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THE EFFECTS OF GRAVITATIONAL STRESS UPON VISUAL ACUITY

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FOREWARD

This report was prepared by the Psychology Branch of the Aero Medical Laboratory, Directorate of Research, Wright Air Development Center, under Research and Development Project 7193, "Operator Performance under Stressful Environmental Conditions," with Dr. W. D. Chiles acting as Project Scientist.

This research was presented by the senior author to the Graduate School of the Ohio State University in partial fulfillment for the degree of Master of Arts.

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ABSTRACT

It was the purpose of this study to determine the relationship between increased gravitational force and visual acuity when the factor of reduced cerebral circulation is minimized by the use of protective measures known to ameliorate the gross visual symptoms associated with g stress.

It was found that gravitational stress has a significant and progressive effect upon visual acuity. Hypotheses are advanced to account for the difference in visual performance during gravitational stress.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

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INTRODUCTION

With the advent of high performance jet and rocket propelled aircraft, the problems of gravitational forces and their effect on the human body have multiplied. During and immediately after World War II, a large amount of research was performed by investigators in this and other countries to determine the effect of short term application (seconds) of increased gravitational force on man.(13). Engineering advances during recent years have made possible aircraft that can withstand tremendous structural strains over long periods of time (minutes), but under such tension the performance of their human operators may be handicapped by gross disturbances of circulation, vision and consciousness. It is to this problem of prolonged acceleration and its effect on human vision that this paper is addressed.

Subjective Effects of Acceleration

The sensations occuring during positive radial acceleration are well known to pilots and to those who serve as subjects in centrifuge experiments. Relaxed subjects seated in an upright body position experience dimming of vision (amblyopia) at 3 to 4.9 g, loss of peripheral vision (tunnel vision) at 3.5 g to 5 g, complete blackout (amaurosis fugax) at 4 to 5.5 g and true unconsciousness between 4.5 and 6 g (13). Lambert (17) has shown that centrifugal force induces visual symptoms by causing a decrease in arterial pressure at eye level. When the normal arterial pressure is inadequate to overcome the increased effective weight of the blood, impairment of circulation and unconsciousness result. The return to consciousness may require as long as 60 seconds and is generally accompanied by disorientation. If the range of the force environment is less than that required for unconsciousness, normal vision occurs in 3 to 5 seconds after the force abates (13).

Another factor which influences the effect of g on the human body is the duration of the g force. At least 3 to 4 seconds are required to produce symptoms for forces up to 10 g and these symptoms will develop fully during 4 to 10 seconds of exposure. However, when moderate force (3.5 to 5 g) is maintained beyond this time, these symptoms are likely to abate due to the vasopressor response (20).

Methods for Ameliorating Effects of Acceleration

Paralleling the research on the effects of acceleration on man is a program concerned with the amelioration of those effects. The military services have developed anti-g suits which have been highly effective in raising man's g tolerance by mechanical means.

In addition to the g suit, there are other means by which we can raise man's tolerance to centrifugal force. One of these involves changes in body position so that a reduction occurs in hydrostatic distance between the heart and the eye. Currently under investigation are the prone, supine and semisupine body positions. In the prone and supine positions, the vertical distance between heart and head are reduced almost to zero, and accordingly gravitational stress does not appreciably reduce cerebral arterial pressure (19). In these positions man can withstand sustained forces in excess of 12 g without experiencing the visual symptoms that usually occur with an increase in the force environment (8). When the subject has assumed the prone or supine protective positions, positive g is translated into transverse g. That is, the forces are applied at right angles to the long axis of the body. In anticipation of some of the practical difficulties of flying from these positions, consideration is being given to the semisupine position. In the semisupine position, a reduction in g tolerance occurs which is proportionate to the increased hydrostatic distance between the heart and the eye (21).

Human Factors and Prolonged Acceleration

The performance characteristics of proposed aircraft have presented a whole new range of problems that are different in magnitude and kind from those that were of concern in the immediate past. For example, the physiological problems of attaining the escape velocity for a "free" ride through space would be simple, were it not for the mechanical ones. For instance, a 3 g acceleration for 9 1/2 minutes would give an escape velocity satisfactory in terms of human factors, but mechanically costly from the standpoint of fuel economy. The reverse would be true, however, of a 30 g acceleration for 44 seconds. This would give an escape velocity which might be mechanically sound but would be physiologically unwise. Additional physiological research is being undertaken in an effort to obtain information about the parameters of human circulation. Engineers responsible for the development of high performance aircraft have presented to aero medical specialists the tentative specifications of new airframes and are seeking an understanding of the relationships that exist between psycho-physical performance and prolonged accelerative forces. The understanding of these relationships is as important to the aerodynamicist as are the physical parameters of the proposed aircraft, for the entire system is ultimately dependent upon the human operator.

Perception and Psychomotor Function as Affected by G

From the psychological point of view, very little is known about the parameters of perception and psychomotor functions as they are affected by accelerative forces. The pioneering European research reviewed by Armstrong and Heim (2) was concerned with gross visual changes -- peripheral dimming, blackout and "red-out" -- that were experienced during acceleration. Canfield (4) has recently reviewed research performed at the University of Southern California relating gravitational stress to various aspects of performance: a) ability to apply forces to a control stick, b) ability to make reaching movements with the hand and arm, c) simple and complex reactiontime, d) spatial orientation, and e) perceptual speed ability. The results of this latter study are germane to this paper. Comrey, et al., (7) in discussing their findings on perceptual speed ability points out that accelerative forces as high as 4 g have little effect on the ability to note minor differences in visual detail. In a later paper (5) this generalization is amended to read, "Possibilities of reduced visual acuity... are...unlikely." To make such a generalization seems inadvisable when one realizes that perceptual speed ability, and hence, visual performance, was measured through the use of test items similar to those in the Guilford-Zimmerman Aptitude Survey. Such a survey test is not a good measure of acuity as the differences in visual details are well above the threshold values given for minimum separable acuity.

The effects of moderate values of g with specific reference to instrument reading have been reported by Warrick and Lund (26). They found that reading errors increased from 18 per cent at 1.5 g to 24 per cent at 3 g. This performance decrement was interpreted in terms of a reduction in cerebral blood supply. An alternate interpretation of these results is discussed later in this paper.

The literature in this area of study has recently been reviewed by Gerathewohl (10) in an attempt to arrive at some theoretical conclusions concerning the interaction of the proprioceptive and visual senses under conditions of sub and zero gravity. He concludes, after surveying the anatomical and physiological data on the eye in relation to positive and negative acceleration "... that the eye is affected but indirectly by mechanical forces." In his evaluation the only changes in vision which are likely to occur in an increased force environment are those directly attributable to a failure of circulation to the head. Such an evaluation, however, seems premature when one considers the anatomy and physiology of of the visual apparatus. For example, the exactitude of the optical imagery of the eye is dependent, within a fraction of a millimeter, on such measures as the length of the eye and the shape of the cornea and the lens. It would be strange, indeed, if a progressive change in the force environment did not result in a similar change in visual performance, when that performance is measured independently of cerebral circulatory competence during gravitational stress. Also, it appears unlikely that optical imagery could be maintained adequately in a stress-producing environment where the positions of the optical elements may be changed, where anomalies of the refractive surfaces may occur or where the elements may be moved obliquely.

PURPOSE

It is the purpose of this study to determine the relation between increased gravitational force and visual acuity when the factor of reduced cerebral circulation is minimized by the use of protective measures known to ameliorate the gross visual symptoms associated with an increase in the force environment. In other words, when cerebral circulation is maintained, what will be the effects of centrifugal force acting directly upon the eyeball? It is the general thesis of this and future studies of this subject that stress developed in the experimental situation may clarify certain visual mechanisms which would otherwise be difficult to examine. The experimental variables in these studies would have specific reference to flights that may place man outside the earth's gravitational field, but the results of these studies may also be applicable to the understanding of human senses and the role they play in the attainment of knowledge and regulation of behavior.

METHOD

Visual acuity was selected for measurement because this function is largely dependent on the perfection of the retinal image as it is formed by the optical system of the eyeball.

Apparatus

The Aero Medical Laboratory human centrifuge (13) used in this study is pictured in Figure 1. This centrifuge produces radial acceleration in exactly the same manner as does a turning aircraft. A rotating boom carries the cab around in a horizontal circle. The cab is free to pivot on a horizontal axis tangent to the circle of rotation of the boom. As the speed of the rotation of the boom increases, centrifugal force causes the bottom of the cab to swing outward and upward toward the horizontal. Thus, the g force may be applied to any axis of the subject's body by the proper placement of his body in the cab.

