AMRL-TR-75-113

p.s.

ADA030476

MECHANICAL RESONANT FREQUENCY OF THE HUMAN EYE IN VIVO

AEROSPACE MEDICAL RESEARCH LABORATORY

AUGUST 1976

Approved for public release; distribution unlimited

DDC
OCT 6 1976
D

4

AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEM COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICES

Please do not request copies of this report from Aerospace Medical Research Laboratory. Additional copies may be purchased from:

National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

Federal Government agencies and their contractors registered with Defense Documentation Center should direct requests for copies of this report to:

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22314

TECHNICAL REVIEW AND APPROVAL

AMRL-TR-75-113

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 80-33.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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

FOR THE COMMANDER

CLYDE R. REPLOGLE, PhD
Chief
Environmental Medicine Division
Aerospace Medical Research Laboratory

AIR FORCE - 23 SEPTEMBER 76 - 100

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: (14) AMRL-TR-75-113

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): (6) MECHANICAL RESONANT FREQUENCY OF THE HUMAN EYE IN VIVO.

5. TYPE OF REPORT & PERIOD COVERED: Doctoral Dissertation

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): (10) Morton K./Ohlbaum

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62~~20~~2F, 7222

11. CONTROLLING OFFICE NAME AND ADDRESS: (Same as block 9)

12. REPORT DATE: (11) August 1976

13. NUMBER OF PAGES: 95

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (9) Doctoral Thesis, (12) 105p.

15. SECURITY CLASS (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report): (16) AF-7222

Approved for public release; distribution unlimited

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

18. SUPPLEMENTARY NOTES

Submitted to the faculty of the Graduate School in partial fulfillment of the requirement for the degree, Doctor of Philosophy in Physiological Optics, Indiana University, August 1973, under the sponsorship of the Air Force Institute of Technology.

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

Vibration
Vision

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

A hypothetical mechanism of partial visual tracking to account for the viewing distance dependancy of visual performance in vibration was criticized because ocular resonance was not considered.--By means of mechanical and photographic techniques, the resonant frequency of the eye was found to be 18 Hz; however, the amplification factor is insufficient to account for the observed performance. Additional psychophysical tests were not inconsistent with the original hypothesis, and also demonstrate that the major component of the eye movement is rotational rather than translational.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

009 850

SUMMARY

Contemporary aerospace missions including those involving space flight, rotor wing vehicles, VTOL and STOL aircraft as well as high speed, low altitude flights. have intensified the problems associated with vibration induced visual decrements.

Recent investigations have demonstrated that visual losses are a function not only of input load and frequency, but also of viewing distance. A mechanism involving at least partial visual tracking of distant targets at low frequencies to account for these data has been proposed earlier by this author.

The tracking hypothesis had been criticized since it did not consider the possibility of resonance effects either in terms of seat to head or head to eye transmission. This experiment was devised to measure the transmission across a reasonable vibration spectrum through the body to the eye, and to relate transmission, resonance and eye movement to visual performance.

Fifteen human volunteers were subjected to vertical whole body vibration from 5 to 50 Hz at ±0.5 to ±2.0 Gz seat input. Skull movement was measured with a miniature accelerometer, while eye movement was monitored by photographic imagery of a corneal reflection spot. These measures, accomplished simultaneously, and for each vibration condition, were used to determine seat to skull and skull to eye transmission ratios.

Consistent results indicate that the vibration transmission ratio from seat to head monotonically decreases from 1.65 at 5 Hz to 0.21 at 50 Hz. The eye however apparently follows the skull movement in a passive manner except in the vicinity of 18 Hz. A peak in the transmission ratio curve of 1.33 indicates ocular resonance at this frequency.

Measured eye movement amplitudes correlated highly (r = .92) with visual acuity decrements when viewing a nearby target, but poorly (r = .42) for a distant target. Although the 1.33 amplification factor at the 18 Hz resonant frequency contributes to total eye movement, it does not explain the viewing distance dependency of visual acuity.

The amplitude of apparent movement of a fixed target was psychophysically measured at two viewing distances. Perceived movement at frequencies greater than 20 Hz was proportional to the viewing distance, indicating that the induced eye movement was primarily rotational. At lower frequencies the proportionality does not hold.

Although this nonlinearity might be explained on the basis of a variable phase lag between translational and rotational components of the eye movement, it is more parsimonious to accept the partial tracking hypothesis since the latter can account for both nonlinear effects. Furthermore, the majority of subjects introspectively reported that they did indeed track the target at low frequencies.

PREFACE

This effort was performed under the sponsorship of the Air Force Institute of Technology. The dissertation was accepted by the faculty of the Graduate School, Indiana University, in partial fulfillment of the requirements for the Doctor of Philosophy degree in Physiological Optics.

The experimental effort also supports the mission of the Environmental Medicine Division of the Aerospace Medical Research Laboratory, under project 7222, Combined Stress Environments in Air Force Operations.

The author thanks the officers, men and staff of the Aerospace Medical Research Laboratory who gave their time and technical assistance, and especially to SSgt Roy Lowe who acted as chief technician and coordinator for the actual experiment.

TABLE OF CONTENTS

LIST OF FIGURES AND ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

The fact that various physiological stresses encountered in the aerospace environment including vibration can result in a decrement in human visual performance has been recognized for some time (Wulfeck et al 1958). Given this qualitative statement, research and development in the field of the aerospace sciences must take two directions. The first, which to a certain extent is dependent on the second, is in the area of vehicle design. Obviously, optimum design would eliminate or reduce those vibrations which would detract from the efficiency of the system, not only in terms of mechanical factors, but also to remain within the survival, comfort, and performance tolerance limits of the human passenger-operator. This then represents the second direction; the determination of the permissible limits of vibration.

