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Relationship Among Accommodation, Focus and Resolution with Optical Instruments
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By

John C. Kotulak
and Stephen E. Morse

Aircrew Health and Performance Division

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Relationship among accommodation, focus, and resolution with optical instruments

John C. Kotulak and Stephen E. Morse

Visual Sciences Branch, U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama 36362-0577

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Key words: instrument myopia, accommodation, user focus adjustment, resolution, dark focus, no-instrument control, night vision goggles, contrast, luminance

INTRODUCTION

Optical instruments typically are focused as though the users were myopic, regardless of the observers' true refractive states.[1–6] This phenomenon has led to the idea that instrument viewing induces a transitory myopic condition, hence the term instrument myopia. The mechanism for instrument myopia is thought to be an increase in accommodation.[1–6]

Previous studies on instrument myopia usually have been limited to a single dependent variable, which was normally user focus adjustment (the focus setting made by the user of the instrument) but was occasionally either instrument accommodation (the observer's accommodation during instrument viewing) or instrument visual resolution (the visual resolution of the observer during instrument viewing). Until now, no investigation has dealt simultaneously with all three variables. In the research reported here we studied instrument myopia as an overall effect consisting of interactions among instrument accommodation, instrument visual resolution, and user focus adjustment, and we studied how these interactions vary with target luminance and contrast.

The focusing of optical instruments by the observer generally is thought to compensate for instrument accommodation; however, this has not been verified experimentally.[2–4,6] In past studies in which instrument accommodation was measured, the dioptric values of the focus settings were not reported,[3,7] and in studies in which user focus adjustment was measured, accommodation was not reported.[1,2,4,8,9] Thus we do not know whether observers adjust their instruments merely to compensate for existing instrument accommodation or whether they overadjust the focus and thus stimulate additional accommodation. We do know that user focus adjustment varies with technique, i.e., whether the change in focus is from positive to negative diopters (D) rather than the opposite.[2,3,8,9] This raises the possibility that user focus adjustment is not merely a compensation for existing instrument accommodation.

The presumed benefit of user focus adjustment is maximum resolution for the observer, but there is only indirect evidence that user focus adjustment actually improves resolution. Subjects without refractive error (emmetropes) were found to have better resolution when the instrument eyepiece was set (by the investigator) to low minus powers than when the eyepiece was set to infinity or to high minus powers.[10,11] The optimum power range was reported to be −0.50 to −1.00 D by Pearce *et al.*[10] and −1.00 to −2.25 D by Mouroulis and Woo.[11] However, no one has actually demonstrated an improvement in resolution when the observer, not the experimenter, adjusts the focus.

In addition to studying interactions among variables associated with instrument viewing, we also measured accommodation without the instrument under similar target conditions. This was done because we do not know whether there is any difference in level of accommodation between instrument and no-instrument conditions, given that the stimulus is similar.[5,6]

Current theory about instrument myopia comes from Leibowitz and Owens, who proposed that instrument myopia is a particular manifestation of a general tendency of accommodation to regress to its resting state, or dark focus.[7] Without instrument viewing, this bias of accommodation for the dark focus has been demonstrated under degraded stimulus conditions,[12–15] to a lesser extent under optimal conditions,[12–14] and when the accommodative feedback loop is opened with a small artificial pupil that increases the depth of focus of the eye.[16] With instrument viewing, a correlation between accommodation and dark focus has been described by several investigators.[3,7,17]

In the present study we sought to learn how the bias of accommodation toward the dark focus is affected by certain instrument design features. Earlier investigations of instrument accommodation were done with monocular, exit-pupil-forming instruments.[3,7,17] Monocular instruments probably increase dark-focus bias, as a result of the absence of vergence accommodation,[18] and instruments that form an artificial pupil that is smaller than the pupil

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of the eye also probably increase dark-focus bias by expanding the depth of focus of the eye.[3,7,17] By using a binocular instrument that does not form an exit pupil, we were able to test two predictions of the dark-focus-bias theory. First, the slope of the regression line that relates instrument accommodation to dark focus should be flatter than it was with monocular, exit-pupil-forming instruments. Second, the magnitude of accommodation should be less than it was with monocular, exit-pupil-forming instruments, possibly even approaching the magnitude of no-instrument accommodation.

One of the sequelae of using a binocular instrument is the possibility of an induced anisometropia secondary to discrepant between-eyepiece focusing. It is likely that at least some observers might focus the two oculars to different end points; e.g., one ocular might be overfocused more than the other. In such cases, it would be worthwhile to know what strategy accommodation adopts to deal with the conflicting stimuli to the two eyes. It is consistent with the dark-focus-bias theory that accommodation be driven by the eyepiece that is focused closest to the dark focus. In the present investigation we tested this strategy against several others.