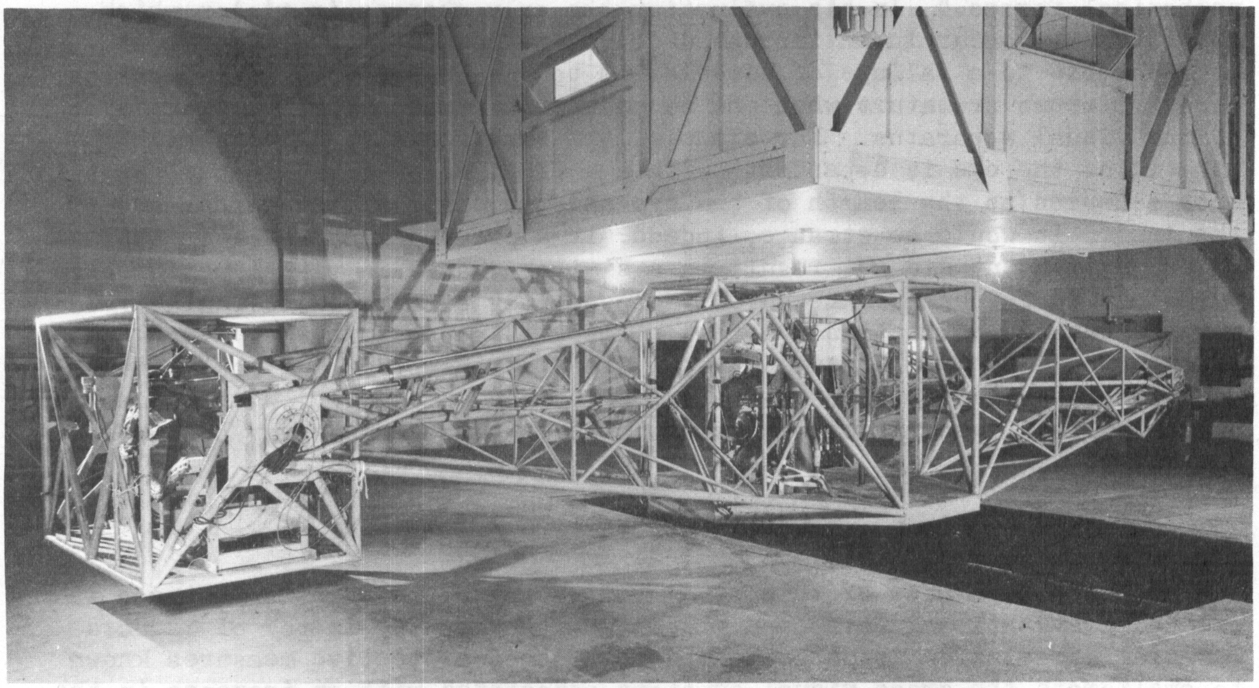

Figure 1. The Aero Medical Laboratory Human Centrifuge

Visual acuity was measured with the checkerboard targets that are standard with the Bausch and Lomb Ortho-Rater (15). The Ortho-Rater was selected for use in this experiment because it is a standard self-administered visual test battery (12), it gives reproducible scores (14), and has a high loading on a factor that has been named "retinal resolution" (3).* In this instrument a testing distance of 26 feet (far) is simulated optically while the near reading distance is 13 inches. Binocular, right and left eye acuity were measured at the near and far positions. The visual angles subtended by the critical detail vary by equal steps on a decimal visual acuity scale (reciprocal of visual angle) from 0.1 to 1.5 (20/200 to 20/13). A photograph of the slide for testing the right eye is shown in Figure 2.

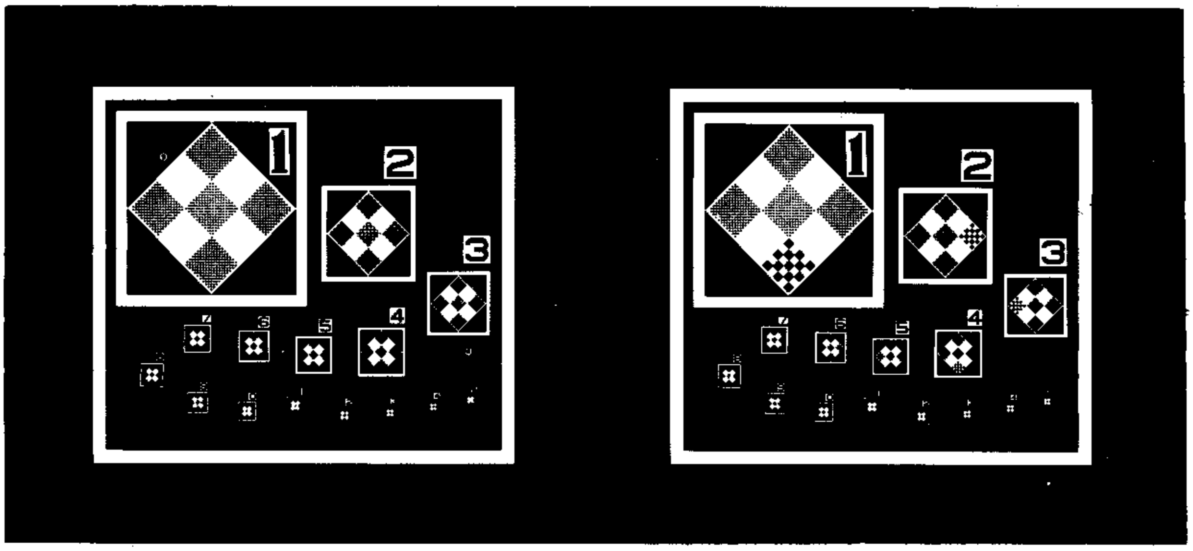

Figure 2. The Checkerboard Slide Used in Testing Far, Right Eye Acuity

Two modifications were made to the Ortho-Rater. One of these enabled the safety observer who rode in the center of the centrifuge to place the slides according to a prearranged schedule, while the second involved a 180 degree rotation of the test slides and viewing box so that the instrument could be inverted to accomodate the semisupine subject. From the point of view of the apparatus, the only essential differentiations between these positions, except as noted above, are those required to maintain the lines of visual regard through the center of the lenses and in the proper

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*The term "retinal resolution" does not seem to be an appropriate name for a factor that has been extracted from a visual test battery designed for the measurement of impairment of acuity associated with uncorrected ametropia.

angular relation to the direction of the accelerative forces. Figure 3 is a graphic display of the body positions and g values used in this study: in the prone and supine positions the lines of regard are parallel to the direction of the forces, while in the seated and semisupine positions the lines of regard are at right angles to the direction of increased force.

Verbal responses made by the subjects during an experimental session were placed on a magnetic tape recorder. These recordings were later played back and two independent listeners recorded the subjects' scores. These scores were compared, and points of disagreement were settled by repeated playings of the tapes. The number of disagreements was small and was usually caused by the presence of high ambient noise.

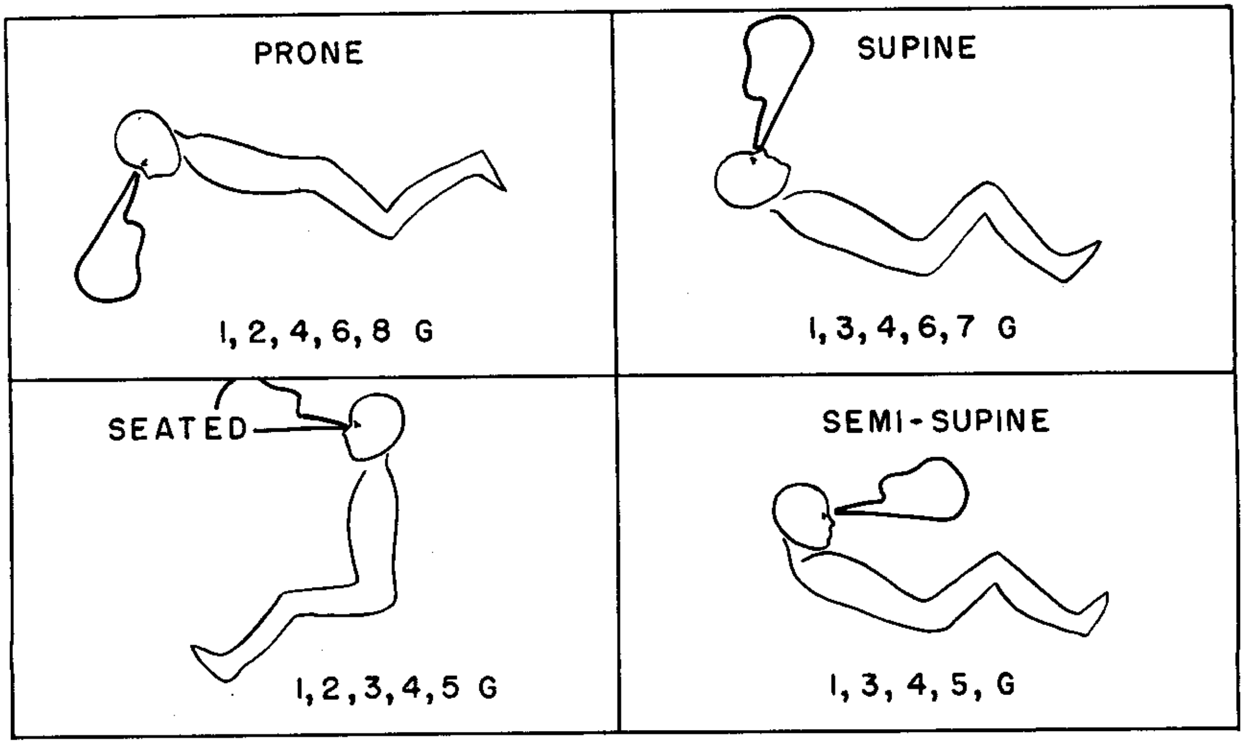

Figure 3. The Body Positions and G Values Used in the Study. The relation between the lines of visual regard and the Ortho-Rater can be seen also.