For several reasons it is inappropriate to demand of the aerospace engineer that he eliminate all vibration from the system. Not only would this be a qualitative impossibility but the very attempt to do so could be prohibitively expensive, not merely from the fiscal aspect, but also in terms of possible loss of efficiency of the vehicle itself. The time involved in designing the more sophisticated vehicle cannot be measured in money and furthermore such increased complexity can, in itself, result in further pyramiding of complex factors.

Moreover, such efforts may, under practical conditions, be completely unnecessary. That is to say, in terms of vibration, as in any other stress modality, there are acceptable levels that can be tolerated by the human operator without ill effects or decrements in performance (Magid 1960).

The task of those involved in the medical aspects of the aerospace sciences is that of the determination of three basic parameters regarding the effects of vibration in the human. Firstly, we must determine those levels of vibration stress that are readily tolerable by our crew members without seriously compromising safety or performance. Secondly, we must, in the laboratory, reach beyond this point in order to carefully evaluate the significance of stronger vibration effects, not only to avoid impossible physical or performance demands upon aerospace crews, but in order to evaluate the extent of their capability limitations under these conditions. Thirdly, we must discover those physical or physiological factors underlying performance and tolerance limitations so that they may be eliminated, or at least minimized by appropriate vehicle design.

II. VISUAL PERFORMANCE IN A VIBRATING ENVIRONMENT

Qualitative observations of visual decrements associated with vibration have been reported and recognized as a problem in aviation medicine (Chiles and Custer 1963, Mercier 1962, Wulfeck et al 1958) but serious attempts to derive quantitative data have appeared only in the past decade.

Lange and Coermann (1962) reported on their study of visual acuity under controlled sinusoidal vibration. They carefully explored the effects of ±Gz* vibration in increments from one to twenty Hz and considered only the subject vibrating/target stationary display. A decrement in visual acuity that seems, on the surface, to increase in a linear fashion with frequency, on close inspection turns out to be a function of the relationship between frequency and amplitude. If the reported decrements in visual acuity are computed for the "G" forces involved, without regard to frequency, then a minimal effect is noted at frequencies less than 4 hz while at higher frequencies, there seems to be some effect on visual acuity that may actually remain for a short period following the vibration.

The resonant frequency for the entire human body is usually taken as being in the vicinity of 3-8 Hz, with

*Standardized terminology designates "Z" as vertical, "Y" as lateral and "X" as anterior/posterior acceleration axes.

5 Hz a reasonable average (Magid et al 1960). Harris et al (1964) reported on their work involving visual tracking performance under 5 Hz ±G stress. Although visual tracking represents a relatively complex psychomotor function rather than a single visual parameter, it is nevertheless pertinent to this discussion. With frequency fixed at 5 Hz, their independent variable was the amplitude of the vibration, the dependent variable being performance compared to baseline state testing. Although their data hints strongly at decrements in performance at any amplitude of vibration, only at higher test levels were their results statistically significant. The description of their experimental procedure is incomplete and neither the axis of vibration nor the subject-target phase relationship is specified, nevertheless it was demonstrated that moderate vibration is tolerable without decrement in tracking performance.

Taub (1964) also attacked the problem from a performance standpoint, by presenting his subjects with a "dial reading task" under many conditions of sinusoidal vibration. His experiment was quite broad, covering many variables never previously investigated. With the subject in a semi-supine position, he evaluated performance at 6, 11 and 15 Hz in the X, Y, and Z axes, at varying levels of acceleration, with and without helmet restraint with both an "easy" and a "difficult" task. The display was attached to the "shake table" and vibrated in phase with it and the subject. Although results with the "easy" task were inconclusive, a significant loss in performance directly related to the acceleration or amplitude of vibration (and not frequency) was noted for the difficult task when the head was not restrained.

The use of a helmet and restraint to restrict body movement produced mixed results. Although helmet restraint attenuated the visual loss during X axis vibration, it was ineffective with Z vibration and actually resulted in further performance loss when vibration was at 11 and 15 Hz in the Y axis.

An unpublished investigation by Ohlbaum and O'Briant (1970) involving the effects of a helmet also produced mixed results. At low frequencies (3-10 Hz) the wearing of a helmet produced greater visual degradation than was experienced without the helmet. At frequencies above 12 Hz the visual losses were considerably reduced when the subject wore a helmet, apparently due to attenuation of the head vibration at these frequencies.

Dennis (1965) contrasted the effects of Z axis subject and display vibration. His targets were a series of numbers subtending 4.4' of arc and subjects were required to read them in a limited time period. His estimate of performance degradation was based on the increase in errors during vibration tests compared to baseline static performance. Target versus subject vibration situations were equated by producing identical angular velocity and amplitude relative to the visual axis.

At 6 Hz, which approximates the frequency for whole body resonance, target vibration resulted in a greater decrement of visual performance than did subject vibration. However, at 14, 19 and 27 Hz, subject vibration resulted in greater visual loss than did display vibration. Dennis draws these conclusions: (1) Subject vibration at frequencies in the 14 to 27 cps range cause greater visual loss than at lower rates because of the resonance of facial tissues; (2) Whole body resonance does not affect the eyes or vision as such; (3) The adjustment of eye movements by labyrinth reflex is quicker and more reliable than by pursuit movements.

