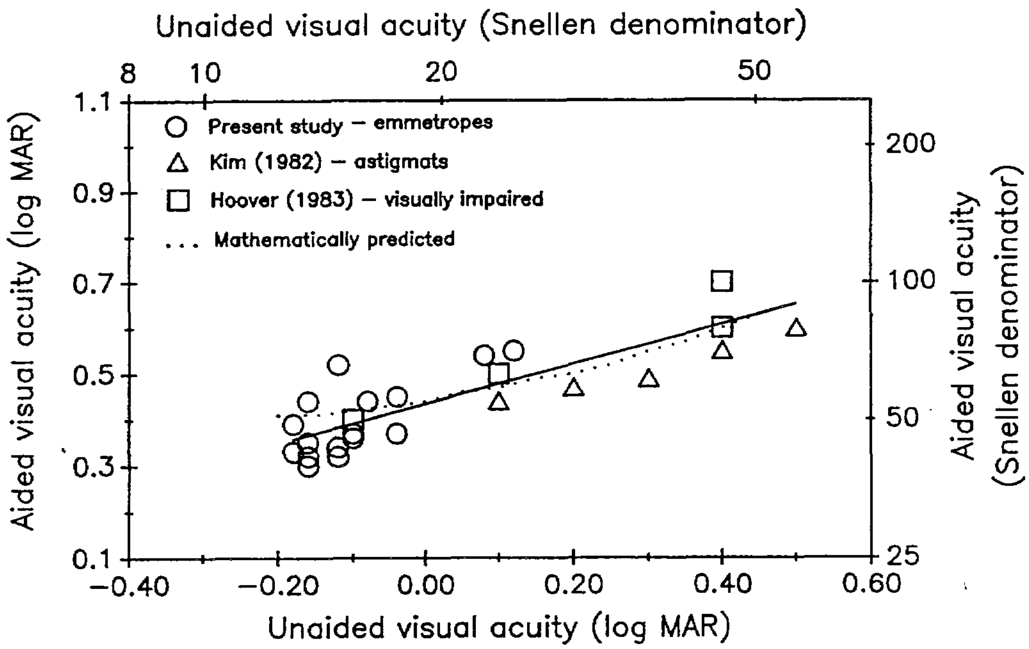

Figure 8. The relationship between NVG to unaided VAs, comparing observed to predicted results. A simple mathematical model seems to agree well with laboratory data from three independent studies.

Because Kim did not report unaided VA, we converted his measured astigmatism data to unaided VA based on the known relationship between the two (Peters, 1961). We controlled for between-study differences in NVG generation by comparing VAs from infinity focus third generation NVGs to VAs from adjustable focus second generation NVGs, because VAs have been shown to be similar under these two conditions (Kotulak and Morse, 1994a). In addition, we modified the exponents of the equation described in the introduction (Farrell and Booth, 1984) to obtain a better fit of the data, i. e.,

$$\frac{1}{R_C^{1.6}} = \frac{1}{R_H^{1.6}} + \frac{1}{R_L^{1.6}}$$

As can be seen in Figure 8, the predictions based on the modified equation are in close agreement with the observed results. This suggests that the Farrell and Booth resolution model is applicable to the eye-NVG system with only minor modification. Additional work needs to be done to determine the relationship between NVG and unaided VA for subjects with unaided VAs beyond the range of Figure 8.

The military significance of the present work lies with night vision devices which are either not spectacle compatible or which have a fixed focus eyepiece. An example of the former is the full faceplate AN/PVS-5 NVG that is used for ground troops, and an example of the latter is the helmet mounted display that is under development for the Comanche helicopter. The AN/PVS-5 has adjustable focus eyepieces, which when set properly, compensate for spherical refractive error (i.e., simple myopia or hyperopia) but not for astigmatism. The Comanche helmet mounted display will be spectacle compatible, but will have eyepieces in which the focus is fixed at infinity. The results of this study, whether considered alone or with the works of Kim (1982) and Hoover (1983), suggest that for either type of device any decrement in unaided VA produces an analogous loss in NVG VA.

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