Subjects

In this study, eight male subjects and one female subject were used. Their ages were between 23 and 30 years. This age range is below the age generally reported for the onset of presbyopia. As there are many factors incident to riding the centrifuge other than simple increase in g force, only those persons with considerable centrifuge experience were selected as subjects. The number of people who could meet this qualification was small and even fewer persons were available for testing at the times the individual experiments reported in this paper were being conducted. The other restriction places on the subjects was that they have an uncorrected visual acuity of 20/20 in both eyes. For these reasons no effort was made to select a group of subjects which was representative of any particular segment of the population.

The average acceleration at which blackout occurred in this group of subjects when no protection was used and when in the seated body position was 4.1 g with a standard deviation of .89 g. When riding in the seated position in the test situation all subjects wore the standard Air Force - Navy G-4A g suit which raised the average blackout threshold by 1.7 g.

The initial selection of subjects was made by using the Ortho-Rater test battery. Those candidates who had uncorrected acuity of 20/20 on this instrument were referred to a competent professional group for further test of vision. The results of the Ortho-Rater tests did not disagree with later clinical evaluations.

All subjects were given a complete ocular evaluation which consisted in part of manifest and cycloplegic refractions. The results of this clinical evaluation showed that all subjects were free from ocular diseases and had a visual acuity of 20/20 or greater. Individual results are indicated in Tables 1 and 2. More than one week was allowed to lapse between the clinical evaluation and the experimental runs on the centrifuge so that any residual effect from the cycloplegic drug would be completely dissipated.

Procedure

On the day prior to the first experimental ride on the centrifuge, each subject was individually indoctrinated concerning the test procedure and given a practice ride on the centrifuge. Each subject was shown a photograph of a slide and was instructed as to what he might expect to see in the Ortho-Rater. Finally, each subject was informed that when riding the centrifuge it would be his task to report the location of as many of the checkerboard targets as possible.

Table 1

Information Concerning the Subjects Used in This Study

Subject	Age	Position	Blackout Threshold (g)	Ortho-Rater Acuity Score
CAD	29	P.S.Su.SS.*	4.2	OU 20/20 OD 20/20 OS 20/20
GJR	24	Su.SS.	4.4	OU 20/20 OD 20/20 OS 20/20
RFM	27	P.SS.Su.	3.6	OU 20/15 OD 20/15 OS 20/15
REL	23	P.S.Su.	3.8	OU 20/15 OD 20/15 OS 20/15
TS	23	P.	Unknown	OU 20/15 OD 20/15 OS 20/15
JR	24	P.	Unknown	OU 20/15 OD 20/15 OS 20/15
JAB	28	S.Su.SS.	4.2	OU 20/15 OD 20/15 OS 20/15
NKM	30	S.SS.	4.6	OU 20/15 OD 20/15 OS 20/15
RM	24	S.	3.8	OU 20/15 OD 20/15 OS 20/15

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*P - Prone Experiment, S - Seated Experiment, Su - Supine Experiment SS - Semisupine Experiment.

Table 2

Results of the Clinical Evaluation of the Subjects Used in the Study

	Manifest Refraction					Cycloplegic				
Subject		Sphere	Cyl	Axis	Acuity		Sphere	Cyl	Axis	Acuity
CAD	OD	0.50	0.25x	90	20/15	OD	1.00	0.25x	90	20/15
	OS	0.50	0.25x	90	20/15	OS	0.75	0.25x	90	20/15
GJR	OD	1.00	0.75x	10	20/15	OD	1.00	0.75x	5	20/15
	OS	0.75	0.50x	175	20/15	OS	1.00	0.50x	175	20/15
RFM	OD	0.75			20/15	OD	0.75			20/15
	OS	0.75			20/15	OS	0.75			20/15
REL	OD	1.00	0.50x	180	20/15	OD	1.25	0.25x	180	20/15
	OS	1.00			20/15	OS	1.00			20/15
TS			Unknown					Unknown		
JR			Unknown					Unknown		
JAB	OD	0.50	0.25x	85	20/15	OD	0.50	0.25x	85	20/15
	OS	0.25			20/15	OS	0.25			20/15
NKM	OD				20/15	OD				20/15
	OS				20/15	OS	0.25			20/15
RM	OD	0.50	0.50x	175	20/15	OD	0.50	0.50x	180	20/20
	OS	0.50	0.25x	15	20/15	OS	0.50	0.50x	5	20/20

Following this indoctrination the subject was given a practice ride under 1 *g* conditions which duplicated the conditions of the experiment in every respect. After the subject had placed himself on the bed or seat, adjustments were made so that he was looking through the center of the lenses in the instrument. The experimenter took his position in the control room and checked the operation of the two-way communications system. The room lights were turned off and a few seconds later it was announced to the subject that the terminal *g* had been reached and that he was to begin reading. The experimenter checked each response as it came over the loudspeaker as correct or incorrect according to the key supplied with the Ortho-Rater. This check was in addition to the tape recording of all verbal communication carried on during the experiments. After completion of the three acuity tests the subject was told that he was being "brought down." After a five minute rest period he was returned to *g* conditions for further testing under the condition of near or of far acuity as the schedule required.

The test procedure for measuring visual acuity during the experiments differed in the following important respects from that recommended in the Ortho-Rater manual:

1. The position of the subject's body varied, as did the *g* forces, compared with the instruction, "...the subject will be seated comfortably..." Instrument and subject were placed so that the lines of visual regard were either parallel or at right angles to force of gravity, according to body position.

2. Each individual score was determined by the last item read correctly before the first error was made. This is in contrast to the recommended scoring "...answer incorrectly...two items in succession." This scoring procedure was selected on the basis of the observation made by Sloan, et al., (24) that the recommended method of scoring overestimates the acuity of many subjects.

3. As there was complete counterbalance between near and far measurements the standard presentation sequence was not used, nor were the recommended test questions, due to the impracticability of administering them in this situation. The acuity test sequence of binocular, right and left eye was always used.

On the day following the indoctrination session and practice run the instructions were repeated in an abbreviated form for the actual experiment. The subjects appeared to understand their part of the task. The subjects were not informed of the gravity conditions they would experience while participating in the study. Neither were the subjects told of their scores at the various gravity levels nor how they compared with each other.

The subjects in this study, as can be seen in Figure 3, were exposed to a force environment ranging from 1 to 8 *g*. Two factors set the upper *g* value for any one experiment. The first had to do with the relation between visual dimming and the average accelerative force required to produce this symptom. In view of previously cited evidence, it is obvious that at excessively high *g* values, all visual functions will be impaired. It was decided, for the purposes of this study that the highest *g* value to be used, for each body position, remain at least one *g* below that value at which peripheral dimming would occur. The second factor concerned the comfort of the subject. In the prone position no visual symptoms have been reported at 12 *g*, however, nasal drip, mouth watering and difficulty in breathing tend to make a subject uncomfortable. In an attempt to minimize extraneous variables, no attempt was made to reach the maximum force attainable in any one of the protective body positions.

The *g* sequence for each subject, in three of the four experiments, was determined by use of a table of random numbers as was the order in which subjects were tested. In the experiment in which the prone position was used, the *g* sequence for all subjects was 1, 6, 2, 4 and 8. The testing order for subjects was randomized. The body positions used in this study were prone, seated, supine and semisupine, and the individual experiments were conducted in this order. In the prone, supine and semisupine positions, the torso of the subject was tilted 20 degrees with respect to the floor of the cab, the shoulders being higher than the hips. In the latter position the head was flexed forward with the chin almost on the chest. The seated position is the customary position taken when seated in a chair.

The technique and procedure for measuring acuity was the same in each of the four experiments. In all, six different acuity measures were made on each of the five subjects in each experiment: binocular, right, and left eye acuities at both near and far. Complete counterbalance of the near and far distances was maintained. In an effort to minimize fatigue and after effects of acceleration, the maximum *g* runs were held to about a one minute duration while the intermediate *g* values were of several minutes duration. With this reduction in time of exposure to high *g*, it was possible to test only near and far binocular acuity.

It has been shown (20) that if one starts with a slow onset of *g* it is possible to avoid the visual symptoms associated with sudden acceleration. In fact, it is possible to reach 5 *g*, unprotected under these conditions. Therefore, in all of the experimental runs the buildup of acceleration was arranged so as to take advantage of increased *g* tolerance associated with the slow onset of an increasing gravitational force.

RESULTS

In the following report of results all acuity values are expressed as means of the individual subject's scores. The acuity values shown in the tables and graphs are expressed in decimal notations. Visual acuity in this notation is equal to the reciprocal of the visual angle. Each individual's acuity score was determined by the last item read correctly before the first error was made.

Experiment 1: Prone Position

Table 3 contains the means and standard deviations of the visual acuity scores by g level when this function is measured with the subject in the prone body position. The acuity scores reported under 1 g conditions are the results of combining data obtained at two different times. Scores were obtained both at 1 g (centrifuge stationary), as part of the sequence of gravity conditions, and also at 1 g immediately following each experimental run. The difference between the means of these two sets of acuity scores was examined by the t test and was not found to be significant. It was for this reason that these data were combined and the collection of these additional data was not contined in subsequent experiments.

Figure 4 is a graph of the mean binocular acuity scores plotted against the gravity forces used in the first experiment. At 1 g the mean far acuity is 1.15 and the near acuity is 1.10. The final points on the graph are as follows: near acuity 0.56, far acuity 0.54. If we consider that the visual angle subtended, by the last item read correctly under 8 g conditions, is 1.8 minutes of arc and that the visual angle of the last correct item, under conditions of 1 g, is 0.91 minutes, then the graph shows that at 8 g a target must subtend a visual angle twice as large as that required for resolution at 1 g. Figure 5 shows graphs of mean right and left eye acuity.