In 1965, Clarke et al reported on the effects of ±Gx vibration at 11 Hz in combination with X axis bias acceleration. In this study, the visual task was similar to that used by Taub (1964) and vibration of subject and target were in phase. Although instrumental factors (harmonic distortion in their apparatus) may have had some quantitative effects on their data, the experiment is quite significant. The compound stresses of acceleration and vibration did not summate, as might be expected; instead visual performance and subjective tolerance was actually greater than for either stress alone. They used as their maximum stress 3.85 Gx combined with ±3.0 Gx so that instantaneous Gx was always positive, varying from 0.85 to 6.85 Gx. Although it apparently has never been confirmed, it would seem that the transition from positive to negative G is at least as significant as the G load itself.

One must be cautious however and be aware that X axis effects are not necessarily the same as those produced in the more troublesome and more frequently investigated Z axis.

Rubenstein and Taub (1967) evaluated the suitability of various instruments for use in evaluating visual acuity under vibration conditions. They rejected the more common clinical tests as well as the Lange and Coermann (1962) device as being either unsuitable or unsafe and developed their own technique based on detection of a fixed vernier separation under conditions of varying illumination.

The effects of three frequencies (5, 8, 11 Hz) of the whole body Z-axis vibration were investigated with subject only vibrating, as well as when subject and display vibrated in phase. As an additional factor, they evaluated the effect of a bite-bar to insure in phase vibration of the subject's head. When the bite-bar was not used, the results were quite similar to those of Taub (1964). Decrements in performance were demonstrated at all frequencies and were similar when equated for constant acceleration. The use of the bite-bar resulted in further decrements in all test modes, and was attributed to the lack of attenuation of the imposed vibration by the body. It was also noted that the results were similar in subject-only and in subject-plus-display vibration tests. The authors conclude that geometric displacement is not the crucial factor leading to visual function impairment during vibration.

Rubenstein and Kaplan (1968) extended the excellent work of Rubenstein and Taub (1967) by investigating the effects of Y axis vibration.

The visual task, essentially the same as that used in the 1967 study, required recognition of a fixed vernier separation when luminance was varied. Although the psychophysical method used (ascending method of limits) may not adequately control response bias, this is only a minor weakness in their otherwise excellent experiment.

Vibration between 13 and 78 Hz equated for constant acceleration (Gy = 1.0) or for control displacement (D.A. = .03 cm) was applied directly to the head or to the target. (In phase subject-target vibration was not investigated.) When the head was vibrated, with either displacement or acceleration held constant, the curves of visual acuity are U-shaped, with the most severe attenuation of acuity in the range of 20 to 40 Hz.

At very high (over 60 Hz) or very low (below 15 Hz) frequencies, the decrement in acuity was relatively small.

When the presentation was altered to that of target vibrating/subject fixed, only small mean decrements in acuity were found and these were not statistically significant from visual acuity in the static condition.

As mentioned earlier, one must be cautious with regard to generalizing the effects encountered with one vibration axis with those encountered in another.

It would seem that the visual problems created in a vibrating environment had been well identified. However, serious difficulties were encountered in the course of recent attempts in the exploration of space.

Inflight vibration, occurring at critical times in two of the 1966 Gemini missions, seriously interferred with visual monitoring of the control systems and nearly caused one mission to be aborted. Although engineers had accurately predicted the orientation, magnitude and time of occurrence of the vibration, the loss of visual acuity under this stress was far greater than that which had been expected on the basis of experimental reports and prevented the crew from making appropriate instrument observations.

Henning von Gierke, a bioengineer who had worked with Coermann (1962), and C. R. O'Briant, a flight surgeon whose experiences in vision included the evaluation of the McKay-Marg tonometer for the Air Force, working at the Vibration and Impact Branch of the 6570th Aerospace Medical Research Laboratory, were unable to account for this problem. In 1968 I joined them and almost by accident we stumbled across the critical, uncontrolled parameter that had confused the issue. Apparently, in order to predict functional visual losses under vibration stress, not only is it necessary to consider the vibration parameters of G load, orientation, frequency and amplitude, but also the viewing distance. That is to say, visual losses were linked not only to the input vibration, and the degree of attenuation through the body, but also to changes in the dynamic geometry of the viewing situation (O'Briant and Ohlbaum 1970, Ohlbaum et al 1971).

This new information was published in a series of papers which indicated the following: (a) At higher frequencies (>30 Hz), the body attenuates the relatively low* input amplitude resulting in comparatively mild visual disturbance at any viewing distance;

---

*amplitude is inversely proportional to the square of the frequency with G load held constant

(b) At frequencies below 15 Hz, the visual acuity loss for a near target is far greater than for a distant target. Furthermore, while for the near target, the loss seems to be a function of the vibration amplitude, a distant target is relatively more disturbed by the mid-frequencies of 20-25 Hz than by 5 or 10 Hz. This turns out to be the factor involved in the Gemini problem. The Coermann (1962) data used to predict the visual loss were apparently based upon distant vision experiments while the visual task involved a nearby instrument panel and the spacecraft vibration was in the 8-10 Hz range. (See Figure 1)

An interaction of angular velocity, angular amplitude and partial visual tracking was proposed to account for the differences in performance as a function of viewing distance and is discussed in Chapter X.

