5C LEVEL II

(12)

NAMRL MONOGRAPH - 28

A REVIEW OF DYNAMIC VISUAL ACUITY

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DEPARTMENT OF THE NAVY ★ AEROSPACE MED RESEARCH LABORATORY

March 1980

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Naval Medical Research and Development Command
MF51.524.004.2011
MR041.01.03.0154

Approved by	Released by
Ashton Graybiel, M.D. Assistant for Scientific Programs	Captain R. E. Mitchel, MC, USN Commanding Officer

11 March 1980

Naval Aerospace Medical Research Laboratory
Naval Air Station
Pensacola, Florida 32508

ABSTRACT

In many everyday situations relative motion exists between human beings and the visual information which they must acquire and resolve in order to perform their tasks successfully. In particular, tasks, such as flying aircraft, driving automobiles and other vehicles, and resolving moving information presented via visual displays, impose a requirement on the human operator to process moving information. Since Dynamic Visual Acuity (DVA) is a critical visual skill involved in performing such visual tasks, the present review was undertaken in order to better understand this visual skill and to provide a basis for continuing research in this area.

Considerable research in the area of DVA has been undertaken since the review published in 1962 by Miller & Ludvigh, which included DVA research performed prior to 1960. The present review summarizes the DVA literature and findings included in the 1962 review, presents findings of DVA investigations reported between 1960 and 1978, and relates some of the latter findings to the former.

ACKNOWLEDGMENTS

The author gratefully acknowledges the valued comments, personal interest, time, and effort directed toward this review by Captain James E. Goodson, MSC, USN (Ph.D), and the assistance of Ms. Rachel Gadolin and Mr. Delbert Turner, who typed the manuscript.

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6 11 5 80

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER
⑭ NAMRL-Monograph-28

2. GOVT ACCESSION NO.
AD-A085 860

3. RECIPIENT'S CATALOG NUMBER

4. TITLE [illegible]
⑥ A Review of Dynamic Visual Acuity.

~~5. TYPE OF REPORT & PERIOD COVERED~~
⑨ Interim rept.,

~~6. PERFORMING ORG. REPORT NUMBER~~

7. AUTHOR(s)
⑩ Tommy R. Morrison, LT MSC USN

⑫ 28

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Aerospace Medical Research Laboratory
NAS, Pensacola, Fl 32508

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
MF51.524.004.2011
MR041.01.03.0154

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Medical Research and Development Command
Navy Department, Washington, D. C.

~~12. REPORT DATE~~
⑪ Mar[illegible]80

~~13. NUMBER OF PAGES~~
24

~~14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office)~~
⑯ F51524, MR04101

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

⑰ MF51524004, MR0410103

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

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Naval Air Development Center, Warminister, Pennsylvania 18974

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Visual Information
Visual Displays
Dynamic Visual Acuity
DVA
Visual Skills

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

406061

20. (Cont'd)

Considerable research in the area of DVA has been undertaken since the review published in 1962 by Miller and Ludvigh which included DVA research performed prior to 1960. The present review summarizes the DVA literature and findings included in the 1962 review, presents findings of DVA investigations reported between 1960 and 1978, and relates some of the latter findings to the former.

INTRODUCTION

Dynamic visual tasks are differentiated from static visual tasks by the presence of relative motion between the target and the observer. Ludvigh and Miller (22) first used the term "Dynamic Visual Acuity" (DVA) to distinguish visual acuity ability during ocular pursuit of a moving target from "Static Visual Acuity" (SVA); i.e., visual acuity for stationary targets. In a comprehensive synthesis of DVA-related literature, Miller and Ludvigh (38) summarized in detail the results of investigations performed between 1937 and 1960. The present report reviews work in DVA since 1962 and relates these later studies to the findings and conclusions of the earlier review. A brief summary of Miller and Ludvigh's 1962 report is presented to provide a framework for discussion of current findings.

I. DVA FINDINGS/CONCLUSIONS PRESENTED BY MILLER & LUDVIGH (1962)

Relationship Betweeen DVA and Target Angular Velocity

The most ubiquitous finding reported in the DVA literature is that visual acuity deteriorates as relative angular velocity between observer and target object increases. This general relationship has been investigated under various conditions; e.g., for targets moving in both vertical and horizontal directions (34) at different levels of illumination (21, 32); with circular versus linear target movement (30), with observer rotating while target was stationary (33); and for inflight subjects observing ground-based targets (16). Studies since 1960 have demonstrated similar effects of target angular velocity upon DVA utilizing various types of apparatus, procedures, and test targets (2,3,4,5,13), and have investigated the effects upon DVA of sex and age (5,7,8) and species; i.e., man and monkey (1).

Ludvigh (21) was first to describe mathematically the general relationship between visual acuity and target angular velocity. In his equation, $V.A. = \underline{a} - \underline{b}\,\underline{\alpha}$; where V.A. = visual acuity, $\underline{a}$ = static visual acuity, $\underline{\alpha}$ = target angular velocity, and $\underline{b}$ = rate of deterioration of visual acuity. Ludvigh and Miller (22) modified Ludvigh's (21) equation and found the equation $Y = \underline{a} + \underline{b}\,\underline{x}^3$ to provide a good empirical fit for their grouped data, where Y = visual angle in minutes of arc, $\underline{x}$ = target angular velocity in deg/sec, $\underline{a}$ = the individual's predicted SVA level, and $\underline{b}$ = a dynamic acuity component. As Ludvigh and Miller (22) pointed out, the equation is most applicable when 0.4 sec is allowed for target viewing. When target angular velocity is zero, the equation reduces to $Y = \underline{a}$, and $\underline{a}$ is the predicted SVA with 0.2 sec allowed for attaining fixation and 0.2 sec allowed for observation. For high target angular velocities, the value of Y is determined mainly by the $\underline{b}\,\underline{x}^3$ term. In their numerous investigations, Ludvigh and Miller were able to best fit their grouped data to the latter equation (22,23,24,26,33,34,35,36).