Table 3

Means and Standard Deviations of Visual Acuity Scores by G Level for Prone Position (N=5)

G Values		1		2		4		6		8	
	Eyes	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
FAR	Both	1.15	.04	.92	.15	.74	.10	.64	.23	.54	.10
	Right	1.15	.06	.90	.15	.82	.10	.62	.19		
	Left	1.05	.17	.92	.19	.74	.05	.62	.16		
NEAR	Both	1.10	.06	.94	.10	.80	.09	.78	.04	.56	.16
	Right	1.09	.05	.98	.07	.84	.08	.74	.08		
	Left	1.10	.05	.96	.10	.88	.10	.72	.04		

The results of an analysis of variance, performed on all but the 8 g acuity scores, are shown in Table 4. The binocular scores at 8 g in this and in subsequent experiments were omitted from the analysis, since comparable values of g were not used in the measurement of right and left eye acuity. The statistical procedures used in selecting the denominator for the F ratios are those recommended by Mentzer (22). Examination of F ratios in Table 4 show that acceleration and subjects, one second order interaction, and one third order interaction make significant contributions to the variance of the acuity measures.

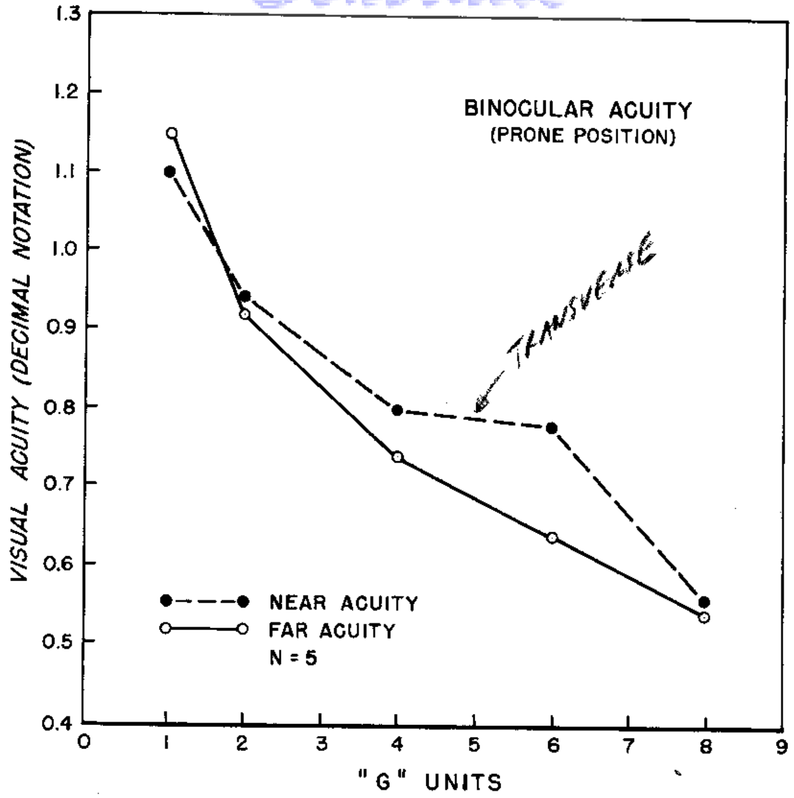

Figure 4. Means of the Binocular Acuity Scores at Each Gravity Condition

Table 4

Analysis of Variance of Binocular, Right Eye, and Left Eye Visual Acuity Scores for Prone Body Position

Source	df	Mean Square	F
Accelerations	3	97.56	39.98**
Subjects	4	13.08	5.36*
Distances	1	9.03	1.63
Eyes	2	.34	.45
AxS	12	2.44	9.04**
AxD	3	2.59	1.14
SxD	4	5.54	2.44
AxE	6	.58	1.41
SxE	8	.75	1.83
DxE	2	.54	.43
AxSxD	12	2.27	8.41**
AxSxE	24	.41	1.52
AxDxE	6	.52	1.93
SxDxE	8	1.25	4.63**
AxSxDxE	24	.27	

*P >.05
**P >.01

Since binocular visual acuity is more representative of normal visual functions, a separate analysis was made of these acuity scores. In Table 5 is shown the F ratios resulting from an analysis of the binocular data. In this analysis the significant contributors to the total variance of the acuity scores are acceleration and subjects. These F ratios are significant beyond the 1 per cent level of confidence. The assumption of homogeneity was tested by Cochran's test and found tenable. This assumption is also tenable for subsequent experiments.

Table 5

Analysis of Variance of the Binocular Visual Acuity Scores for Prone Body Position

Source of Variation	df	Mean Square	F
Accelerations	4	47.76	37.90*
Subjects	4	8.24	6.54*
Distances	1	1.71	1.16
AxS	16	1.26	1.31
SxD	4	1.48	1.54
AxD	4	1.26	1.31
AxSxD	16	.96	

P* >.01

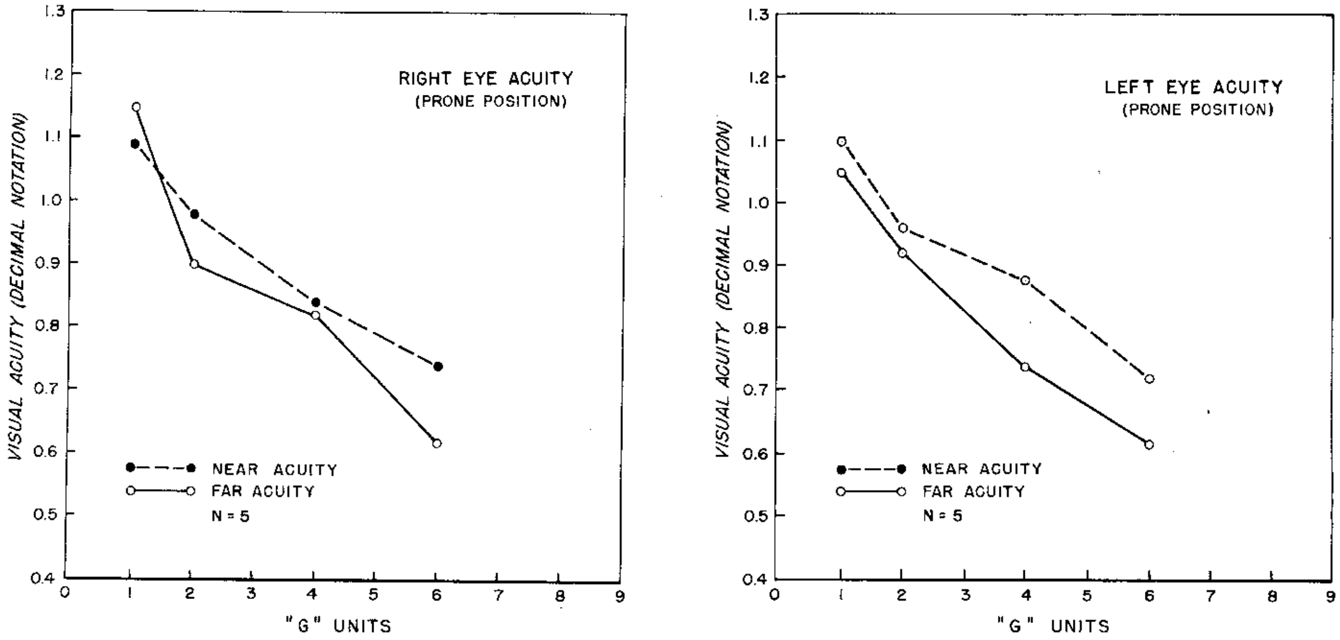

Figure 5. Means of the Right Eye and Means of the Left Eye Acuity Scores at Each Gravity Condition

Controls

[illegible]

Experiment 2: Seated Position [illegible] AF/[illegible]

6-4a g-seat

The visual acuity data obtained with the subjects in the seated body position are shown graphically in Figures 6 and 7, and in tabular form in Table 6.