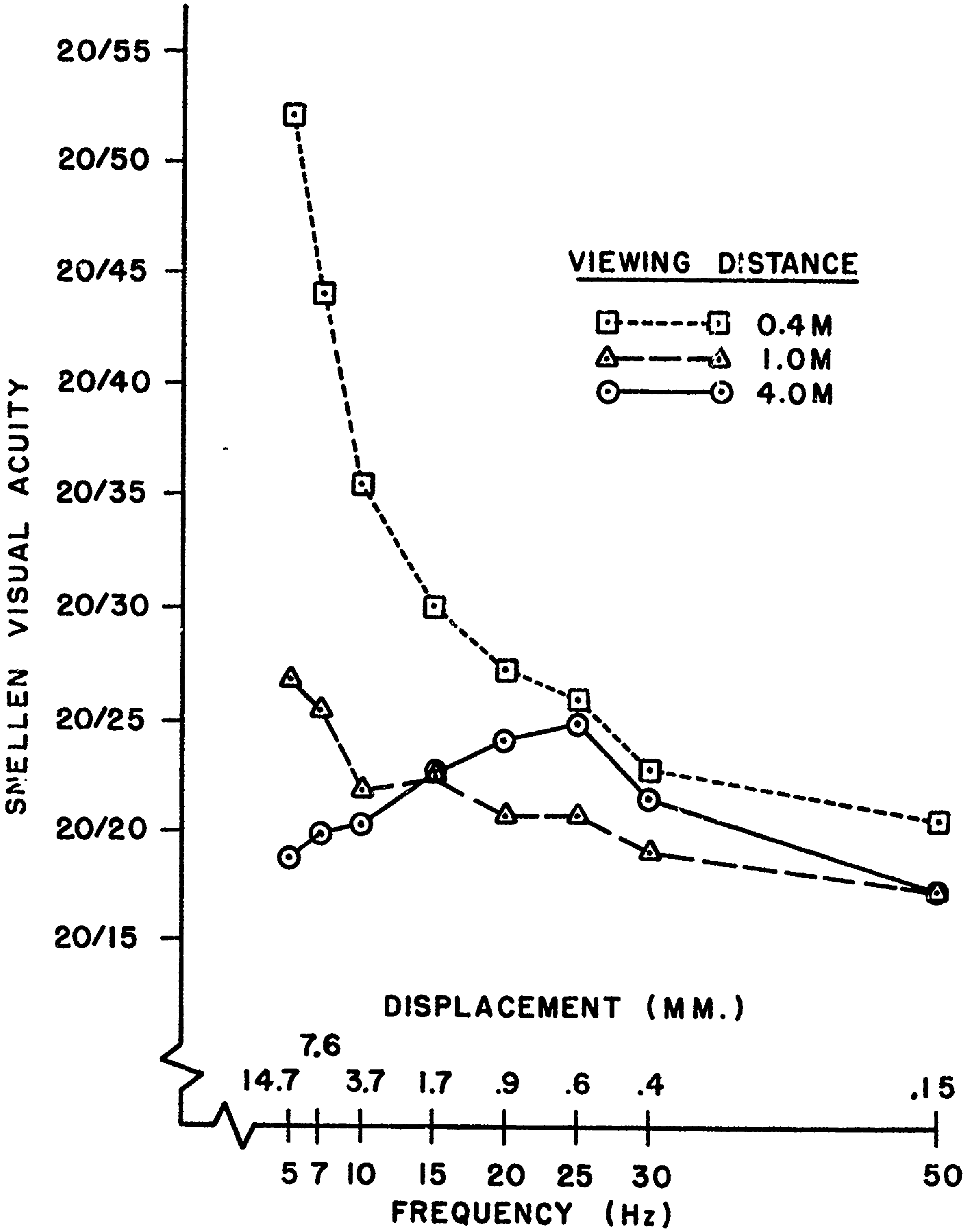


Figure 1: Snellen Visual Acuity at ± 0.75 Gz as a function of frequency (or displacement) and viewing distance.
(from O'Briant and Ohlbaum 1970)

III. OCULAR RESONANCE STUDIES

The major criticism of these reports has been based on the fact that possible resonance phenomena have not been investigated. The tacit assumption, probably ungrounded, was that the attenuation through the body is not frequency dependent, and furthermore that the eye moves passively following the forcing function of the skull vibration pattern.

These two points may well be irrelevant in terms of the effect of seat input on visual performance, and indeed one may "Black-Box" all factors between the input and output functions. Nevertheless, not only is academic interest raised concerning the possibility of these interactions, but practical engineering solutions to the problem would be aided by a more complete knowledge of the contents of the "Black-Box".

The factor of resonance is important since it can indicate the reason for unusual performance results at particular frequencies and it may also be considered in terms of specific frequencies to be avoided in the design of aerospace equipment.

Although we are primarily concerned with human testing, the nature of certain experiments precludes the use of human subjects. Nickerson et al (1963) investigated the question of physical damage to the eye, using anesthetized dogs as subjects. Since the amplitude of the vibration was far beyond that at which we expect to expose humans, I will consider only their resonance studies for the purpose of this discussion.

In the frequency ranges below 22 Hz and above 45 Hz, transmission from head to eye was close to unity, suggesting passive following by the eye of the input vibration load. A sharp transmission peak at about 40 Hz with an amplification factor of eight, indicates a strong resonance at this frequency. This cannot be accepted however as the resonant frequency of the eye itself since the input load was presented at the jaw of the dog rather than at the orbit. It must be considered then not as ocular resonance, but only jaw-head-eye system resonance. It also refers only to an anesthetized laboratory animal; any implications for or extrapolation to the intact human being should be considered very approximate at best.

Lee and King (1970) reported on their attempt to monitor eye movement as a function of seat input and head movement. Utilizing a rather ingenious method to "neutralize" perceived target movement, they presented data on head and eye transmission for both amplitude and phase.

Seat to head transmission shows a maximum at 5 Hz which is not surprising since this is the whole body resonant frequency.

The head to eye data, however, appear to be grossly unreasonable. In a freely resonating, undamped system (a tuning fork for example), large amplification of the input forcing functions are to be expected. Intuitively, one would expect that the eye is neither undamped nor freely resonating. Thus their report of transmission factors increasing from .33 at 3 Hz to unity at 12 Hz are reasonable, but the balance of their monotonic curve which increases to an amplification factor of 55 at 70 Hz must be examined with suspicion.