In addition, we attempted to explain more of the variance of instrument accommodation than is explained by dark focus alone. Even under conditions that favor a correlation between instrument accommodation and dark focus, i.e., viewing through a monocular instrument with a small exit pupil, the largest value reported for Pearson's correlation coefficient was 0.78.[3] This means that, at most, only 61% ($0.78^2 = 0.61$) of the variance of instrument accommodation was explained by dark focus. Furthermore, with instruments that limit the bias of accommodation for the dark focus, it has been shown that the variance explained by dark focus decreases; e.g., Smith[17] used a telescope with an exit pupil larger than the pupil of the eye and found Pearson's R to be 0.54, which means that the variance explained by dark focus was only 29%.

Our approach was to use multiple regression so that we could simultaneously look at dark focus and at other factors that might explain the variance of instrument accommodation. Two other variables were selected: user focus adjustment and no-instrument accommodation. Neither of these new variables is necessarily completely independent of dark focus; however, as long as they have some independence, it is possible that they could contribute uniquely to the prediction of instrument accommodation. User focus adjustment was selected because of its obvious association with instrument accommodation, i.e., through either compensation or stimulation, as discussed above. No-instrument accommodation was selected because, unlike either dark focus or user focus adjustment, it takes into account properties of the stimulus, such as contrast, luminance, and spatial frequency, that are known to affect accommodative behavior.[12–14]

Another question of theoretical interest is, How are user focus adjustment and instrument visual resolution affected by the bias of accommodation toward the dark focus? Under monocular conditions visual performance tends to be optimal when the stimulus to accommodation is near the dark focus.[12,19,20] This is true probably because retinal image contrast is maximal when accommodation is most accurate, and this typically occurs when the stimulus is at the dark focus.[12] However, under binocular conditions, placement of the stimulus at the dark focus could produce a mismatch between accommodation and convergence, which could degrade visual performance. This mismatch would be minimal, however, if the dark focus were not too far from the convergence demand position, which is infinity for a binocular instrument with parallel optics. Thus a reasonable prediction of the dark-focus-bias theory is that user focus adjustment to the dark focus with a binocular instrument can improve visual performance if the dark focus is remote enough.

METHODS

Design

The dependent variables were accommodation, user focus adjustment, and instrument visual resolution. The experiment used a repeated-measures design, in which there were three independent variables: focus condition (fixed versus adjusted by user), contrast (high versus low), and luminance (high versus low). Accommodation was measured across three conditions: instrument, no-instrument, and in darkness. No-instrument accommodation was measured with both high- and low-contrast targets.

Optical Instrument

The optical instrument that we used in our study was a set of night vision goggles, i.e., the AN/AVS-6 Aviator Night Vision Imaging System (ANVIS).[21] ANVIS is a unity-magnification pair of binoculars that 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 monoculars are mounted such that their optics are parallel. The image is monochrome because it is displayed on a screen coated with a phosphor that has a narrow spectral bandwidth. The eyepiece functions as a simple magnifier,[22] which distinguishes ANVIS from exit-pupil-forming systems. The eyepiece has no measurable astigmatic aberration for on-axis viewing and no more than 0.125 D aberration for extreme off-axis viewing. The ANVIS modulation transfer function (Fig. 1) demonstrates that the image is spatially low-pass filtered. As a

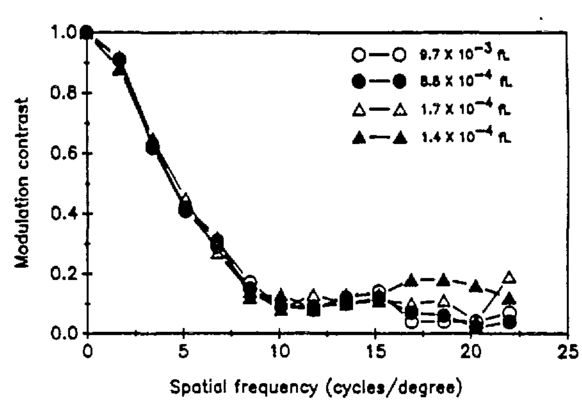

Fig. 1. ANVIS modulation transfer function at four levels of target luminance.