Table 6

Means and Standard Deviations of Visual Acuity Scores by G Level for Seated Position (N=5)

G Values		1		2		3		4		5	
	Eyes	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
FAR	Both	1.16	.10	1.04	.10	.94	.17	.98	.07	.78	.15
	Right	1.12	.10	.94	.10	.82	.07	.84	.07		
	Left	1.18	.10	1.00	.13	1.00	.14	.92	.15		
NEAR	Both	1.10	.06	1.02	.07	.96	.10	.78	.13	.80	.09
	Right	1.06	.05	.94	.14	.88	.07	.82	.10		
	Left	1.14	.12	1.06	.12	.92	.13	.86	.14		

96

Table 7 summarizes the results of the analysis of variance performed on all but the 5 g acuity scores. The differences in the scores for three of the primary effects, are interpreted as significantly different from chance as indicated by the F test. The F ratio for acceleration is significant at the 1 per cent level of confidence whereas the ratios for subjects

Table 7

Analysis of Variance of Binocular, Right Eye, and Left Eye Visual Acuity Scores for Seated Body Position

Source	df	Mean Square	F
Accelerations	3	38.34	14.92**
Subjects	4	10.22	3.98*
Distances	1	3.33	1.70
Eyes	2	7.91	4.88*
AxS	12	2.57	3.52**
AxD	3	1.82	1.46
SxD	4	1.96	1.57
AxE	6	.25	.32
SxE	8	1.62	2.10
DxE	2	.91	.88
AxSxD	12	1.25	1.71
AxSxE	24	.77	1.05
AxDxE	6	1.03	1.41
SxDxE	8	.47	.64
AxSxDxE	24	.73	

*P > .05

**P > .01

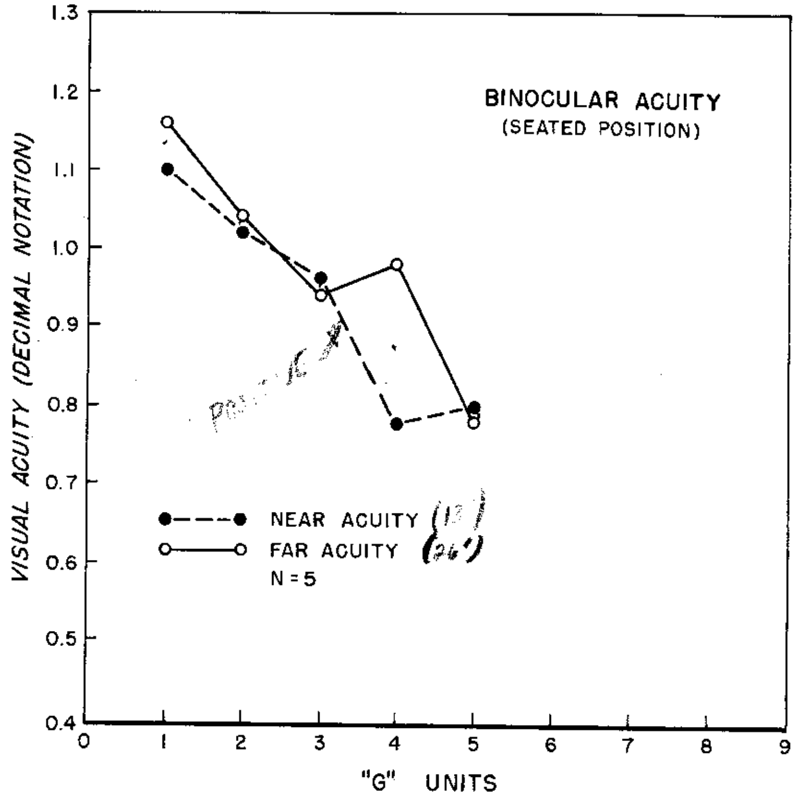

Figure 6. Means of the Binocular Acuity Scores at Each Gravity Condition

and eyes are significant at the 5 per cent level of confidence. A similar analysis performed on the binocular data reveals that accelerations and subjects are the only major source of variance and the F ratios of 20.82 and 5.10 are significant beyond the 1 per cent level of confidence. This analysis is summarized in Table 8.

The results of this experiment appear particularly significant if we consider the interpretation given by Warrick and Lund (26) to their data.

Table 8

Analysis of Variance of the Binocular Visual Acuity Scores for Seated Body Position

Source of Variation	df	Mean Square	F
Accelerations	4	17.28	20.82*
Subjects	4	4.23	5.10*
Distances	1	2.88	1.57
AxS	16	.83	.54
SxD	4	1.83	1.20
AxD	4	2.08	1.36
AxSxD	16	1.53	

*P >.01

These investigators found an impairment in ability to read instrument dials at 3 g, as compared to 1.5 g, in the seated position. A significant difference in reading errors was found between the two g conditions. They concluded that the probable cause of the decrease in performance was a reduction in blood supply to the eye or brain. Our data from the seated and semi-supine experiments indicate that the increase in the force environment results in a lowering of visual acuity but that this change is not a function of diminished cerebral circulation. Therefore, the above mentioned impairment in reading performance could be accounted for by reduced visual acuity associated with increased g rather than by cerebral hypoxia.

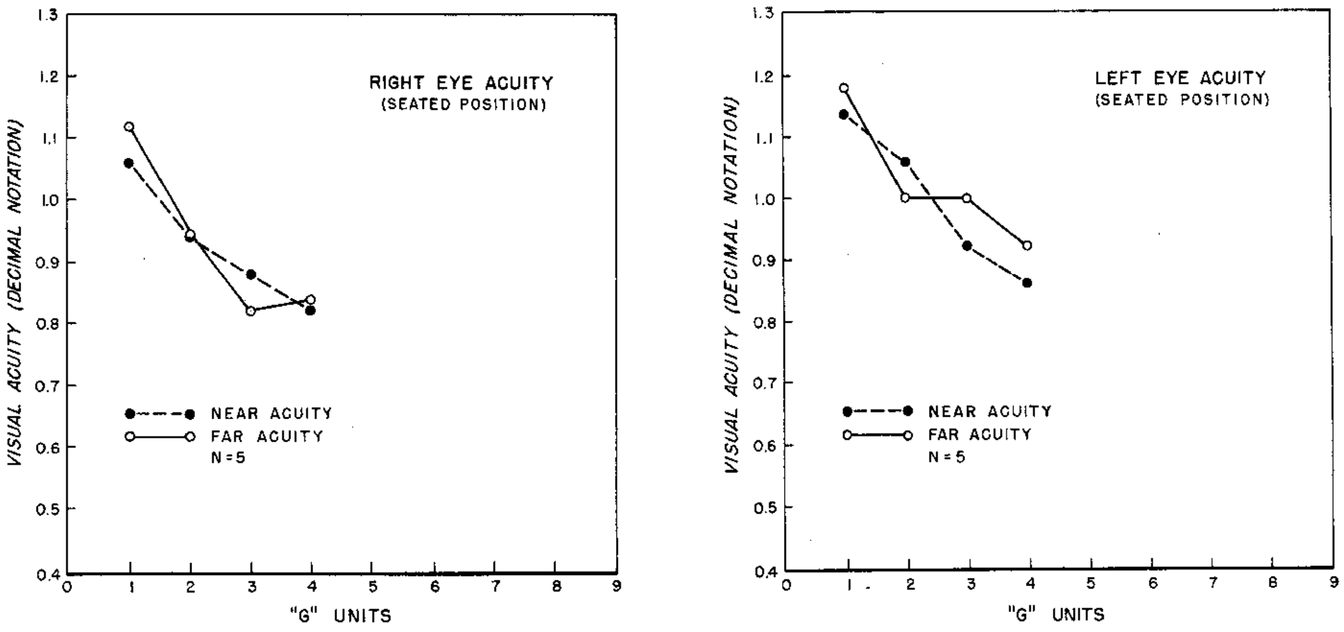

Figure 7. Means of the Right Eye and Means of the Left Eye Acuity Scores at Each Gravity Condition

Experiment 3: Supine Position

The results of this third experiment are summarized in Table 9 and in Figures 8 and 9.

The summaries of the statistical analyses of the data are given in Tables 10 and 11. In the first of these tables are the F ratios resulting from the analysis of bincoular, right and left eye data. The acuity scores at 7 g are not included in this analysis, since comparable values of g were not used in the measurement of right and left eye acuity.

Two of the main effects, accelerations and subjects, make significant contributions to the total variance of the acuity scores. The interactions of subjects and eyes, and the interaction of accelerations, subjects and distances is significant at the 5 per cent level of confidence. In Table 11, which contains the results of the analysis of the binocular scores,

Table 9

Means and Standard Deviations of Visual Acuity Scores by G Level for Supine Position (N=5)

G Values		1		3		4		6		7	
	Eyes	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
FAR	Both	1.16	.10	.96	.14	.98	.12	.90	.09	.68	.12
	Right	1.16	.10	.94	.14	1.00	.11	.88	.10		
	Left	1.12	.15	.94	.19	.92	.16	.86	.14		
NEAR	Both	1.10	.11	.88	.12	.94	.14	.72	.15	.70	.11
	Right	1.14	.08	.98	.13	.90	.14	.76	.14		
	Left	1.12	.12	1.0	.09	.90	.14	.88	.13		

there are two significant contributions to the total variance. As in the preceeding experiments, the acceleration factor is significant at the 1 per cent level of confidence. The other significant contribution is that of subjects. The F ratio of 39.36 for subjects is significant at the 1 per cent level of confidence. This latter finding is not surprising since individuals differ in their ability to withstand radial acceleration and a given individual's tolerance to acceleration changes from time to time.