Plane of Pursuit

Miller and Ludvigh (34) investigated DVA with targets moving in the vertical plane. Nine subjects were employed who had been tested previously for DVA in the horizontal plane in the Ludvigh and Miller (22) study. The vertical plane thresholds were fitted to the equation $Y = \underline{a} + \underline{b}\,x^3$, and the $\underline{a}$ and $\underline{b}$ parameters for the vertical and horizontal planes were compared. Miller and Ludvigh (38), in reference to the Miller and Ludvigh 1953 study, stated that a significant difference was found between the two planes of pursuit for the $\underline{a}$ parameter at the 0.03 level of confidence, while no difference was found between the $\underline{b}$ parameters. Miller (33) was unable to explain this difference for the $\underline{a}$ parameter, which would predict different SVA levels for the two mirror orientations even if the mirror was not moving. Miller and Ludvigh (38) also reported a study which compared DVA thresholds obtained at a 110°/sec for horizontal and vertical target movement. A significant difference ($\underline{p} < .01$) was obtained for the four subjects employed.

In addition, Miller and Ludvigh (34) examined the relationship between DVA ability for horizontally and vertically moving targets. They correlated the $\underline{a}$ parameters for horizontal and vertical target movement, and likewise the $\underline{b}$ parameters. The correlation between the $\underline{a}$ parameters was $\underline{r} = .53$ (s.d. = 0.254, N = 9), and for $\underline{b}$, $\underline{r} = .96$ (s.d. = 0.028, N = 9). Miller and Ludvigh (34) concluded that individuals with superior DVA for horizontally moving targets were also superior with vertically moving targets.

E. F. Miller, II (30), investigated the relationship between DVA measured with targets moving in the horizontal plane and targets moving in a circle perpendicular to the line of sight. He obtained correlations of $\underline{r} = .61$ (s.d. = 0.082, N = 60), and $\underline{r} = .60$ (s.d. = 0.083, N = 60) for 110°/sec (horizontal movement) versus 50°/sec (circular movement) and 110°/sec (horizontal) versus 77°/sec (circular), respectively, for the threshold measures. Thus, individuals who were velocity resistant to targets moving in the horizontal plane were also velocity resistant to rotary motion of the test target.

Illumination

Numerous investigations have demonstrated that SVA improves with increasing illumination up to approximately 100 ft-c, above which little further improvement results with further increases in illumination (18,42,46). Ludvigh (21) investigated SVA and DVA under illumination conditions from -3.6 to 2.7 log ft-c. For SVA, Ludvigh (21) found little improvement above 100 ft-c; however, DVA at 90°/sec target velocity was still improving at 505 ft-c. In the DVA task, the target moved in a circle perpendicular to the subject's line of sight.

J. W. Miller (32) investigated the effect of illumination on DVA with the target stationary and the subject rotating in a Link trainer. He employed speeds of 0, 20, 50, 80, 110, and 120°/sec and illumination levels from 0.04 to 125.0 ft-c. With the subject stationary SVA thresholds were practically asymptotic at 10 ft-c, while DVA thresholds at 110 and 120°/sec were still improving under 125 ft-c illumination. J. W. Miller (32) indicated that the beneficial effect of illumination on DVA was greater for the higher target angular velocities.

Observer Rotating

Having previously demonstrated the relationship between DVA and target angular velocity with a moving target and stationary observer, Miller (33) investigated DVA while the observer rotated and viewed a stationary target. Subjects were rotated at 20, 50, 80, 110 and 124°/sec in a Link trainer and viewed the target through a mirror mounted in the trainer. The mirror was masked in the same manner as the rotating mirror in the Ludvigh and Miller 1953 study.

The equation $Y = \underline{a} + \underline{b}\,\underline{x}^3$ was fitted to these data and found to satisfactorily describe the functional relationship between visual acuity and target angular velocity. Miller (33), therefore, concluded that the deterioration of DVA with increasing target angular velocity is similar whether the target is moving and observer is stationary, or vice versa.

Practice Effects and Transfer of Training

Ludvigh and Miller (23) investigated the effect of practice on DVA at target angular velocities of 20 and 110°/sec within 200 subjects. At 110°/sec substantial improvement occurred -- the initial mean theshold was 11.28' of arc, while the twentieth was 4.97'. For 20°/sec the first and twentieth mean thresholds were 2.48' and 1.55' of arc, respectively. Further, Ludvigh and Miller (23) obtained 180 thresholds on eight other subjects over a 3-week period. It was found that the threshold level after 180 determinations was not significantly lower than threshold values obtained during the initial 15-20 threshold measures.

Miller and Ludvigh (37) performed a similar investigation of the effect of practice on DVA, using 1,000 subjects. The results indicated substantial improvement occurred with practice at 110°/sec, but only slight improvement was observed at 20°/sec. Initial mean thresholds were 2.27' and 8.53' of arc, while the tenth (last) thresholds were 1.84' and 5.48' of arc for 20 and 110°/sec, respectively. In both the Ludvigh and Miller (23) and Miller and Ludvigh (37) investigations, substantial individual differences in terms of improvement in DVA with practice were found.

The effect of transfer of training on DVA was investigated by Ludvigh and Miller (25). No significant improvement resulted at 110°/sec following practice at 20°/sec when thresholds across the 20 trials were combined. However, subjects who had received previous practice at 20°/sec obtained an asymtotic threshold level faster, although the threshold level asymptote was the same. No significant improvement occurred at 20°/sec following practice at 110°/sec.

Reliability of DVA Scores

Miller and Ludvigh (32) found their method of measuring DVA to have extremely high internal consistency. Means of odd and even threshold obtained at a target speed of 110°/sec correlated .99. Original and retest scores (7-month interval) for 120 subjects correlated .65 for the $\underline{a}$ parameter and .87 for the $\underline{b}$ parameter. Higher test-retest correlations for $\underline{b}$ values were attributed to the wider range of $\underline{b}$ values relative to the small range of $\underline{a}$ values within their subjects (38).

Individual Differences

Ludvigh and Miller performed two investigations which examined the manner in which DVA ability was distributed among their subject population -- naval aviation cadets. In the Ludvigh and Miller (24) investigation, 200 subjects were run at 20 and 110°/sec target angular velocity. The mean thresholds were 1.74' and 6.71' of arc, while the threshold ranges were 0.88' - 3.63' and 1.5' - 12.5' of arc for 20 and 110°/sec, respectively. Analysis of the data indicated that DVA thresholds obtained at 20 and 110°/sec were not normally distributed.