Table 1. Target Parameters

Parameter	Instrument High	Instrument Low	No Instrument High	No Instrument Low
Contrast (%)	62	12	98	21
Luminance (cd/m^2)	12	1	6.5	6.5

result, visual acuity with ANVIS under optimum conditions is only 20/35, and it gets worse with decreasing night sky luminance.[23]

Apparatus

Accommodation was measured with a dynamic infrared optometer, which provides continuous, precise (±0.1 D), and objective measurements of accommodation.[24] A beam splitter enabled the subject to view through the night vision goggles while accommodation was recorded by the optometer. The optometer was calibrated with human subjects ($n = 3$), each of whom wore (in turn) six hydrophilic contact lenses of varying powers. Cycloplegic eye drops were used on the subjects during the calibration so that accommodation was eliminated as an error source.

The resolution targets were high- and low-contrast Bailey–Lovie visual acuity charts.[25] The optotypes on these charts are letters that are made up predominantly of horizontal and vertical elements, although each line has at least one diagonal element. Two versions of the chart, differing only in letter sequence, were used at each level of contrast. Bailey–Lovie charts have a scale that is five times finer than that of Snellen-like charts, and their test–retest reliability is twice as great.[26] In addition, these charts incorporate an equal-interval scale that permits the use of parametric statistics.

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 in calculation of target contrast, both on the ANVIS phosphor screen under simulated night sky conditions (labeled Instrument in Table 1) and on the charts themselves under photopic conditions (labeled No Instrument on Table 1). Because the ANVIS modulation transfer function does not vary with night sky conditions (see Fig. 1), target contrast and spatial-frequency content are equal for the high- and the low-luminance conditions. Table 1 also gives the background luminance for the instrument and the no-instrument conditions, i.e., the luminance of the white portion of the chart.

Procedures

Before making focus adjustments, the subjects were trained how to reach a most-plus end point, i.e., how to use the most-plus (or least-minus) dioptric power that is required for best vision. This is consistent with established clinical technique for refraction.[27] Eyepiece power was verified with a dioptometer.[28] For the fixed-focus condition the eyepieces were set to 0.0 D. The distance between the optical centers of the eyepieces was set equal to the subject's interpupillary distance, and the subjects were aligned so that each eye was centered on its respective eyepiece. We made contrast changes by switching between charts and achieved changes in display luminance (Table 1) by setting the chart luminance to 0.01 cd/m^2 (full moon) for the high-luminance condition and to 0.0002 cd/m^2 (clear starlight) for the low-luminance condition. Contrast and luminance during instrument viewing were manipulated with a 2 × 2 block design; i.e., both high and low contrast were presented at high and low luminance.

In the no-instrument control experiment the charts were the same as those used in the with-instrument procedures described above; however, they were viewed directly (without the instrument) under photopic conditions (Table 1). The charts were located 5.8 m (0.17 D) from the subjects. Resolution and accommodation were measured with luminance fixed (Table 1) and with contrast varied (as above) by a change of charts.

Both resolution and accommodation were measured under binocular conditions, regardless of whether viewing was with or without the instrument. Resolution thresholds, which were defined as the common logarithm of the minimum angle of resolution (log MAR),[25] were recorded with use of Bailey–Lovie scoring procedures,[25] without a time limit and without reinforcement.

Accommodation was measured in the left eye for a period of 30 s per trial. Measurements were made only under steady-state conditions, in which the stimulus did not vary over time. The optometer output, which is analog, was input to an analog-to-digital converter installed in a computer and was sampled at 20 Hz. We determined the steady-state values for accommodation by averaging across the 600 samples that were collected per trial (30 s × 20 samples/s). The standard deviation (SD) of the means was generally less than 0.1 D, which is typical under steady-state conditions when the mean level of accommodation is low.[29] The SD varied little across conditions. Infinity was adopted as the zero reference point for accommodation. Positive values of accommodation were assigned when the eye was focused between infinity and the near point, while negative values were assigned when the eye accommodated less than would be required for it to compensate fully for a hyperopic refractive error. The subjects were instructed to keep threshold-sized letters clear by using the same effort that would be required for taking a visual acuity test and to change fixation from letter to letter on the same line every few seconds. The latter was done to prevent perceptual fading of the target that is due to the Troxler phenomenon.[30]

Dynamic infrared optometers are subject to artifacts from small pupils and from head and eye movements.[31] Small-pupil effects were prevented by dilation of the pupil with 2.5% phenylephrine hydrochloride. Two doses of phenylephrine, consisting of one drop each, were administered at 5-min intervals. It has been shown that a much stronger concentration of phenylephrine (10%) had no effect on the dark focus[32] and only a minimal effect on the amplitude of accommodation.[33] Artifacts from head and eye movements were eliminated by use of a chin cup and forehead rest to stabilize the head and a fifth-generation, dual-Purkinje image eyetracker to maintain alignment of the eye with the optometer.[34] Integration of the optometer with the eyetracker allowed the subjects to make small