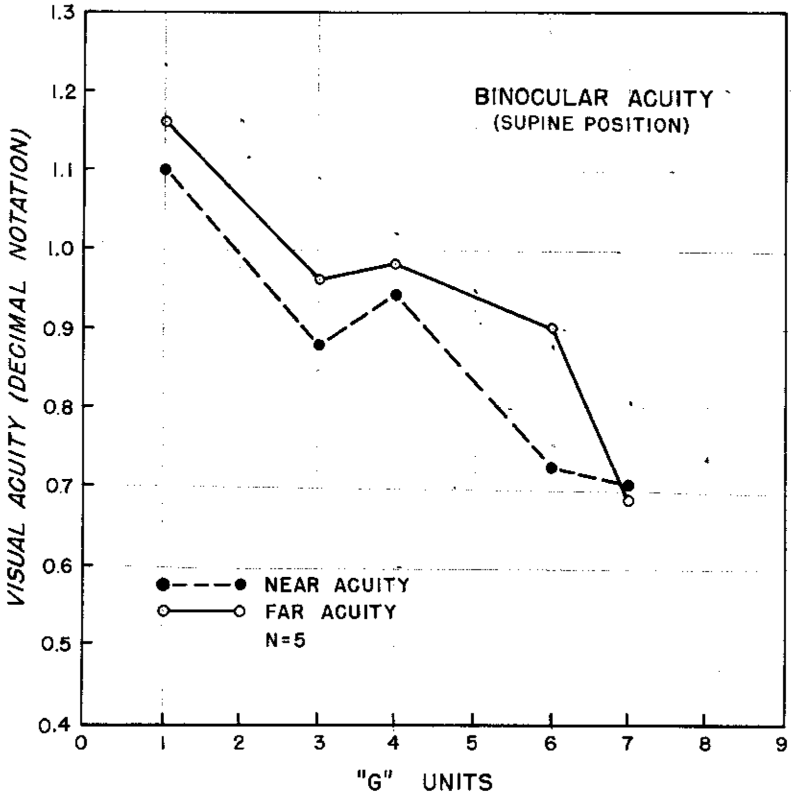

Figure 8. Means of the Binocular Acuity Scores at Each Gravity Condition

Table 10

Analysis of Variance of Binocular, Right Eye, and Left Eye Visual Acuity Scores for Supine Body Position

Source	df	Mean Square	F
Accelerations	3	46.52	108.19**
Subjects	4	35.68	82.98**
Distances	1	5.21	3.89
Eyes	2	.26	.27
AxS	12	.43	.93
AxD	3	1.34	1.22
SxD	4	.27	.24
AxE	6	.80	2.22
SxE	8	.97	2.69*
DxE	2	2.80	4.38
AxSxD	12	1.10	2.39
AxSxE	24	.36	.78
AxDxE	6	.64	1.39
SxDxE	8	.56	1.22
AxSxDxE	24	.46	

*P >.05
**P >.01

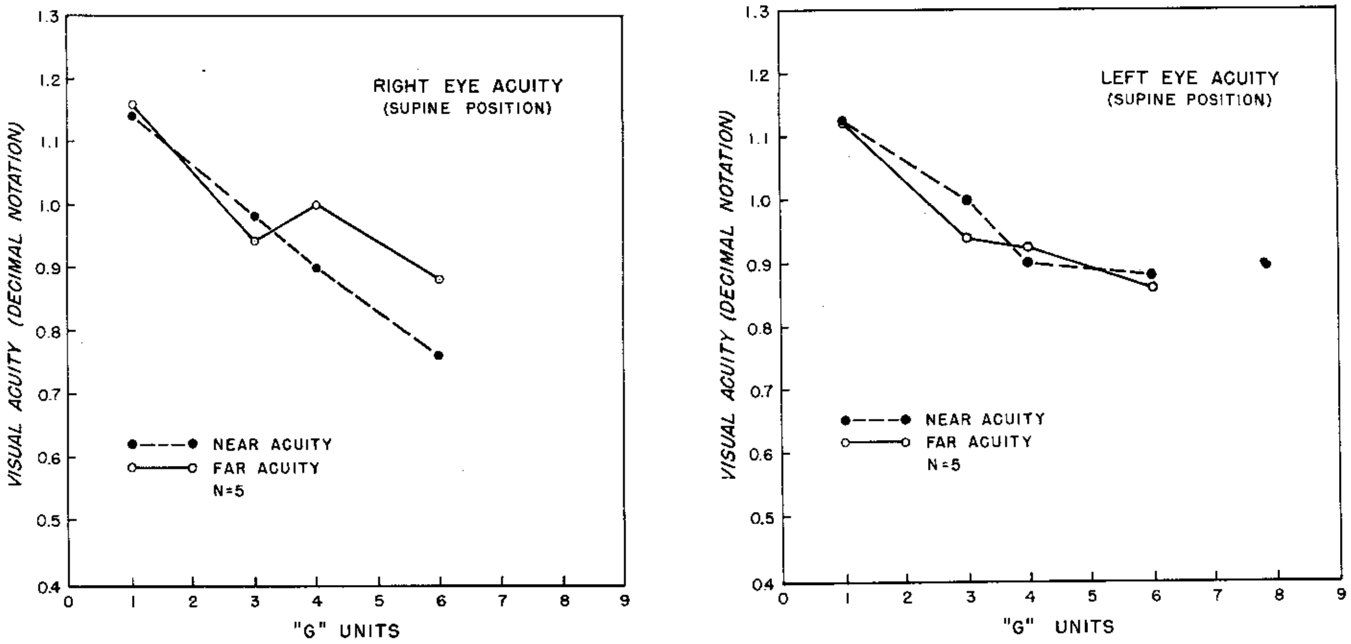

Figure 9. Means of the Right Eye and Means of the Left Eye Acuity Scores at Each Gravity Condition

Table 11

Analysis of Variance of the Binocular Visual Acuity Scores for Supine Body Position

Source of Variation	df	Mean Square	F
Accelerations	4	27.27	75.75*
Subjects	4	14.17	39.36*
Distances	1	5.78	4.35
AxS	16	.36	.73
SxD	4	.13	.26
AxD	4	1.33	2.71
AxSxD	16	.49	

*P $>$ .01

Experiment 4: Semisupine Position

This experiment is similar to the seated position experiment in that g force is applied at right angles to the lines of visual regard. However, the body position is arranged to minimize circulatory stress associated with radial acceleration. The data gathered on visual acuity in the semisupine position are shown in Table 12, Figures 10 and 11. It is to be noted that this experiment differs from the preceeding three experiments in that only four values of g were used and that acuity measures were made on the right and left eyes at the maximum g level. Maximum g was arbitrarily set at 5 g, since the trends in the acuity scores were already established, and time was pressing due to other commitments of the centrifuge.

The results of the statistical analyses are given in Tables 13 and 14. The first of these tables summarizes the analysis of variance performed on all the visual acuity scores. Accelerative forces are again a significant contributor to the total variance of the acuity scores. As in the preceeding experiments the variance due to subjects is significant. The statistical analysis of the binocular acuity data, which is given in Table 14, shows that two of the main effects and one interaction are significant. The F ratios for accelerations and subjects are significant at the 1 per cent level of confidence. The interaction between subjects and distance is statistically significant, but the theoretical significance of this result is not apparent at this time.

Table 12

Means and Standard Deviations of Visual Acuity Scores by G Level for Semisupine Position (N=5)

G Values		1		3		4		5	
	Eyes	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S. D.
	Both	1.10	.09	.94	.10	.94	.08	.78	.07
FAR	Right	1.14	.14	.92	.07	.92	.10	.80	.06
	Left	1.02	.10	.92	.10	.90	.11	.76	.15
	Both	1.04	.12	.94	.10	.86	.10	.86	.15
	Right	1.02	.12	.90	.06	.92	.04	.82	.12
	Left	1.06	.08	.94	.14	.88	.07	.86	.19

Table 13

Analysis of Variance of Binocular, Right Eye, and Left Eye Visual Acuity Scores for Semisupine Body Position

Source	df	Mean Square	F
Accelerations	3	32.07	25.66**
Subjects	4	11.47	9.18**
Distances	1	.03	.01
Eyes	2	.26	.13
AxS	12	1.25	2.91*
AxD	3	1.92	4.46*
SxD	4	2.52	5.86**
AxE	6	.22	.21
SxE	8	1.98	1.85
DxE	2	1.16	.89
AxSxD	12	.43	1.00
AxSxE	24	1.07	2.49*
AxDxE	6	.48	1.12
SxDxE	8	1.30	3.02*
AxSxDxE	24	.43	

*P >.05
**P >.01

Table 14

Analysis of Variance of the Binocular Visual Acuity Scores for Semisupine Body Position

Source of Variation	df	Mean Square	F
Accelerations	3	10.89	17.56**
Subjects	4	4.54	7.32**
Distances	1	.22	.08
AxS	12	.62	1.03
SxD	4	2.79	4.62*
AxD	3	1.29	2.15
AxSxD	12	.60	

* >.05
** >.01

Comparison of Performance for the Four Body Positions

The second major analysis performed on the data obtained in this study involved a comparison between acuity scores obtained by each subject at the four body positions under two values of g (1 and 4). Such an analysis is complicated by the fact that the same subjects did not serve in all the experiments and that some of the subjects served in more than one experiment. By referring to Table 1 it is possible to see which experiments any one of the nine subjects served. The analysis of the data for the effect of body positions on binocular visual acuity was accomplished by the use of a