In a later investigation Miller and Ludvigh (36) performed a similar analysis of data obtained from 1,000 subjects. The mean thresholds obtained were 1.93' and 6.10', and the threshold ranges were 0.6' - 5.0' and 0.5' - 15.5' of arc for 20 and 110°/sec, respectively. Further analysis of the mean data indicated that DVA ability at 20 and 110°/sec was neither normally distributed, nor distributed according to a Poisson distribution, among the subject population tested. Miller and Ludvigh (36) suggested that the finding of nonnormality of the distribution of DVA ability possibly resulted from their subjects having previously been selected with respect to SVA, but not with respect to DVA.

The Miller and Ludvigh (36) and Ludvigh and Miller (24) data clearly demonstrated that individuals possessing similar SVA ability (20/20 or better) differed dramatically on the basis of their DVA. The range of threshold sizes in minutes of arc for 110°/sec are comparable to standard visual acuity scores ranging from 10/20 to 20/310. Further, as shown by the Ludvigh and Miller (22) data, the DVA of certain individuals was superior to that of other individuals at low speeds but was inferior at higher speeds, and vice versa.

II. ORGANISMIC VARIABLES RELATED TO DYNAMIC VISUAL ACUITY

Relationship Between SVA and DVA

Miller and Ludvigh have on various occasions examined the relationship between SVA and DVA by computing product moment correlations between their *a* and *b* parameters. The obtained correlations which follow indicate that the *a* and *b* parameters are unrelated: .08 (N = 200) (24), .08 and .03 (N = 200) (35), and .13 (s.d. = 0.0311, N = 1,000) (36). "Since *a* is a measure of static acuity and *b* a measure of velocity susceptibility, there is no very obvious *a priori* reason why *a* and *b* should be related" (36, p.9).

Further evidence for a lack of a substantial relationship between DVA and SVA has been ascertained from the following obtained correlations between acuity thresholds obtained at a slow speed, 20°/sec, and at a fast speed, 110°/sec: .30 (N = 200) (24), .38 and .19 (N = 200) (35), and .09 (N = 1,000) (36). "This low *r* demonstrates that the two variables are not intimately related, further demonstrating the fact that the concepts of static and dynamic visual acuity are indeed relatively independent of each other" (36, p. 10).

Thus, in view of the above lack of relationship between the *a* and *b* parameters, and low correlation between 20°/sec and 110°/sec thresholds, one would predict a high correlation between 20°/sec thresholds and the *a* parameter, and between 110°/sec thresholds and the *b* parameter if indeed *a* and *b* represent static and dynamic acuity, respectively. The following correlations were obtained between *a* and 20°/sec thresholds: .98 (N = 200) (24), .98 and .99 (N = 200) (35), and .97 (N = 1,000) (36); and obtained correlations between *b* and 110°/sec thresholds were .92 (N = 200) (24), .92 and .97 (N = 200) (35), and .96 (N = 1,000) (36). Miller and Ludvigh's data offer strong support for a lack of relationship between SVA (*a*) and DVA (*b*).

Ferguson and Suzansky (14) have presented data supporting a lack of relationship between SVA and DVA scores. In their investigation DVA thresholds were obtained at four speeds (25, 30, 40, 45°/sec) and four target exposure durations (0.4, 0.6, 0.8, and 1.0 sec), thus resulting in 16 DVA conditions. In only two of these conditions significant correlations were obtained between DVA and SVA; in one case the correlation was positive, in the other, negative.

Although Miller and Ludvigh consistently reported no relationship between SVA and DVA, the following investigators have reported findings indicating that SVA and DVA are related. Hulbert et al. (19) correlated SVA and binocular DVA thresholds, using Ortho-Rater checkerboard acuity targets in both dynamic and static tests. No relationship was found between SVA and DVA scores for target velocities of 120°/sec and 180°/sec; however, correlations between SVA and DVA scores for target speeds of 20°/sec and 60°/sec were .41 and .43, respectively, both $p < .01$. Hulbert et al. (19) suggested that the critical speed above which the relationship between SVA and DVA breaks down is probably between 60°/sec and 120°/sec. Basically, the Hulbert et al. (19) apparatus consisted of a projector mounted on a revolving turntable and a cylindrical white screen which had a 4-ft radius and was 180° in azimuth. The center of the screen, rotation axis of the projector, and the subject's head were all in vertical alignment.

Burg and Hulbert (8) investigated the relationship between DVA and SVA, sex and age, using the same DVA apparatus as Hulbert et al. (19). Binocular SVA measures were determined by: 1) standard techniques using a Bausch and Lomb Ortho-Rater (O-R SVA), and 2) presenting Ortho-Rater checkerboard acuity targets on the DVA screen via the DVA apparatus but with the projector stationary (Screen O-R SVA). During DVA testing the 236 subjects viewed the Ortho-Rater checkerboard targets binocularly during "one sweep across the screen."

When subjects were allowed free head movement during DVA, correlations between O-R SVA and DVA were .31 ($p < .02$), .28 ($p < .001$), .24 ($p < .01$), .21 ($p < .01$), and .17 ($p < .02$), for 20, 60, 90, and 150°/sec target angular velocities, respectively. Again, allowing free head movement during DVA, the correlations obtained between Screen O-R SVA and DVA were .52 ($p < .001$), .63 ($p < .001$), .27 ($p < .001$), .46 ($p < .001$), and .41 ($p < .001$), for 20, 60, 90, 120, and 180°/sec target angular velocities, respectively.

When subjects performed DVA with head fixed by means of a bite bar, only DVA at 120°/sec was found to be related to O-R SVA, $r = .47$ ($p < .001$); while for Screen O-R SVA and DVA, significant correlations of .35 ($p < .01$) and .32 ($p < .01$) were obtained at 60 and 120°/sec target angular velocities, respectively.

Burg and Hulbert (8) suggested that factors other than SVA are involved in DVA ability. Although such nonacuity factors are not known, things such as the efficiency of integration of the entire oculomotor system, attention, and practice are probably involved. Such a suggestion is congruent with that of Miller and Ludvigh, " . . . that dynamic visual acuity is indeed dependent upon the entire oculomotor pursuit mechanism . . . " (38, p. 92). The inaccuracy of pursuit would undoubtedly result in image movement across the retina. As Ludvigh (21) reported, such image movement of 10°/sec over a circular path 2° concentric from the fovea resulted in deterioration of DVA to about one-fourth of the SVA value determined at the same retinal location.