Table 2. Astigmatism of Subjects

Type of Astigmatism	Mean (D)	SD (D)	*N*
Myopic	0.31	0.17	9
Mixed	0.83	0.29	3
Hyperopic	0.25	—	1

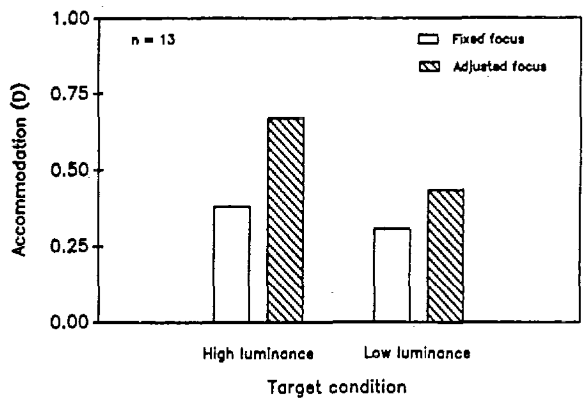

Fig. 2. Instrument accommodation as a function of target luminance for the fixed and the adjusted-focus conditions. Accommodation was averaged across target contrast because there was no significant main effect or interaction involving contrast.

horizontal and vertical eye movements without affecting the accuracy of the optometer.

Subjects

Thirteen volunteer subjects, who were either U.S. Army aviators ($n = 10$) or flight school students ($n = 3$), were recruited for the experiment. The mean (± SD) age was 27.1 ± 4.9 years. All subjects had unaided visual acuities of at least 20/20 in each eye and were free from eye disease and other ocular anomalies. The mean (± SD) equivalent-sphere refractive error (sphere power + half the cylinder power) was 0.1 ± 0.4 D of myopia. The mean (± SD) astigmatic refractive error was 0.4 ± 0.3 D, and the distribution of astigmatism by category is given in Table 2. The magnitude and type of astigmatism are such that the subjects probably would not exhibit a bias of accommodation for specific target orientations.[35]

RESULTS

Accommodation

The mean (± SD) no-instrument accommodation for high- and low-contrast targets was 0.44 ± 0.34 D and 0.45 ± 0.39 D, respectively, and the mean (± SD) dark focus was 0.48 ± 0.43 D.

The instrument accommodation data are summarized in Fig. 2. There was a significant main effect for focus condition ($F = 31.97$, $p = 0.0001$), indicating that accommodation was greater when the focus was adjusted by the user for best vision (mean across all conditions = 0.55 D) than when the focus was fixed at infinity (mean across all conditions = 0.35 D). In addition, there was a main effect for luminance ($F = 10.30$, $p = 0.008$), indicating that there was significantly more accommodation with high luminance (mean across all conditions = 0.53 D) than with low luminance (mean across all conditions = 0.37 D). This effect is more pronounced for adjusted than for fixed focus, as is evidenced by the significant interaction between focus condition and luminance ($F = 8.21$, $p = 0.01$). There was no main effect for contrast ($F = 1.24$, $p = 0.29$), and there were no other significant interactions.

Figure 3(a) shows that no-instrument accommodation is correlated with dark focus, and Figs. 3(b) and 3(c) show a similar effect for instrument accommodation for the fixed and the adjusted focus conditions, respectively. Accommodation is averaged across luminance and contrast in Figs. 3(b) and 3(c).

Visual Resolution

Mean (± SD) no-instrument visual-resolution thresholds for high- and low-contrast targets, expressed as log MAR, were −0.09 ± 0.09 (20/16 Snellen) and 0.16 ± 0.07 (20/29 Snellen), respectively.

Figure 4 shows how visual resolution through the instrument varies with focus condition, contrast, and luminance. There were significant main effects for focus condition ($F = 31.94$, $p < 0.0001$), contrast ($F = 861.98$, $p < 0.0001$), and luminance ($F = 136.41$, $p < 0.0001$). The main effect for focus condition indicates that there