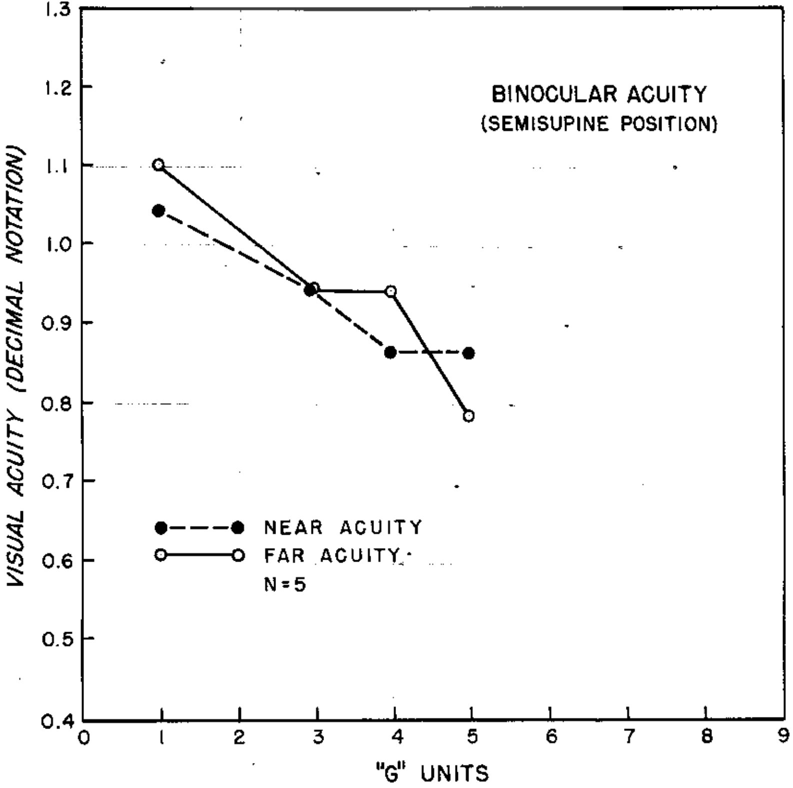

Figure 10: Means of the Binocular Acuity Scores at Each Gravity Condition

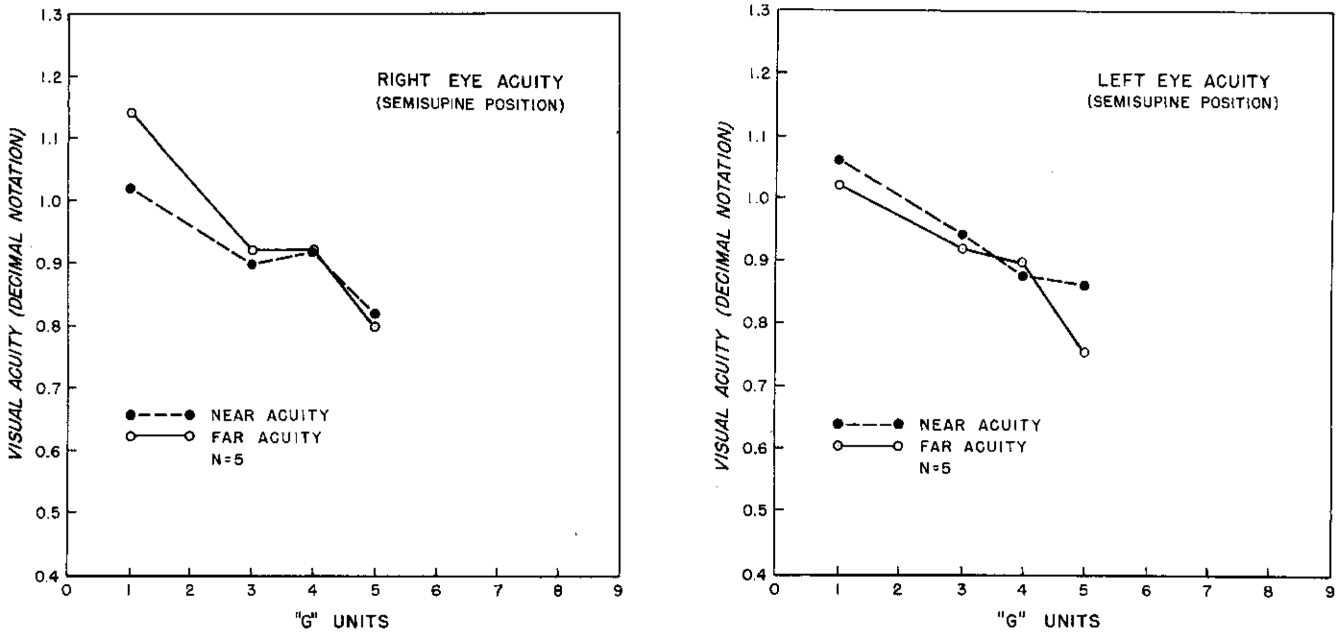

Figure 11. Means of the Right Eye and Means of the Left Eye Acuity Scores at Each Gravity Condition

hierarchal statistical model (16). The two levels of acceleration were selected as components of the design since they were the only two values common to all experiments. The analysis of the acuity data by this procedure is summarized in Table 15.

Table 15

Analysis of Variance of the Binocular
Visual Acuity Scores for All Body Positions

Source of Variation	df	Mean Square	F
Distances (D)	1	6.34	7.86*
Positions (P)	3	7.44	1.00
Accelerations (A)	1	310.54	135.61**
Subjects(S)within positions	16	7.46	14.63**
Eye Combinations (E)	2	0.205	0.27
DxP	3	2.45	3.04
DxA	1	0.200	0.27
DxS within positions	16	0.807	1.58
DxE	2	3.24	4.87*
PxA	3	5.78	2.52
PxE	6	1.29	1.69
AxS within positions	16	2.29	4.49**
AxE	2	0.085	0.13
SxE within positions	32	0.762	1.49
DxPxA	3	1.50	2.02
DxPxE	6	0.500	0.75
DxAxS within positions	16	0.743	1.46
DxAxE	2	0.310	0.61
DxSxE within positions	32	0.665	1.30
PxAxE	6	0.450	0.71
AxSxE within positions	32	0.634	1.24
DxPxAxE	6	0.773	1.52
DxAxSxE within positions	32	0.510	

*P > .05
**P > .01

The most significant factor as shown in Table 15 is the accelerative forces. This F ratio is significant at the 1 per cent level of confidence. Such a finding is consistent with the results of analyses reported earlier. Significant F ratios were also found for the variables of distance and subjects within positions and for two of the interactions. The interaction between accelerations and subjects within positions is considered to be significant at the 1 per cent level of confidence. The interaction between distances and eye combinations is significant at the 5 per cent level of confidence. It must be pointed out that in this analysis, acceleration was considered as a constant factor which means that no reliable generalization can be made to other values of gravitational stress. However, certain interpretations may be given the results which appear to be suggestive of further research.

The analysis of the visual acuity scores across all body positions makes possible the statement that these positions did not, in themselves, have a significant effect on the acuity scores obtained under the 1 and 4g conditions. The significant interaction between accelerations and body positions is interpreted to mean that visual acuity scores for the different body positions are affected differently by gravitational stress. The contribution to the total variance made by distance and the second order interactions provides a measure of support for an hypothesis that will be suggested later to account for the change in visual acuity under gravitational stress. This second order interaction is interpreted to mean that the interaction between distances and positions is different at the two levels of acceleration used in the analysis.

In this study the assumption was made that no difference would be found between mean visual acuity measured with the subject "seated comfortably" in front of the Ortho-Rater and the acuity scores obtained with the subject in any one of the protective body positions under the condition of 1 g. This assumption was tested with the t test and found tenable. Such a finding is inconsistent with the results reported by Charnwood (6). He made a comparison between visual acuity for subjects in the supine and seated position with letter recognition as a test of acuity and found higher acuity scores for subjects in the seated position.

DISCUSSION

An examination of these data suggests several hypotheses to account for changes in visual acuity under gravitational stress. These are listed below. They are intended to be neither mutually exclusive nor exhaustive.

1. Deterioration of the physiological image due to retinal ischemia or edema.

It has been shown (17) that centrifugal force induces visual symptoms by causing a decrease in blood pressure at eye level. Is it possible, then, to account for the data obtained in this study by hypothesizing a deterioration of the physiological image due to reduced cerebral circulation? In the case of the prone, supine and semisupine positions no direct measures of cerebral blood pressure have been reported. However, the subjective data referred to by Armstrong (1) would indicate that in these protective positions none of the usual visual symptoms of increased g would be expected even at the highest accelerations used in this study. Such reports are in accord with the view that any reduction in the hydrostatic distance between the heart and eye will result in higher g tolerance.

In the case of the seated position continuous observations (20) have been made on radial arterial pressure at head level. These observations show that a two minute 5 g run produces an initial drop (almost to zero) in arterial pressure which lasts for six to seven seconds. After this time the vasopressor response to reduction in pressure takes effect and blood pressure is sustained above symptom level. In this study, the measurement of acuity was not begun until 10 seconds after peak acceleration. Therefore, the initial reduction in blood pressure does not appear to be a factor when the subject is in the seated position. Although no recordings of radial arterial pressure at head level in the semisupine position are available it is logical to suppose a similar pattern of pressures, although of different magnitude, would be obtained.

Another argument for assuming that visual acuity changes are due to the effect of cardiovascular mechanics would postulate retinal edema. The loss of vision with increased arterial pressure is reported (18) to be caused by edema in and around the retina. Such edema would be analgous to the pooling of blood in the lower extremities when centrifugal force is applied parallel to the long axis of the body. A test of this retinal edema hypothesis was attempted by measuring visual acuity immediately after each experimental run. A comparison between these measures and those taken before an experimental run were interpreted as not differing significantly, as indicated by the t test. The collection of these data was discontinued after the completion of the first experiment. The weakness of such evidence lies in the fact that the acuity measurement made after each experimenal run could have sampled this visual function when the effects of edema, if any, had been dissipated. Perhaps the more sensitive test of the hypothesis would be made with the Hardinger's brush test (11). This test of the function of the macula lutea makes possible the determination of retinal edema independent of visual acuity. The test could be administered during the stress conditions.

In summary, the evidence indicates that any alternative interpretation of the experimental results must rest on some grounds other than deterioration of the physiological image due to retinal eschemia or retinal edema.