Burg (5) investigated the relationships between driving record, SVA, DVA, age, and sex. The obtained correlations between SVA and DVA at 90 and 120°/sec were .62 (N = 1,219) and .57 (N = 1,216), respectively, for males, and .53 (N = 663) and .54 (N = 662), respectively, for females. Burg (5) also derived multiple regression equations which predicted DVA (Y) from SVA (X_1) and age (X_2). Separate regression equations were derived for males and females for each speed, i.e., 90 and 120°/sec, thereby producing four regression equations. The obtained multiple correlation coefficients (R) were: 1) $R_{Y.X_1X_2} = .75$ for DVA at 90°/sec with males, 2) $R_{Y.X_1X_2} = .73$ for DVA at 120°/sec with males; 3) $R_{Y.X_1X_2} = .73$ for DVA at 90°/sec with females; and 4) $R_{Y.X_1X_2} = .70$, for DVA at 120°/sec with females. All multiple correlation coefficients and b-coefficients were significant ($p < .01$). The b-coefficients were 0.488, 0.378, 0.345, and 0,347 for SVA, and -0.005, -0.0053, -0.0054, and -0.0046, for age. Thus, in Burg's regression equations, the major determiner of DVA was SVA. Burg concluded, "The relationship between dynamic and static acuity, then, is strong, and in all probability, static acuity can be considered the best single predictor of dynamic visual acuity" (5, p. 99). The DVA apparatus used by Burg (5) was functionally similar to the earlier test unit (19) and was later described in detail by Burg (6).

In a definitive effort to determine the relationship between SVA and DVA, Burg (7) measured the two abilities in an extremely large and heterogeneous group of subjects. Of the 17,500 subjects, 62.8 percent were male and 37.2 percent were female; ages ranged from 16 to 92 years; and SVA ranged from 20/13 to 20/200. The same rotating projector system as described by Burg (6) was used in this investigation. As in Burg and Hulbert (8), SVA was measured via standard Ortho-Rater techniques (O-R SVA) and by projecting Ortho-Rater checkerboard acuity targets on the DVA screen with the projector stationary (Screen O-R SVA), while DVA was measured at target angular velocities of 60, 90, 120 and 150°/sec. During DVA testing, targets were exposed for 180° of target movement.

Burg's results (7) showed quite high correlations existing between all the acuity tests, with rs between SVA and DVA decreasing with increasing test speeds. The obtained rs between O-R SVA and DVA were .598 (N = 16,923), .541 (N = 17,254), .499 (N = 17, 186), and .350 (N = 6,629); while Screen O-R SVA and DVA rs were .710 (N = 9,798), .634 (N = 9,796), .565 (N = 3,763), and .452 (N = 6,195) for target angular velocities of 60, 90, 120 and 150°/sec, respectively.

Elkin (13) reported evidence of a relationship between DVA and SVA. His apparatus consisted of a boom which pivoted overhead the seated subject and from which a target was mounted to the end of the boom. The target mount was fabricated so that the Landolt-C target was viewed through an annulus cut through a piece of material attached to the boom end between subject and target. The subject was enclosed by a cylindrical partition of 180° azimuth, the top portion of which could be opened and closed in various azimuth amounts. The top portion of the partition precluded viewing of the target through the aperture, thus controlling target exposure time. Anticipatory tracking time (ATT) consisted of the time allowed for viewing the annulus prior to the target coming into view. Two ATTs were used; they were 0.2 and 1.0 sec. Target exposure time (ET) was the time during which the target was visible through the aperture. Two ETs, 0.2 and 0.5 sec, were used. The subject's left eye was occluded by an eye patch.

Elkin reported " . . . significantly positive correlations on the order of .17 were found between the subject's static and dynamic visual acuity scores when 0.5 sec was allowed for target viewing" (13, p. 32). However, no probability values were presented for the significant correlations, nor were the ATTs given which were used with the 0.5 sec ET, nor did he indicate for which of his target speeds (30, 60, 90, and 120°/sec) DVA was related to SVA.

For comparison purposes, Elkin (13) reported a mean DVA threshold of 2.42' of arc for 120°/sec, with ATT = 0.2 sec and ET = 0.2 sec, while Ludvigh and Miller (22) reported a mean DVA threshold slightly greater than 6' of arc at 110°/sec for the intermediate of their three groups of subjects. The SVA level of the subjects used in both investigations was comparable: 20/15 - 20/20 for Elkin (13) and 20/20 or better for Ludvigh and Miller (22).

Evidence exists that subjects possessing similar levels of SVA (i.e., 20/20 or better) exhibit quite different levels of DVA ability (22,26) and that in subjects possessing wider ranges of SVA ability, DVA has been found to be related to SVA (5,7,8). Weissman and Freeburne (45) further investigated the degree to which SVA and DVA are related, as well as the nature of the relationship between them. Weissman and Freeburne (45) used a rotating projector to present Landolt-C targets at speeds of 20, 60, 90, 120, 150, and 180°/sec on a white semicircular screen. SVA was measured with the same apparatus with the projector stationary. A shutter was employed to provide a 1-sec target exposure duration for all DVA and SVA testing. In both SVA and DVA testing, subjects performed binocularly and were allowed free head movement. Weissman and Freeburne (45) obtained correlations of .71, .66, .64, and .67 (all $\underline{p} < .01$) between SVA and DVA at 20, 60, 90, and 120°/sec, respectively. Further, tests for linearity indicated a significant ($\underline{p} < .01$) linear relationship between SVA and DVA for the four lowermost DVA speeds. It was also found that for 150 and 180°/sec the relationship between SVA and DVA was non-linear ($\underline{p} < .05$).

With respect to the above findings the following conclusions are made concerning the relationship between SVA and DVA:

1. When subjects are pre selected on the basis of SVA; e.g., 20/20 or better, the resulting $\underline{r}$ between SVA and any other variable (e.g., DVA) would necessarily decrease. Since the $\underline{r}$ computed between two variables is dependent upon the variability of the scores on each variable (17), if all subjects possessed exactly the same level of SVA, the $\underline{r}$ between SVA and another variable (e.g., DVA) must equal zero. As the range of the SVA scores increases, the $\underline{r}$ between SVA and another variable (e.g., DVA) would necessarily increase. As Burg (7) demonstrated, when the SVA of the subjects varied over a substantial range; e.g., 20/13 - 20/200, a relationship between SVA and DVA did result.

2. Miller and Ludvigh's findings (34) clearly demonstrated that subjects who possessed the same level of SVA still differed dramatically in terms of their DVA.