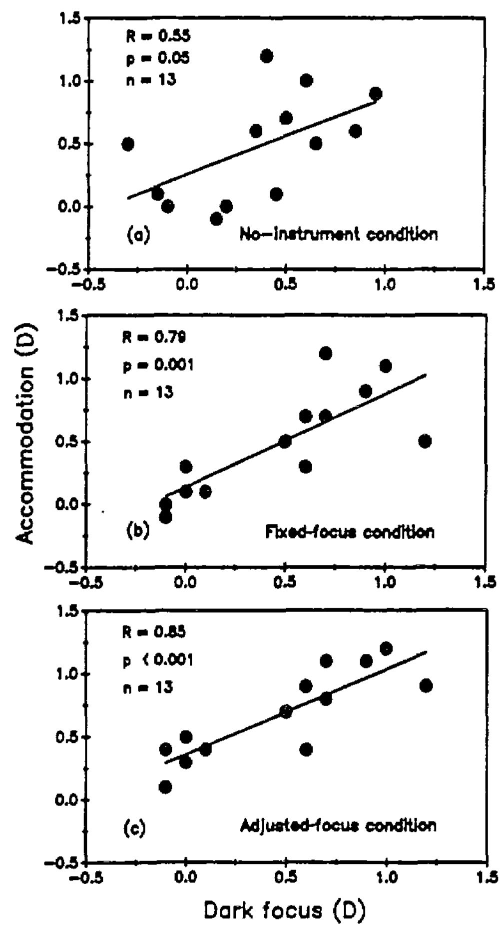

Fig. 3. Relationship between accommodation and dark focus. The correlation of no-instrument accommodation with dark focus is shown in (a). The correlations of instrument accommodation with dark focus for the fixed- and the adjusted-focus viewing conditions are shown in (b) and (c), respectively.

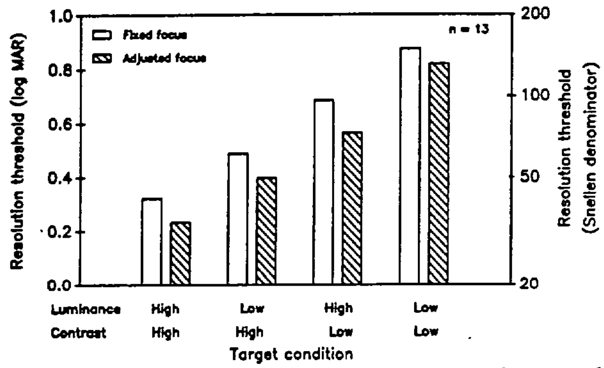

Fig. 4. Visual resolution through the instrument as a function of target contrast and luminance for the fixed- and the adjusted-focus conditions. The resolution thresholds are expressed both as the log MAR and in Snellen notation.

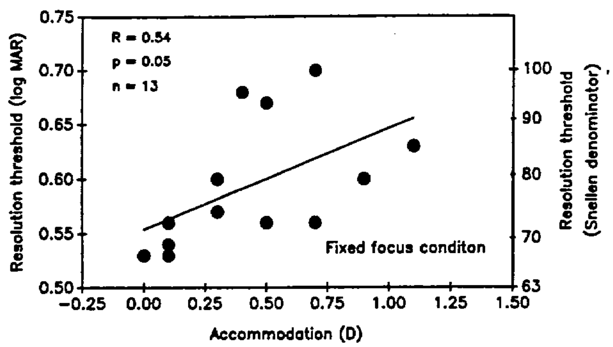

Fig. 5. Relationship between visual resolution through the instrument and instrument accommodation when the focus was fixed at infinity. The resolution thresholds are expressed both as the log MAR and in Snellen notation.

was significantly better resolution when the focus was adjusted by the user for best vision (mean log MAR across all conditions = 0.50, or 20/64 Snellen) than when the focus was fixed at infinity (mean log MAR across all conditions = 0.59, or 20/80 Snellen). There were also significant interactions between focus condition and luminance ($F = 5.51$, $p = 0.04$) and contrast and luminance ($F = 9.94, p = 0.008$) and among focus condition, contrast, and luminance ($F = 8.18, p = 0.01$). The interaction between focus condition and luminance suggests that the difference in resolution between fixed and adjusted focus at high luminance (log MAR = 0.10) is significantly greater than the difference at low luminance (log MAR = 0.06). The interaction between contrast and luminance is not within the scope of the present study, but it has been described elsewhere.[23] The three-way interaction among focus condition, contrast, and luminance suggests that the difference in resolution between fixed and adjusted focus that was found to be greater at high luminance than at low luminance (in the two-way interaction mentioned above) is greater when target contrast is low (log MAR = 0.12) than when contrast is high (log MAR = 0.08). Multiple-comparison testing, in which the p values were adjusted for alpha inflation with use of the Bonferroni method, revealed a significant difference between all meaningful pairings; e.g., the difference in resolution between fixed and adjusted focus was significant at high luminance and high contrast ($p = 0.05$), at low luminance and high contrast ($p = 0.02$), at high luminance and low contrast ($p = 0.008$), and at low luminance and low contrast ($p = 0.008$).

Figure 5 shows that, for the fixed-focus condition, subjects with less instrument accommodation tended to have better resolution than subjects with more instrument accommodation.