Their paper has some other questionable points. By measuring head acceleration at the jaw by means of a bite-bar, any torsional movement of the skull (known to occur as a contaminant of nominally translational vibration) becomes exaggerated as a function of the distance between the jaw and the orbit.

IV. THE METHODOLOGY OF RESONANCE DETERMINATION

Under ordinary conditions, it is a fairly simple problem to evaluate the resonant frequency of an inanimate object and its experimental determination is relatively straightforward.

One simply applies to the object various forcing functions from a pre-selected vibration spectrum of pure frequencies. The output amplitude (at each frequency) is compared to the input amplitude (for the sake of simplicity it is conceptually easier to keep input amplitude constant). That frequency where the output is the greatest represents the resonant frequency. In Figure 2 for example, the peak is fairly obvious and is unimodal. In fact, in many experiments of this nature, one would expect subpeaks to occur, representing harmonics of the resonant frequency (Figure 3).

With these basic concepts in mind, let us consider the difficulties which arise in a noninvasive, nondamaging investigation of a biological entity, specifically the human eye in vivo.

In order to make an evaluation of this kind, one should consider realistic levels of vibration. The stress should be enough to cause measurable effects, yet remain within tolerance limits. Human tolerance to

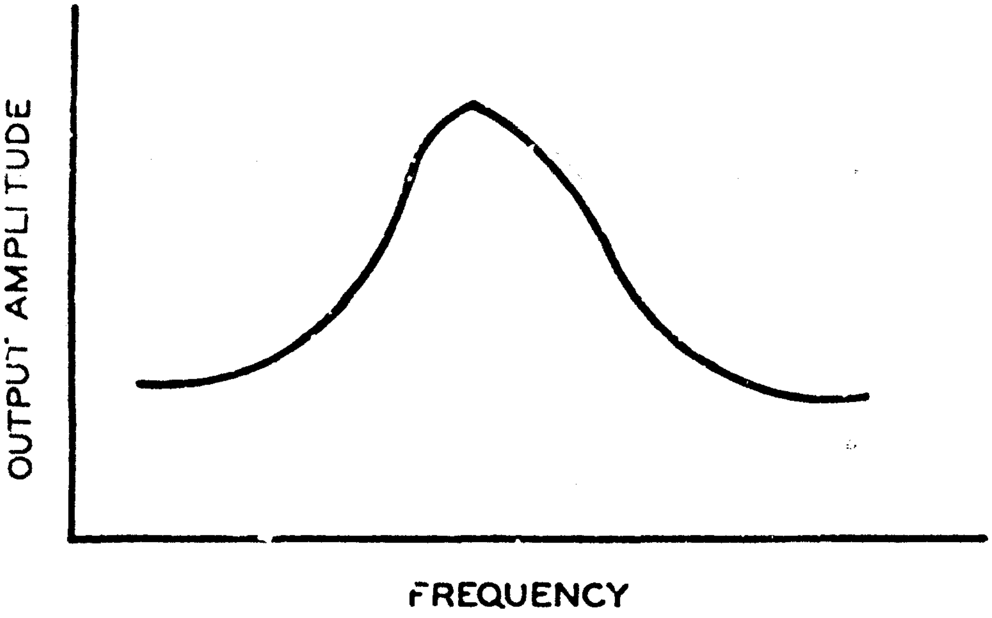


FIGURE 2. RESONANCE. With equal input loads, the frequency of maximum output represents resonance.

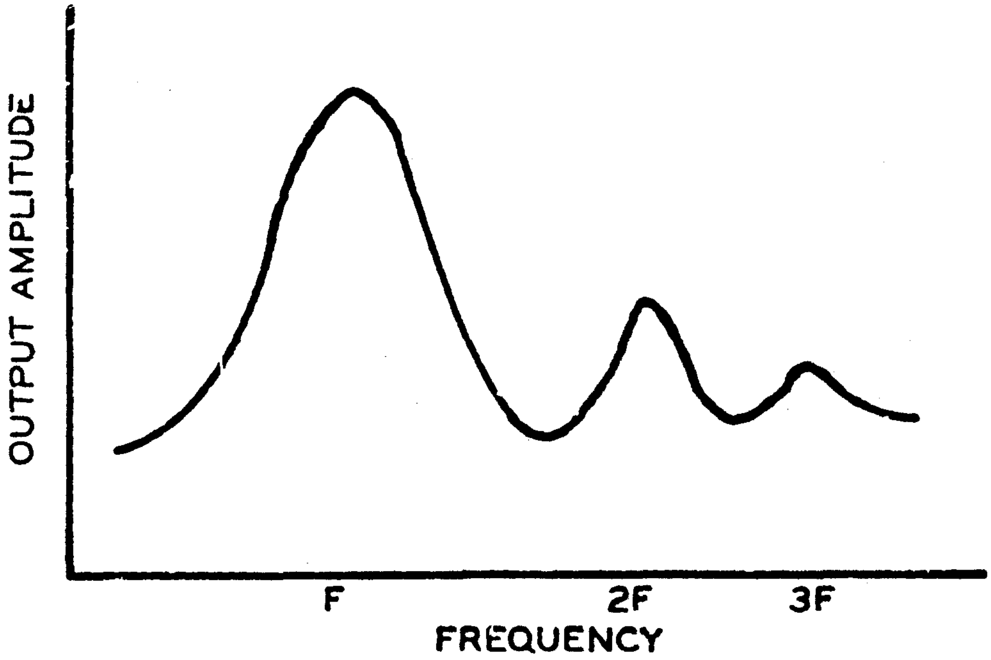


FIGURE 3. RESONANCE WITH HARMONICS. Subpeaks may appear at multiples of the resonant frequency.

vibration stress, in terms of comfort, performance, and tissue damage varies with frequency (Magid 1960). In order to use reasonably large inputs so as to minimize experimental error, neither of the two vibration parameters, G load, or amplitude may be held constant. For purposes of obtaining meaningful results, it would be desirable to test 40-50 Hz at about ±2 Gz while safety and comfort factors at low frequencies limit us to a maximum of about ±0.5 Gz (Figure 4).