Sex

Burg and Hulbert (8) investigated both DVA and SVA in 236 subjects (110 males and 126 females) whose ages ranged from 16 to 67 years, with the great majority (79%) falling in the 16-25 year age group. Across the five target speeds of 20, 60, 90, 120, and 180°/sec, 30 comparisons were possible between males and females for the seven age groups. (Note: In 5 cases no measures were obtained for the age group x speed combination). In 24 of the 30 comparisons male group mean thresholds were lower than the respective female group means. For Screen O-R SVA and DVA at 20, 60, and 120°/sec, thresholds for males were significantly (all $\underline{p} < .002$) lower than those for females when the data were combined across age groups, respectively.

Burg's investigation (5) demonstrated significant sex differences in DVA ability for target speeds of 90 and 120°/sec. Two analyses of variance were performed: The first utilized the obtained DVA threshold data, while in the second analysis the effects of SVA and age were statistically controlled. The results of both analyses indicated that males performed significantly better (all $\underline{p} < .01$) than females, at both target speeds.

Burg (7) related DVA to age and sex in 17,500 subjects, whose ages ranged from 16 to 92 years (37.2% were female and 62.8% were male). The target angular velocities used in measuring DVA were 60, 90, 120, 150°/sec. The 14 age groups and four target speeds provided 56 possible group mean comparisons between males and females. Out of 56 possible comparisons the females exhibited superior group mean DVA thresholds only seven times. For age groups up to 64 years, the male groups always had lower mean DVA scores (out of 40 comparisons). For these 40 comparisons the average Ns across age groups for males was 973, 994, 991, and 375; the average Ns for females was 593, 605, 604, and 253 for target angular velocities of 60, 90, 120, and 150°/sec, respectively. The author stated that several theories for this apparent male superiority in DVA had been proposed -- such as "differential motivation and physiological and/or physiognomic differences" (7). No support for these theories was available at that time. Further, with respect to SVA, possible sex differences were indicated. For the 10 age groups, including ages 16-64, the SVA mean for each male age group was consistently lower than the corresponding mean for females. This result was obtained for SVA when measured either by standard Ortho-Rater procedures or by Screen O-R. However, no statistical tests for significant sex differences were performed on the data.

Age

Burg and Hulbert (8) found no apparent DVA or SVA differences as a function of age. Of Burg's 236 subjects, 79 percent were between 16 and 25 years of age, with only eight subjects being older than 40 years. Due to the small number of subjects in the higher age brackets, no generalization could be made about differential DVA or static acuity as a function of age.

In his later group of 17,500 subjects, Burg (7) found a substantial decline in both SVA and DVA as a function of age. Only a slight, gradual deterioration of SVA and DVA as a function of increasing age was found for ages 16 to 44 years. For example, at a target angular velocity of 150°/sec, mean acuity thresholds for 18-19 year old males and females were 2.0 and 2.2' of arc, and for ages 40-44 the mean threshold had only increased to 2.4 and 2.7' of arc, respectively. Above 44 years of age, both SVA and DVA began a progressive decline at a noticeably higher rate as a function of increasing age. At a target speed of 150°/sec, the mean acuity for the 70-74 years age group was 5.5' of arc for males and 6.4' of arc for females. The decline in DVA with increasing age was more pronounced for target angular velocities of 120 and 150°/sec.

The findings of Sharpe and Sylvester (41) provide a basis for explaining findings of poorer DVA performance in older subjects. These investigators measured horizontal eye movements of young (19-32 years) and elderly (65-77 years) subjects during a visual tracking task. The rear-projected target subtended 15' of arc and moved at speeds of 5, 10, 20, 30, 40, 50, 60, 80, and 100°/sec. Analysis of the ratios of mean smooth eye movement velocity to target velocity (i.e., gain) indicated that the gains for the younger subjects were significantly greater than the older subjects gain for 10°/sec and above ($p < 0.02$ at 10°/sec and $p < 0.001$ at 20°/sec and above). That is, smooth pursuit eye movements of the younger subjects more closely approximated the target speeds. Analysis of the saccadic eye movements indicated that the number of saccades per second was greater in the elderly group ($p < 0.05$ for 40°/sec and under). The subjects' visual acuities were corrected to 20/40 or better for the eye used.

III. EFFECT OF CONTRAST ON DVA

Although the relationship between SVA and contrast was established some years ago (9, 20), contrast effects in DVA settings have only recently been investigated. The two studies discussed below apparently are the initial investigations specifically dealing with the problem of resolving a moving target of varying levels of contrasts.

Mayyasi, Beals, Templeton, and Hale (28) obtained four levels of target/background contrast by varying ambient and projector illumination intensities. Contrast values were computed with the formula $C = (B-L)/B$, where C = contrast, L = target luminance, and B = background luminance. Two projector intensities and two ambient room illumination levels resulted in four contrast values: C = .35, .67, .75, and .76. A rotating projector which moved through a 30° arc projected the target onto a translucent screen via an intermediate stationary mirror. No specific target velocities were stated; however, "The speed was controlled such that the velocity of the image was constant and such that the probability of its successful identification was equal to the probability of its being missed . . . " (28, p. 845). The task consisted of correctly identifying block English letters (of a size subtending 40' of arc at subject's eye) on a white background.

The ambient room illumination effect and the ambient illumination x projector illumination interaction were both significant. The three higher contrast conditions resulted in a considerably greater number of accurate target identifications than did C = .35. Since contrast effects were confounded with ambient illumination, the independent effect of contrast on DVA was not discernible.

Brown (4), incorporating a stationary projector, rotating mirror, and hemicylindrical screen, investigated DVA under four levels of positive contrast (23, 30, 51, and 70 percent with target angular velocities of 0, 20, 30, 40, 50, 60, 80 and 90°/sec. Target contrast was defined as $(B_t - B_b / (B_t + B_b) \times 100$ percent, where B_t = target luminance and B_b = background luminance. Eye movements were measured by utilizing the differential reflection of infrared radiation by the sclera and iris/cornea. With the left eye occluded, subjects viewed the Landolt-C targets with their right eye. Target exposure duration was 455 msec and controlled by a shutter.

Main contrast effects upon DVA were found to be significant ($\underline{p} < .001$). For each target velocity the 70 percent contrast condition resulted in the lowest acuity thresholds, followed by 51 percent, then 36 percent, with the 23 percent contrast requiring the largest size targets for acuity threshold. The target velocity x contrast interaction was also significant; lower contrast resulted in a greater deterioration of DVA at the higher speeds.