User Focus Adjustment

User focus adjustment averaged -1.13 ± 0.63 D. A repeated-measures analysis of variance revealed no significant differences for contrast ($F = 0.46$, $p = 0.51$) or luminance ($F = 0.00, p = 0.98$), and there were no significant interactions.

The mean (± SD) between-eyepiece difference in focus was 0.57 ± 0.47 D. All subjects exhibited discrepant focusing at least once (four opportunities to focus, two levels of contrast, and two levels of luminance were presented in a 2×2 block design). The minimum and maximum discrepancies were 0.00 and 1.00 D, respectively. Without regard to eye dominance, which was not measured in the study, we tested four strategies that could have been used by accommodation to deal with the conflicting stimuli to the two eyes: (1) mean dioptric power, (2) least dioptric power, (3) greatest dioptric power, and (4) dioptric power closest to the dark focus. Table 3 gives the results of simple linear regressions of instrument accommodation on user focus adjustment for each strategy. It can be seen that the greatest correlation is between instrument accommodation and the dioptric value closest to the dark focus, although the correlation with least dioptric power is also significant. Figure 6 illustrates the correlation between instrument accommodation, averaged across all target con-

Table 3. Correlation between Instrument Accommodation and Strategy for Resolving Conflicting Stimuli

Strategy	R	p
Mean dioptric power	0.53	0.08
Least dioptric power	0.69	0.01
Greatest dioptric power	0.24	0.43
Dioptric power closest to dark focus	0.72	0.006

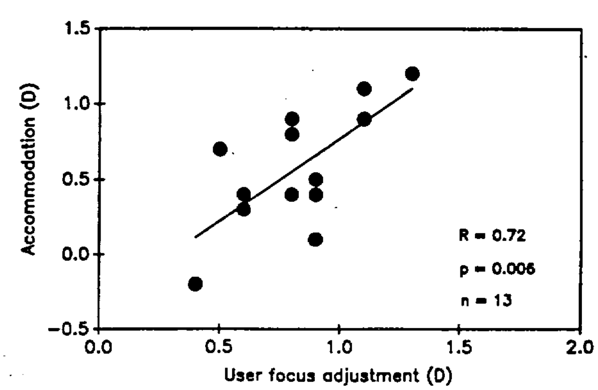

Fig. 6. Relationship between instrument accommodation and user focus adjustment. In cases of discrepant focusing between the two eyepieces, the eyepiece power closest to the dark focus is represented on the x axis.

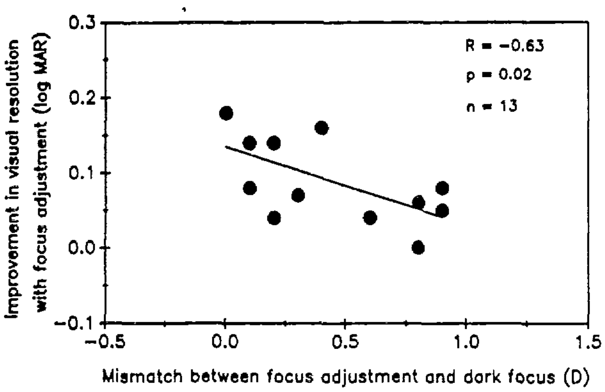

Fig. 7. Relationship between improvement in visual resolution with user focus adjustment and the closeness of the adjustment to the dark focus. The y axis depicts the difference in the log MAR between the infinity-fixed-focus and user-adjusted-focus conditions. In cases of discrepant focusing between the two eyepieces, the eyepiece power closest to the dark focus is represented on the x axis.

Table 4. List of Candidate Independent Variables as Predictors of Instrument Accommodation

Variable	Partial Correlation	F to Enter
User focus adjustment (closest to dark focus)	0.72	11.70
No-instrument accommodation	0.86	30.72
Dark focus	0.66	8.69

ditions, and eyepiece power. For observers who exhibited discrepant focusing between the eyepieces, the adjusted power closest to the dark focus was used.

Figure 7 demonstrates that subjects who adjusted the eyepiece close to their dark focus exhibited significantly more improvement in resolution than those who did not. The x axis in Fig. 7 is the difference between eyepiece power and dark focus. In cases in which eyepiece power differed between the two eyes, the eyepiece power that was closest to the dark focus was used. The y axis in Fig. 7 is the difference in resolution between the fixed and the adjusted focus conditions.

Multiple-Regression Equation for Instrument Accommodation

We used stepwise regression, a form of multiple regression, to select an optimal subset of independent variables for the prediction of instrument accommodation. Stepwise regression builds equations sequentially, at each step adding or deleting an independent variable from the equation. Variables that significantly enhance the prediction of the dependent variable are added, and variables that do not are deleted. Thus we can compare the predictive values of two or more candidate independent variables in a side-by-side manner and determine the relative predictive strength of each when it is weighed against the other variables.