Fortunately, this difficulty can be overcome by simple mathematical manipulation. For each frequency of the vibration spectrum, an appropriate amplitude and G load of forcing function may be selected. The output at each frequency tested (in this case eye movement) is compared to its input, and this output/input fraction is used as the dependent variable for the evaluation of resonance. Figure 5 shows how input amplitude would have to vary with frequency, however, the output would be difficult to interpret directly for resonance. By using the output/input fraction as ordinate, a resonance at "A" becomes apparent (Figure 6).

The problems of choosing appropriate input loads and the mathematical manipulation are relatively simple. Since the head itself is of relatively large mass with regard to that of an accelerometer, instrumentation of

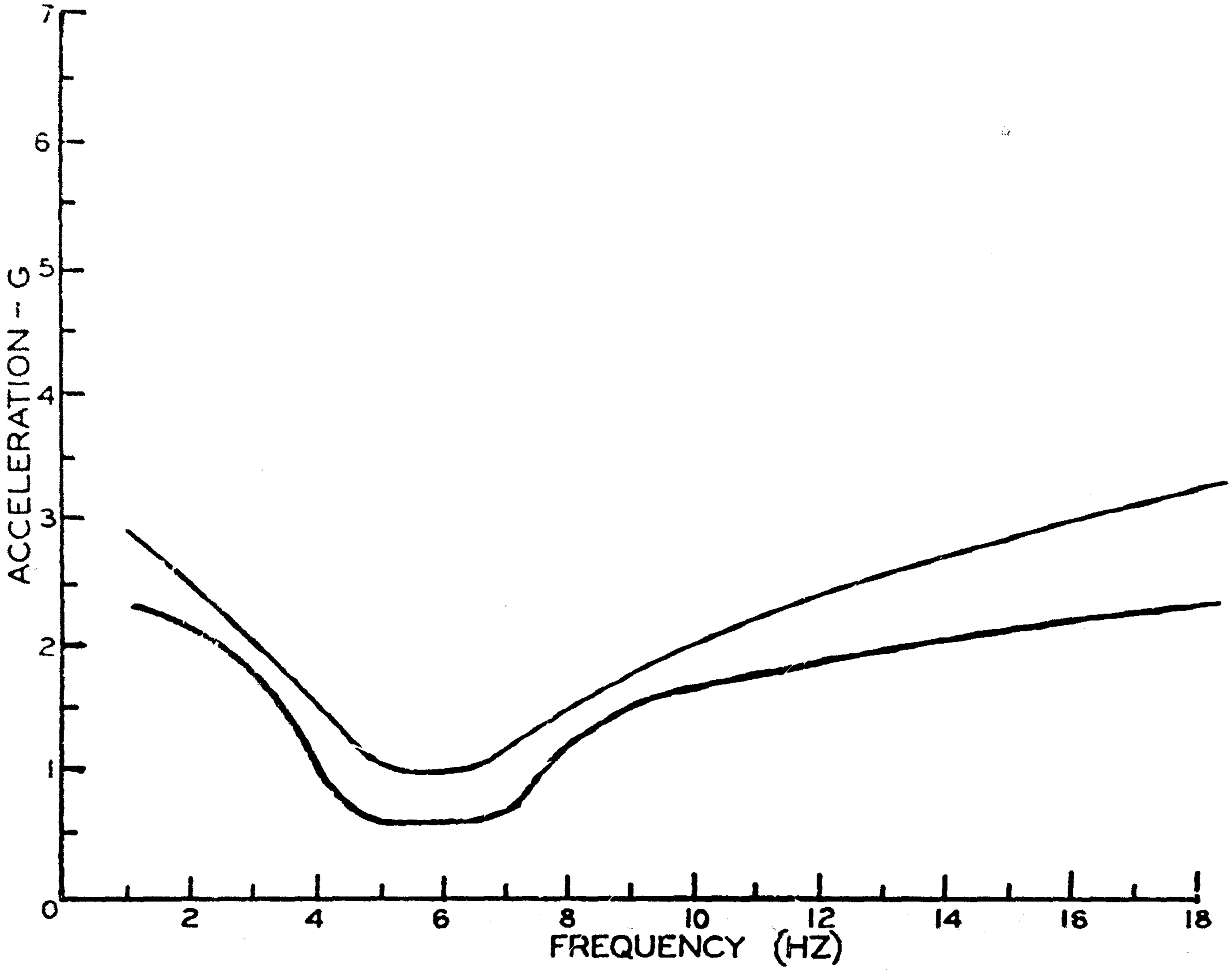


FIGURE 4. SUBJECTIVE TOLERANCE TO VIBRATION. Upper curve shows G load limits for one minute exposure to Gz vibration. Lower curve represents limits for three minute exposure (modified from Magid et al 1960).