Initial eye movement latencies following target presentations generally increased as contrast decreased. Eye movement latency was defined as the time required for the eye to move 0.5° from the initial fixation point following target presentation. A target size effect was suggested as an influence on eye movement latencies at the lower target contrasts. At contrast levels of 23 and 36 percent no eye movement response occurred with the smallest target. As target size was increased a saccade occurred late in the presentation period. As target size was progressively increased, saccades occurred earlier and there was improvement in terms of position and velocity errors, and subject was finally able to correctly resolve the target.

Brown (4) suggested that had constant size targets been used for the different contrast levels, differences in eye movement latencies between different levels of contrast would have been more pronounced. Such greater latencies would likely have the effect of functionally reducing the time allowed for resolution. As Crawford (10), De Klerk and Van de Geer (11), Elkin (13), and E. F. Miller, II (31) have shown, DVA performance improves with increasingly longer target exposure durations up to 1.0 sec. Therefore, shorter exposure durations due to longer initial eye movement latencies should degrade DVA performance. Brown (4) pointed out that a previous study (3) had shown that with high contrast, target size had little effect on eye movements.

With respect to eye/target velocity mismatch error, for speeds below 50°/sec only the 23 percent contrast resulted in considerably above average mean velocity error. Velocity error was defined as the difference in angular velocity between the eye and the target during the last smooth pursuit movement made during pursuit of the target. However, at target speeds between 50 and 90°/sec the mean velocity error for both 23 and 36 percent contrast was greatly increased. The findings concerning position error for the four contrast conditions as a function of target angular velocity were similar in direction to the velocity errors. Position error was defined as the angular difference between eye and target position half way through the last smooth pursuit movement.

IV. RELATIONSHIP OF INITIAL EYE MOVEMENT AND SACCADE LATENCIES TO DVA

Initial Eye Movement

Given a limited target exposure duration, it is apparent that a faster initial eye movement in response to the moving target would allow more time for the resolution process. Crawford (10) reported greater percentages of successful target resolutions in a dynamic situation following initial eye movement latencies of short or medium duration than when the latencies were longer than average. No numerical values for these durations were presented by Crawford (10). The effect was distinctly more apparent with increasing target angular velocity. Crawford (10) used a rotating projector to present a Landolt-C target (subtending 2' arc at subject's eyes) on a curved white screen for 0.4 sec at target velocities of 50, 75, 100, and 125°/sec. The four subjects viewed the targets binocularly.

Brown (3), using the same apparatus as in Brown (4) described above, found mean latencies for initial eye movements immediately following target presentation to decrease as target angular velocity increased. For 73 percent contrast targets moving at a target speed of 20°/sec such mean latencies were approximately 200 msec; for a target angular velocity of 90°/sec the mean latencies were approximately 145 msec. Brown (4) found initial eye movement latencies to decrease with increasing target angular velocities for targets of different contrast levels. For target angular velocities up to 50°/sec there was a noticeable trend for targets of higher contrast values to produce shorter eye movement latencies. This general trend was less clearly apparent with target velocities from 50-90°/sec.

Robinson (40) reported a mean latency for initiation of smooth pursuit eye movements of 142 msec to either dots or lines moving at a speed of 20°/sec. For Robinson's target speeds (5, 10, 15, and 20°/sec) no relationship between eye movement latencies and target speed was suggested by the data.

Saccade Latencies

In addition to initial eye movement latencies, Brown (3) also measured first, second, and third saccade latencies (FSL, SSL, and TSL, respectively) during DVA. Saccade latencies were defined as the duration between target presentation and the occurrence of the particular saccade. The mean FSLs, SSLs, and TSLs decreased as target angular velocity increased. The FSLs decreased progressively from about 240 msec for a target speed of 20°/sec to about 185 msec for a speed of 90°/sec. For the same speeds, SSLs decreased from about 390 msec to about 260 msec, and TSLs from about 380 to about 310 msec. At target velocities less than 50°/sec few third saccades were observed, while with target velocities greater than 50°/sec there was a marked increase in the frequency of occurrence of third saccades. With a target velocity of 90°/sec third saccades occurred almost 80 percent of the time.

Robinson (40) also found that first saccade latencies decreased as target speed increased. For his target speeds of 5, 10, 15, and 20°/sec first saccades occurred at 282, 237, 221, and 224 msec, respectively, following target presentation. Brown's (3) mean FSL of about 240 msec for a target speed of 20°/sec is quite similar to that found by Robinson (40). Robinson found second saccades to occur with target speeds of 15 and 20°/sec. For a target speed of 20°/sec the second saccade occurred at about 300 msec, while for 15°/sec the second saccade occurred approximately 400 msec following target presentation.

V. CAUSE(S) OF DETERIORATION OF ACUITY WITH RELATIVE MOTION EXISTING BETWEEN EYE AND TARGET

Eye Position Error Occurring During DVA Performance

Investigations have shown that SVA decreases as eccentricity from the fovea increases (20, 27, 42). It has been hypothesized that acuity decrement in DVA may be due simply to the position of the target image on the retina (38). Miller and Ludvigh, however, rejected this hypothesis as the main cause for acuity deterioration with increasing target speeds on the basis of Ludvigh's earlier findings (21). Ludvigh found (21) that a target moving 38°/sec in a circular path, 2° concentric to the eye fixation point, resulted in a visual acuity of about 20/100, whereas, peripheral SVA at 2° eccentricity had previously (20) been found to result in a visual acuity of approximately 20/25. Although Miller and Ludvigh (38) favored the hypothesis that the cause of deterioration of DVA was due to image movement over the retina, several studies have suggested that position error does indeed occur during DVA.

Utilizing the differential reflection of infra-red radiation from the sclera and iris/cornea, Brown (3) measured eye movements during a DVA task. The results showed that the mean position error increased in a linear manner with increasing target angular velocity. The mean position errors found were approximately 2, 2.5, 4, 6, 7, 8, and 11° for target speeds of 20, 30, 40, 50, 60, 80, and 90°/sec, respectively. Thus, Brown provided quantitative measures of position error (as well as eye/target velocity mismatch error) occurring during DVA. Brown (3) made no distinction of position error (or eye/target velocity mismatch errors) associated with correct versus incorrect responses during DVA trials. Apparently, for each type error, the data from both correct and incorrect responses were combined.