2. Involvement of the autonomic nervous system and its effect on visual acuity.

General disorientation due to g stress in the centrifuge situation could affect even the most experienced observers. Anxiety or fear is characterized by many combinations of body changes. One of the common manifestations of such reactions is a change in pupil diameter. Another possible result of sympathetic involvement is suggested in a report by Olmstead (23), who has demonstrated that the lens of an animal eye is made hypermetropic by stimulation of the sympathetic system and myopic by stimulation of the parasympathetic component of the oculomotor nerve. The effect of pupil size on acuity could be corrected by the incorporation of artificial pupils into the Ortho-Rater. This change would, however, require a more rigid support for the subject's head than was required in the present study. However, no convenient experimental control would be available if the results reported by Olmstead were shown to be important determinants of acuity performance under gravitational stress.

3. Changes in the shape of the eyeball and refracting surfaces.

If an increase in g force caused the posterior pole of the eyeball to flatten, the eye would become effectively hypermetropic and this refractive error could be compensated for by accommodation. However, if the mechanical forces resulting from increased g should aspherically deform the refracting surfaces of the cornea or the lens, a decrease in both far and near acuity would be expected. A hypothesis of this sort would be difficult to examine in the experimental situation because of problems associated with optical alignment between the eye and measuring apparatus. As a first approach to the test of the deformation hypothesis, measurements would be made for astigmatic errors. The standard Ortho-Rater can be equipped with these astigmatic test plates. If the presence of astigmatic errors is considered as a factor in these experiments it may be concluded that acuity measurements made under stress conditions would vary as a function of the types of acuity targets employed to measure this function. Sloan, et al (24), has shown that for astigmatic errors of 1 diopter or more, acuity measured with the checkerboard target is significantly higher than that measured with letter type test objects.

4. Displacement of the crystalline lens in the direction of gravity.

Fincham (9) has shown that in high degrees of accommodation the lens is displaced in the direction of gravity. Using young subjects he found a difference of over one diopter between the values of the near-point, with vision directed downward and upward. He concludes that with forward movement of the lens the focus within the eye is brought forward and, therfore, in order to bring the image back on to the retina, the object may be brought nearer to the eye. These findings bear directly on the data obtained in this study because similar changes in lens position may be expected as a function of gravitational stress. Let us examine the lens movement hypothesis and one means of subjecting it to experimental verification.

The prone position will serve as an example. If the lens is displaced in the direction of gravity, and if the degree of accommodation is slightly beyond the near point, the consequent blurring of the optical image can be corrected by decreasing accommodation. However, if the non-hypermetropic eye is unaccommodated and the lens is displaced in the direction of gravity, it would not be possible to focus the retinal image sharply by changes in the accommodative apparatus. It is interesting to note that the reverse of this situation would be predicted for the supine position, for here the gravitational displacement would have its greatest effect on the near acuity function. There is some evidence to support this tentative explanation of the progressive change in acuity with g. However, any attempt to interpret the data only serves to emphasize the lack of crucial experimentation in the area of near and far visual acuity. Having considered the data obtained with the subject in the prone position and having decided that the resulting loss in acuity is equivalent to a refractive error of one diopter, let us see what change in the dioptrics of the eye would result if the lens moved as much as 2 mm closer to the posterior surface of the cornea. In Gullstrand's (26) schematic eye the distance between the rear surface of the cornea and the first surface of the lens (the anterior chamber) is 3.1 mm. If the depth of the anterior chamber is reduced by 2 mm the total power of the optical system is increased from the 58.64 of the Gullstrand eye to a power of 60.87 diopters. As a result of the assumed change in lens position, the Gullstrand eye is now 2.23 diopters myopic. Since maximum change in acuity in the prone position was set at one diopter refractive error, it is unnecessary to assume a lens movement as much as 2 mm.

A test of the hypothesis of lens displacement might be made by repeating the prone or supine experiments with the interposition of opthalmic lenses between the eye and the Ortho-Rater. If it were possible to correct the hypothesized refractive error by this technique it would be possible to accept the hypothesis of lens movement, and make additional inquiries into the effects of gravity on accommodation in general. However, no simple relations would be expected.

SUMMARY AND CONCLUSIONS

These experiments were designed to determine the relation between gravitational stress and visual acuity when the factor of cerebral circulatory competence is minimized by the use of protective measures known to ameliorate the gross visual symptoms associated with an increase in the force environment. Gravitational stress was produced experimentally by the AML human centrifuge. Visual acuity was measured with checkerboard targets standard with the Ortho-Rater.

The following basic findings resulted from an analysis of the data gathered from this experiment:

1. Gravitational stress has a significant and progressive effect on visual acuity.
2. The observed changes in visual acuity cannot be accounted for by reduced cerebral circulation.
3. Three other factors have been hypothesized to account for the differences in visual performance during gravitational stress:
    a. Involvement of the autonomic nervous system and its effect on visual acuity.
    b. Changes in the shape of the eyeball or refracting surfaces.
    c. Displacement of the crystalline lens in the direction of gravity.
4. The lens-displacement hypothesis is tentatively accepted to account for the observed acuity changes obtained under gravitational stress.

It should be noted that this is one of a series of studies of the relation of environmental stress to visual functions and that further inquiry may clarify some visual mechanisms that would otherwise be difficult to examine.

References

1. Armstrong, H. G. Principles and practice of aviation medicine. Baltimore: William and Wilkins Co., 1952, 374.

2. Armstrong, H. G., and Heim, J. W. The effect of acceleration on the living organism. J. Aviat. Med., 1938, 9, 199-214.

3. Adjutant Generals Office. Studies in visual acuity. PRS 742. Washington: U. S. Government Printing Office, 1948, 42-61.

4. Canfield, A. A. The human centrifuge. Research Review (Office of Naval Research), 1950, March, 1-4.

5. Canfield, A. A., Comrey, A. L., and Wilson, R. C. The influence of increased positive g on reaching movements. J. Appl. Psychol., 1953, 37, 230-235.

6. Charnwood, Lord. Effect of posture on involuntary eye movements. Nature, London, 1950, 166, 348-349.

7. Comrey, A. L., Canfield, A. A., and Wilson, R. C. The effect of increased positive radial acceleration upon perceptual speed ability. J. Aviat. Med., 1951, 22, 60-64.

8. Duane, T. D., Beckman, E. L., and Hunter, H. N. Some observations on human tolerance to exposure of 15 transverse g. U. S. Navy Air Development Center, Johnsville, Penna., TED Project No. ADC AE 6303, July, 1953.

9. Fincham, E. F. The mechanism of accomodation. British J. Ophth., 1937, Monogr. Suppl. 8, 52-54.

10. Gerathewohl, S. J. Physics and psychophysics of weightless visual perception. J. Aviat. Med., 1952, 23, 373-395.

11. Goldschmidt, M. A new test for function of the macula lutea. Arch. Ophth., 1950, 44, 129-135.

12. Greene, E. R. Measurements of human behavior. (Rev. Ed.) New York: Odyssey Press, 1952, 296-297.

13. Hallenbeck, G. A. Design and use of anti-g suits and their activating values in world war II. Army Air Force, Air Material Command, Dayton, Ohio, AAF Technical Report 5433, 1946, (Restricted).

14. Imus, H. A. Comparison of ortho-rater with clinical ophthalmic examination. J. Aviat. Med., 1949, 20, 2-23.

15. Kuhn, H. S. Eyes and industry. (2nd Ed.), St. Louis, Mo.: C. V. Mosby, 1950, 55-62, 110-122.

16. Kempthorne, O. Design and Analysis of Experiments. New York: Wiley, 1952, 104-113.

17. Lambert, E. H. The physiologic basis of "blackout" as it occurs in aviators. Federation Proc., 1945, 4, 43.

18. Lucic, H. Retina and vitreous. In M. Wiener (Ed.) Vol. 2, Opth. in War Years. Chicago: The Yearbook Publishers, Inc., 1948, 721.

19. Lund, D. W. Effect of postural variations on man's tolerance to g. Engineering Division, Air Material Command, Dayton, Ohio, USAF Memorandum Report TSEAA-695-72B, June 1947.

20. Martin, E. E., and Henry, J. P. The effect of time and temperature upon tolerance to positive acceleration. J. Aviat. Med., 1951, 22, 382-390.

21. Martin, E. E., and Henry, J. P. The supine position as a means of increasing tolerance to acceleration. Engineering Division, Air Material Command, Dayton, Ohio, AF Technical Report No. 6025, August, 1950.

22. Mentzer, E. G. Test by analysis of variance. Wright Air Development Center, Wright-Patterson AFB, Ohio, WADC Technical Report 53-23, 1953.

23. Olmsted, J. M. D. The role of the autonomic nervous system in accomodation for near and far vision. J. Nerv. Ment. Dis., 1944, 99, 794-798.

24. Sloan, Louise L., Rowland, W. M., and Altman, Adelaide. Comparison of three types of test targets for the measurement of visual acuity. Quart. Rev. Ophth., 1952, 8, 4-16.

25. Southall, J. P. C. Mirror, prisms and lenses. (3rd Ed.) New York: Macmillan, 1933, 370-374.

26. Warrick, M. J., and Lund, D. W. The effect of moderate positive acceleration (g) on ability to read aircraft type instrument dials. Engineering Division, Air Material Command, Dayton, Ohio USAF Memorandum Report TSEAA 694-10, November 1946.