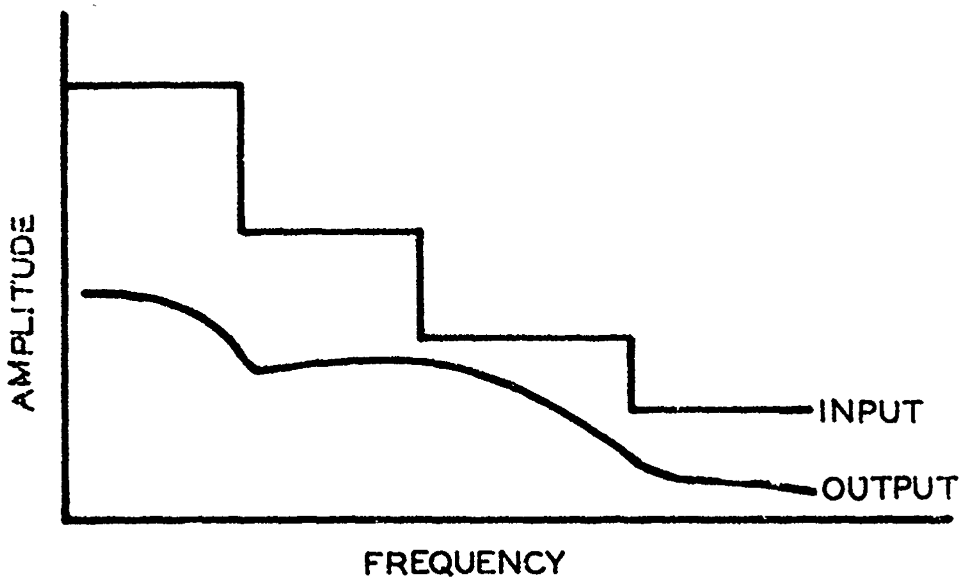


FIGURE 5. STEPPED INPUT AMPLITUDE. The input amplitude is adjusted to be appropriate for the frequency.

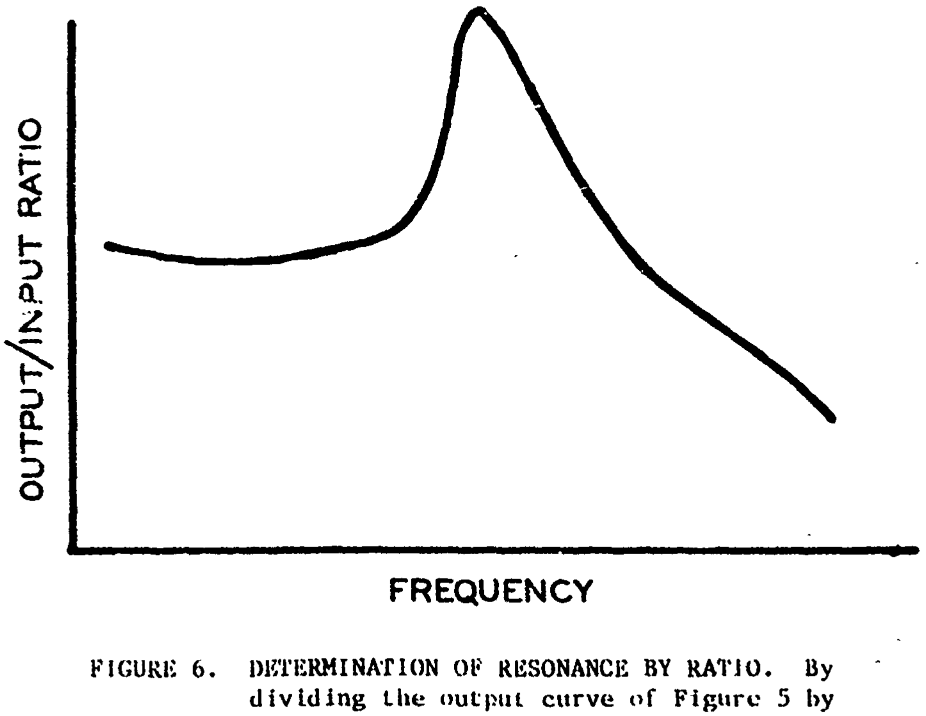


FIGURE 6. DETERMINATION OF RESONANCE BY RATIO. By dividing the output curve of Figure 5 by the stepped input, a ratio is formed. The maximum point on the ratio curve represents resonance.

the subject for precise determination of head movement could be accomplished with relative ease. The major problem is that of measuring the eye movement itself. The simple expedient of mounting an accelerometer on the object in question must be rejected for two reasons. First, the mass of the accelerometer is not insignificant in comparison to the object in question. Second, of course, is the fact that few experimental subjects would consent to the attachment of an accelerometer to their eye.

Not only is electromyography lacking in the sensitivity required for this experiment, but movement of the supporting structures, lids, facial tissue, etc., would contaminate the results to the point where they would not be usable.

Ultra-high speed motion pictures would probably give the precision required, but frame-by-frame analysis is far too tedious and must therefore be considered theoretically possible, but practically unsuitable.

It might be appropriate to note that Guignard and Irving (1962) attempted the cinematographic method but were dubious as to its validity. They did attempt to assess eye movement during Z axis vibration using the reflection of a corneal light spot fed through a photomultiplier. Their methodology required the use of a head restraint which of course seriously contaminated their experiment. I do feel that they were very close to the development of an appropriate technique, however, by their own admission their data for frequencies above 3.4 Hz, or ±0.12 Gz is questionable.

V. EXPERIMENTAL OBJECTIVES

Visual performance as a function of seat vibration input is now reasonably well quantified, although the nature of the physiological mechanisms underlying the performance decrements has not been adequately demonstrated.

Ocular resonance, long considered as a strong possibility, has been difficult to assess because of the technical problems involved in measuring or recording the very small eye movements. Although certain techniques have shown promise, there seem to be two problems, one due to the small amplitudes involved at frequencies higher than 10 Hz, and the second, the requirement for unrestricted head movement.