Table 4 gives the variables that were tested as predictors of instrument accommodation. In this table partial correlation is equivalent to Pearson's correlation coefficient in simple linear regression, and F to enter is the test statistic for determining whether R is significant.

When excessive correlation exists among independent variables, a condition known as collinearity, stepwise regression loses accuracy. For the equation below we tested for collinearity at each step, and in no cases did it occur. It is important to note that collinearity refers only to excessive correlation of a variable in the equation with a variable remaining in the list of candidate independent variables. Thus collinearity cannot be determined merely by inspection of the partial correlations found in Table 4.

Three candidate variables, which were significantly related to instrument accommodation by simple linear regression, were tested: dark focus ($p = 0.01$), no-instrument accommodation ($p < 0.001$), and user focus adjustment closest to dark focus ($p = 0.006$). All three variables were incorporated by stepwise regression into the equation, which suggests that each provides a unique contribution to the prediction of instrument accommodation. The multiple-regression equation, in which A_a represents instrument accommodation for the adjusted-focus condition, F_d represents the user focus adjustment closest to the dark focus, A_n represents no-instrument accommodation, and A_d represents the dark focus, is

$$A_a = 0.47F_d + 0.53A_n + 0.24A_d - 0.11.$$

The R value associated with the above equation is 0.95, which indicates that it explains 91% of the variance of instrument accommodation. The relative predictive strength of each independent variable is given by its F-to-remove value, which is 21.75 for no-instrument accommodation, 8.47 for user focus adjustment closest to dark focus, and 4.86 for dark focus.

DISCUSSION

User focus adjustment generally is believed to compensate for the excessive accommodation that is thought to arise from instrument viewing.[1-6] In the present study, user focus adjustment averaged −1.13 D for emmetropic subjects, which seems to reinforce this view. However, the magnitude of instrument accommodation in our study was no greater than that of no-instrument accommodation, which suggests that myopic user focus adjustment can occur without the antecedent instrument-induced rise in accommodation. The similarity between the levels of instrument and no-instrument accommodation can be predicted from the dark-focus-bias theory and the design of the instrument that was used in this investigation. Because the night vision goggle eyepiece is a simple magnifier,[22] the exit pupil of the instrument is the entrance pupil of the eye; this identity tends to equalize the degree to which the accommodative feedback loop is open under instrument and no-instrument conditions.

Since there was no instrument-induced increase in accommodation, why did our emmetropic subjects focus as though they were myopic? Even without such a rise in accommodation, the subjects were functionally myopic for the fixed infinity-focus condition, on average by 0.35 D, owing to the overaccommodation that typically accompanies the viewing of distant objects. User focus adjustment did compensate for this overaccommodation, but there was a significant degree of overcompensation as well. Of the

0.55 D of accommodation that was measured during the adjusted-focus condition, about a third (0.2 D) seems to be the effect of the overshoot of user focus adjustment.

Resolution did improve with user focus adjustment, despite the apparent overshoot. Figure 7 shows that the subjects whose resolution improved the most with user focus adjustment were those who had the smallest mismatch between eyepiece power and dark focus. Thus what we described above as overfocus could be (in part) alignment of the stimulus with the dark focus. Although such an alignment has been reported to improve visual performance under monocular conditions,[12,19,20] to our knowledge this effect has not been shown binocularly. We hypothesize that such an effect can occur under binocular conditions only if the resultant mismatch between accommodation and convergence is not too great. In the present study the relatively remote dark focus of our subjects tended to keep this mismatch within acceptable limits.

User focus adjustment was not affected by luminance, a finding that is consistent with the findings of some previous investigators[2,8] but not with those of others.[36,37] This dissimilarity may be due to between-study differences in luminance range, which tended to be larger in studies in which luminance affected user focus adjustment. However, we did find a luminance effect on instrument accommodation; i.e., at high luminance the lag of accommodation decreased, and hence the magnitude of accommodation increased for the adjusted-focus condition. This finding is consistent with findings in other studies, in which it was found that accommodative accuracy is proportional to luminance.[12,14] We also found that visual resolution through the instrument was worse at low than at high luminance, an effect that was previously reported for night vision goggles[23] and for no-instrument viewing.[12]

Contrast affected neither instrument nor no-instrument accommodation in our study; however, it did affect both instrument and no-instrument resolution. Ciuffreda suggested that accommodation is independent of contrast until some critical low level of contrast is reached.[38] Resolution, however, does vary over the contrast range that we used in our study, both with night vision goggles[23] and without them.[39]