An earlier investigation by Brown (2) presented information concerning the relative contribution of position errors and eye/target velocity mismatch errors to deterioration of visual acuity (with fixated eye). During that investigation Landolt-C targets were presented for an exposure duration of 180 msec at various specified retinal eccentricities (0, 2.5, 7.5, and 10°) in the horizontal and vertical meridians. The direction of target movement was always in the horizontal plane of the eye. Of course, retinal locations other than the specified eccentricities were necessarily included in the target's traveled arc; however, the arc's center was the above specified eccentricities. The specified eccentricities were produced by having the subject fixate on a given red light during each trial.

Results showed both target velocity and eccentricity to produce significant effects on visual acuity. As the eccentricity increased, visual acuity decreased. For a target speed of 40°/sec threshold sizes were about 3' and 9' of arc for eccentricities of 0 and 10°, respectively (vertical meridian eccentricities). In addition, threshold comparisons between different eccentricities and target angular velocities may be made. For example, a threshold of approximately 4' of arc was obtained for target angular velocities of 40 and 10°/sec at retinal eccentricities of 2.5 and 5°, respectively. As noted previously, Ludvigh (21) obtained a similar threshold of approximately 5' of arc for a target moving 38°/sec in a circle 2° concentric to the eye fixation point.

Visual Pursuit Velocity Error Occurring During DVA Performance

Miller and Ludvigh (38) offered three tentative hypotheses in regard to the cause of the progressive deterioration of visual acuity with increasing target angular velocity. According to the first hypothesis, degraded visual acuity during ocular pursuit may be due to the inability of the eye to move fast enough while pursuing the target. Miller and Ludvigh (38) presented results of investigations of eye movement capabilities which discounted this hypothesis. According to the second hypothesis offered, acuity decrease during DVA may occur because the target image stimulates an extrafoveal retinal locus, even though the eye's pursuit movement may maintain the image stationary on the retina. Miller and Ludvigh (38) rejected the second hypothesis on the basis of Ludvigh's 1949 findings. Ludvigh (21) found that a target moving 38°/sec in a circular path 2° concentric to the eye fixation point resulted in a visual acuity of about 20/100, whereas peripheral SVA at 2° eccentricity had previously (20) been found to result in a visual acuity of approximately 20/25. The third hypothesis which Miller and Ludvigh favored, suggested that ". . . the determination of visual acuity during ocular pursuit is dependent upon inaccuracy of control" (38, p. 108).

Brown (3,4) measured position error and eye movement angular velocity during a DVA task. During the task for a target angular velocity of 50°/sec the eye responded in the following typical pattern: 1) Initial eye movement occurred after about 185-200 msec following target presentation, then 2) during the next 30 msec the first saccade occurred. Next in order of occurrence was 3) the first smooth pursuit movement for about a 100 msec duration, followed by 4) the second saccade, then followed by 5) the second smooth pursuit movement, which lasted for at least 40 msec. Changes in eye movement pattern did result, however, as a function of target angular velocity. For target speeds less than 50°/sec usually no more than two pursuit movements were observed. As target angular velocity increased, so did the frequency of occurrence of the third pursuit eye movements. The third pursuit eye movements usually occurred for at least a 40-msec duration following the third saccade.

The results show that all pursuit velocities increased as target angular velocity increased; however, the mean pursuit eye movement angular velocities were consistently less than the speed required to match that of the target. The mean first pursuit movement velocity (FPV) was less than the mean second pursuit movement velocity (SPV), which was less than the mean third pursuit movement velocity (TPV), which was still less than the velocity required to match that of the target. For example, with a target speed of 50°/sec the mean SPV was about 30°/sec, while the mean FPV was about 28°/sec. In addition to the eye movement pursuit velocities increasing as target speed increased, the velocity mismatch error between the observer's eye velocity and the target's speed also increased with increasing target angular velocity. Again, it is noted that Brown (3,4) made no distinction of pursuit velocities associated with correct versus incorrect responses during DVA trials.

Evidence indicated, however, that the eye was progressively reducing the existing eye/target velocity mismatch error. For example, with a target speed = 90°/sec the mean FPV = 40°/sec, SPV = 50°/sec, and TPV = 60°/sec. Also, in a visual tracking task utilizing relatively low target speeds (0.5 - 11.0°/sec) pursuit speeds have been found to consistently lag behind the target's speed (43). The finding that the pursuit eye velocities are less than the pursued target's velocity is by no means new. Dodge (12) reported that pursuit movement velocities tend to "lag" the target velocity; however, the pursuit movements were supplemented from time to time with saccades in the same direction. Other investigators have shown that in visual tracking, velocity error is about zero for a target velocity of 10°/sec but is approximately 6°/sec at a target velocity of 20°/sec (40). Rashbass (39) also found the eye to accurately match target speeds up to 10°/sec.

For higher target velocities though, up to 90°/sec, it appears that the eye's speed is substantially less than the required target matching speed (3). Nevertheless, the eye tends to be constantly reducing the eye/target velocity mismatch on each successive pursuit movement. Had a target exposure time been increased, one would predict the fourth, fifth, or sixth pursuit movement's velocity to be progressively more similar to that of the target. Elkin (13), De Klerk and Van de Geer (11), Crawford (10), and E. F. Miller, II (31) have reported a negatively decelerated function between increasing target exposure time and threshold size for various angular velocities. But, increasing exposure duration beyond 1.0 sec provided little further improvement of DVA.

Brown's (3) data showed that for speeds of 20, 30, 40, 50, 60, 70, 80, and 90°/sec, the mean eye/target velocity mismatch errors were about 5, 7, 11, 15, 20, 30, and 35°/sec. These mean pursuit velocities were always in the direction of being slower than the required matching speed. Thus, with a greater velocity mismatch, progressively more image movement over the retina would of course occur. Velocity error was defined by Brown (3) as the difference between eye and target angular velocities existent during the last smooth pursuit movement of the particular sample period.

Brown (3) provided actual eye movement recordings indicating that velocity mismatch between target and eye does indeed occur during DVA performance. Such data demonstrate that image movement across the retina does indeed occur in DVA tasks, a finding which supports earlier suggestions or contentions that the integration of the entire oculomotor system is probably the main factor determining DVA (5, 13, 38). Granted that poor integration of the oculomotor system results in poor eye/target velocity mismatch, the following questions remain: How is visual acuity degraded by retinal image movement? And, what are the critical parameters of retinal image displacement which result in degraded visual acuity? Van den Brink (44) investigated the effects of certain critical parameters of retinal image motion on visual acuity for moving targets, and his work is presented next.

Effects of Retinal Image Movement on Visual Acuity

In his studies of visual acuity for moving objects, Van den Brink (44) employed an acuity task which requires subjects to resolve a moving target presented 6° concentric to a visual fixation point. Although the task employed by Van den Brink (44) did not involve visual pursuit of a moving target, the task did involve resolving a target image which moved over the retina. Brown's findings (3) of eye/target velocity mismatch during DVA indicate that retinal image movement occurs during DVA. Van den Brink's results (44) are presented in order to point out critical parameters of retinal image motion and their effects on acuity.

In Van den Brink's acuity studies (44) he employed a target consisting of two luminous bars separated by a dark area equal to that of each bar. Target size was defined as the distance (D) between the center of each luminous bar. For the four target sizes used, D equaled 109', 54', 22', and 10.3' of arc. Threshold energy required to perceive the dark area between the luminous bars 60 percent of the time was measured as the dependent variable. The following results were obtained for target size: D = 54', with the bars oriented perpendicular to the direction of target motion.

(a) For short exposure durations (0.004 - 0.125 sec):

For speeds ⩽ 34.4/sec and resultant retinal image displacements < 2' of arc, thresholds were independent of target speed and exposure time. The influence on threshold energy due to image displacement was negligible. For target speeds between 1.15°/sec and 146.67°/sec, speeds beyond which target critical detail was not discriminable were progressively lower for progressively greater exposure durations.

(b) For longer exposure durations (0.125 - 2.0 sec):

With target speeds ⩽ 1.15°/sec, threshold energy was dependent upon exposure time and not affected by speed. For speeds < 1.15°/sec, threshold energy increased with increasing speed, with greater exposure times requiring greater threshold energy. Above a speed of approximately 18.33°/sec, target detail was not discriminable for any of the longer exposure durations.

Similar functions were obtained for the other size targets. However, corresponding threshold energies were greater for the smaller targets, and critical speeds above which target detail was not discriminable were lower for the smaller targets. The converse was true for the largest target size (D = 109'). The above results were obtained with a dark target background.

Van Den Brink (44) also performed an experiment employing the same apparatus as used above, but he incorporated a 20° adapting field within which the target (D = 54') was centrally presented. His results indicated that threshold energies were less with the adapting field compared to corresponding threshold energies obtained without an adapting field (i.e., with a dark target background) for all exposure durations, for all speeds greater than approximately 2.29'/sec. This finding is particularly relevant to the results of Ludvigh (21) and J. W. Miller (32) who found that higher illumination resulted in improved DVA performance.

To summarize, the above evidence suggests that: 1) Although position error has been found to contribute to DVA deterioration (2,3), its effect has been described as "negligible" (21). The main cause of deterioration of acuity with relative motion existing between observer and target has been attributed to the movement, per se, of the target image over the retina (38). Certain parameters of the target image movement over the retina are critically related to acuity for moving targets (44).

VI. METHODOLOGICAL CONSIDERATIONS

Target Gap Orientation Effects Related to DVA

Some evidence suggests that the orientation of target detail in relation to the plane of target movement affects the discriminability of the target detail. Brown presented the findings of a report (printed in German) by Methling and Wernicke (29) by stating " . . . horizontal target motion diminishes the visibility of targets with vertically oriented gaps more than it does those with horizontally oriented gaps" (2, p. 294).

In an experiment performed by Van den Brink (44) threshold energy required for perceiving the dark area between the two bars was measured for targets presented in various orientations relative to the direction of target movement. The moving target was presented 6° extrafoveally while the eye fixated a given point. Van den Brink (44) found that when the target bars were parallel to the direction of target motion, threshold energy required to perceive the gap was considerably less than the corresponding threshold energy for a target oriented perpendicular to the direction of target movement.

Frank (15), employing a rotating mirror system and Landolt-C targets, investigated the effects of target orientation on DVA. His analysis of variance of threshold sizes obtained for each target orientation revealed a significant main effect. Frank (15) also analyzed the subjects' responses in terms of response bias and found significant differences across target orientations. He then correlated the response bias scores and the threshold size scores and obtained a Spearman Rank-Order correlation coefficient of -.928 ($\underline{p} < .001$). Frank concluded that " . . . response bias contributes to the error in the measurement of psychophysically derived acuity thresholds" (15, p. 12).

It is noted that in Ludvigh and Miller's studies, eight target positions were used; i.e., up, down, right, left and the four 45° oblique positions (22,23, 24,33,34). It is also noted that Miller and Ludvigh randomly positioned the Landolt-C gaps during their DVA investigations, and that high test-retest $\underline{r}$s ($\underline{r}$ = .87) were obtained for their $\underline{b}$ parameter (reflecting DVA ability).

Fixed versus Free Head Movement During DVA

When free head movement is allowed, foveal fixation is possible over approximately 180° of the visual field; however, when subject's head remains stationary (fixed), foveal fixation is possible within an arc of perhaps 90-100° (8). Crawford (10), using a rotating projector by which Landolt-C targets were projected onto a curved screen, found improved DVA with free versus fixed head conditions for all of his four subjects. Crawford used target exposure durations of 0.4, 0.5, 0.6, and 0.7 sec, and target angular velocities of 50, 75, 100, and 125°/sec. This improvement effect, due to free head movement, was readily more apparent for the faster two speeds and the longer target exposure durations.

Burg and Hulbert (8) found generally higher rs between SVA and "Free-Head DVA," than between SVA and "Fixed-Head DVA." In addition, for their free-head DVA condition these investigators obtained significant test-retest rs of .69, .60, .58, and .43 for target angular velocities of 60, 90, 120, and 150°/sec, respectively. Similar test-retest rs for the Fixed-Head DVA failed to obtain significance at any of the four target angular velocities.

It is noted that Miller and Ludvigh (38) reported a test-retest r = .87 for their b values (which represent DVA ability) which was obtained under a fixed-head condition (biteboard). It would appear, then, that free head movement has a beneficial effect on DVA when an experimental apparatus such as a rotating projector with a curved viewing screen is employed (8,10); however, when a rotating mirror apparatus, such as that used by Ludvigh and Miller, is employed, a fixed-head condition does not result in unreliable, or degraded, DVA performance. The two types of experimental apparatus may be measuring two different processes.

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