Our results show that the correlation between instrument accommodation and dark focus that was demonstrated by Hennessy,[3] Leibowitz and Owens,[7] and Smith[17] for monocular, exit-pupil-forming systems also can be observed in a binocular instrument that does not form an exit pupil. In addition, we found that this correlation holds regardless of whether the focus was fixed at infinity [Fig. 3(b)] or was adjusted by the observer for best vision [Fig. 3(c)]. In previous studies the infinity-focus condition was not tested.[3,7,17] Furthermore, like Leibowitz and Owens,[7] we found that no-instrument accommodation (to a real target at optical infinity) was correlated with dark focus [Fig. 3(a)]. However, in our experiment no-instrument accommodation was measured under binocular viewing conditions rather than the monocular conditions used by Leibowitz and Owens.[7] This is further evidence for the general nature of the dark-focus-bias theory of accommodation.

Furthermore, the dark-focus-bias theory predicts a flatter slope for the regression line that relates instrument accommodation to dark focus for a binocular instrument without an exit pupil than for monocular instruments with small exit pupils. Our results confirm these predictions. The slopes reported by Hennessy[3] and by Leibowitz and Owens[7] for monocular instruments with small exit pupils were close to 1.0, while in the present study the slopes were 0.74 and 0.67 for the fixed and the adjusted conditions, respectively [Figs. 3(b) and 3(c)].

Another prediction of the dark-focus-bias theory is that, when one eyepiece of a binocular instrument is overfocused more than the other, accommodation will be governed by the eyepiece that is focused closest to the resting point of accommodation. In the present study we did find a significant between-eyepiece focus difference of 0.57 D, and we also found that accommodation seemed to be driven by the eyepiece that was adjusted closest to the dark focus. The latter finding suggests that accommodation values economy of motor effort over equalization of the blur between the two eyes.

We also found that no-instrument accommodation was itself correlated with instrument accommodation (see Table 4) and that when both no-instrument accommodation and dark focus were entered into the same multiple-regression equation, no-instrument accommodation was the more powerful predictor of instrument accommodation. This suggests that, given an instrument whose design tends to limit dark-focus bias, the target that is viewed through the instrument takes on added importance in the prediction of instrument accommodation.

Because of the great variety that exists among optical instruments, it is worthwhile to consider the degree to which findings on instrument myopia from any one instrument can be generalized to instruments as a whole. We have already devoted considerable attention to the effects of design characteristics that distinguish night vision goggles from the devices used in previous instrument-accommodation research, namely, binocular viewing and the absence of an exit pupil. Both of these design features tend to minimize accommodative dark-focus bias and thus reduce the amount of instrument accommodation, which helps to explain why we found less instrument accommodation than did other investigators.[3,7,17] In addition, the relatively aberration-free optics of the particular night vision goggles used in this study also probably serves to keep the level of accommodation low. Charman and Whitefoot have shown that instrument aberrations, such as astigmatism, stimulate accommodation.[40]

Another factor that likely contributed to the disparity in the magnitude of instrument accommodation between this and other studies is between-study differences in dark focus. The mean dark focus of our subjects was 0.48 D, which is considerably less than the mean of 1.71 D that was obtained by Liebowitz and Owens from a larger sample ($n = 124$).[7] Since the amount of instrument accommodation depends heavily on the magnitude of the dark focus, it is probable that higher degrees of instrument accommodation would have been found in the present study if the dark focus of our subjects had been greater.

Two explanations have been put forth for what causes differences in dark focus among samples: refractive error[41-43] and type of optometer.[44-46] However, neither explanation appears to explain this discrepancy fully. Investigators disagree about the relationship between refractive error and dark focus; e.g., Simonelli[41] found greater values of dark focus associated with myopia, Maddock *et al.*[42] found the opposite, and Fisher *et al.*[47] found no difference. Other investigators have determined that laser optometers tend to overestimate the dark focus.[44-46] However, at least two investigators, using laser optometers, have reported relatively low dark-focus values.[41,48]

In conclusion, because of the diversity among optical instruments the results of this or any other single-instrument study cannot be expected to apply equally well to all instruments. However, we were able to identify a small set of variables, which when taken together account for 91% of the variance in instrument accommodation. Additional research is needed to determine whether this set of variables would be equally predictive with other instruments. It is virtually certain, though, that the relative predictive strength of each variable will change with differing instrument-design features. With instrument designs that favor regression of accommodation to the dark focus, the relative predictive strength of dark focus is expected to increase.

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All reprint requests and other correspondence should be sent to John Kotulak.

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