The thrust of my investigation was to resolve this ten year old problem; to record eye movements across a realistic vibration spectrum, to consider seat to head and head to eye transmission factors, to assess the existence and significance of ocular resonance. and to relate these factors to the established body of knowledge regarding visual performance during vibration.

Four constraints upon my methodology were self-imposed in order to establish meaningful data: (1) The head of the subject would not be restrained. Any encumbrances required for instrumentation would be minimal. (2) The vibration spectrum would include not only the low frequencies, but the entire range in which significant visual decrements have been reported. (3) Forcing functions at each frequency will be adequate to produce observable effects but remain well within tolerance limits. (4) In order to minimize contamination of emotional or anticipatory origin, subjects would be sophisticated in terms of the stresses used.

VI. SUBJECTS

Fifteen male U.S. Air Force officers and enlisted men, ages 22-42, were selected from a panel of volunteer subjects. They were in good physical condition, having passed a U.S. Air Force Class III physical within the past year, and had 20/30 or better vision in at least one eye without correction.

All had been subjects in vibration experiments prior to this occasion and had considerable experience with the stresses involved. Seven had been subjects in earlier vibration/vision experiments. Although the vibration forces used here could be considered uncomfortable, rather than dangerous, subject safety was insured by the utilization of a physician acting as medical monitor. This is standard procedure in all human experimentation at 6570th Aerospace Medical Research Laboratory.

VII. METHOD

Previous experience in the testing of visual acuity showed little, if any, effect at frequencies greater than 50 Hz (Figure 1), and the investigation by Nickerson et al (1963) suggests a maximum of 40 Hz as the resonant frequency of the eye so an upper limit of 50 Hz was placed on my frequency spectrum. The lower limit of 5 Hz was a constraint established by the vibration unit since distortion of the sinusoidal input at lower frequencies make very low frequency analysis somewhat questionable.

Incremental variations in frequency, at intervals close enough to provide meaningful data, at G loads sufficient to induce adequate displacement while remaining within safety limits for human subjects were selected. The eleven seat input loads were: 5, 7.5 Hz @ ±0.5 Gz, 10, 12.5, 15, 18, 21, 25, 30 Hz @ ±1.0 Gz, 40, 50 Hz @ ±2.0 Gz.

The purposes of this experiment included the investigation of resonance. As discussed earlier, the basic method of resonance determination is by a comparison of output and input functions at various frequencies.

The input function was determined by a fairly straightforward method. A zero to two G accelerometer was bonded by screws and epoxy to a fiberglas-reinforced empty spectacle frame. This spectacle-frame-accelerometer unit could then be tightly adjusted to the subject's face so as faithfully to follow and measure skull vibration in the vicinity of the orbit.

The accelerometer was connected to suitable electronic apparatus whose output could be viewed on an oscilloscope calibrated to read in "G" units. A Polaroid camera was used to record the output of the oscilloscope during the test period. Samples of these records for one subject are shown in Appendix A.

As mentioned above, measurement of the output function is somewhat more difficult. A relatively simple methodology was devised utilizing the photographic medium and a light reflection. If a beam of light is directed at the cornea one can observe the reflection, also known as the corneal reflex. If the eye moves, then the position of the reflex moves relative to the cornea. This, of course, has been used as the basic method of determining eye movement during reading.

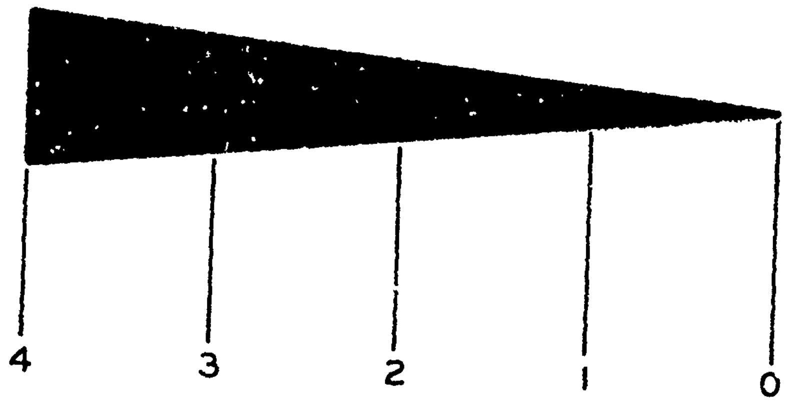
If the subject attempts to fixate on a distant target while he is vibrating in the vertical direction (Z axis), then over a period of time, the corneal reflex will be located on different portions of the cornea. If the time period is equal to or greater than the period of one vibration cycle, then the distance between the extremes of the corneal reflex locus will represent the double amplitude of eye movement. By photographing the eyes of the subject with a slow shutter speed, it would be possible to record this corneal reflex line and to measure it.

A 35mm single lens reflex camera with a 105mm lens was mounted on a tripod 1 meter from the subject, 15° to the left of his primary viewing axis. A Sylvania Sun-Gun (commonly used for making home movies) was mounted on the camera, providing adequate illumination for the photographic operation as well as providing the source for the corneal reflex. A scale (ruler) was mounted along side of the subject's face, in the same focal plane, but of course not moving with the subject. A shutter speed of one-half second provided adequate time to record several cycles of movement on the nearly grainless Kodacolor-X film. By recording the scale directly on the photograph, any degree of projection magnification may be used without the necessity of considering the magnification factors. The film strips were projected after processing, and the length of the corneal reflex measured by using the recorded scale. Samples of these photographs for one subject were printed and are shown in Appendix B and dramatically demonstrate the objective effects of the vibration spectrum used in the experiment. The spectacle-frame-accelerometer can also be seen in these photographs.

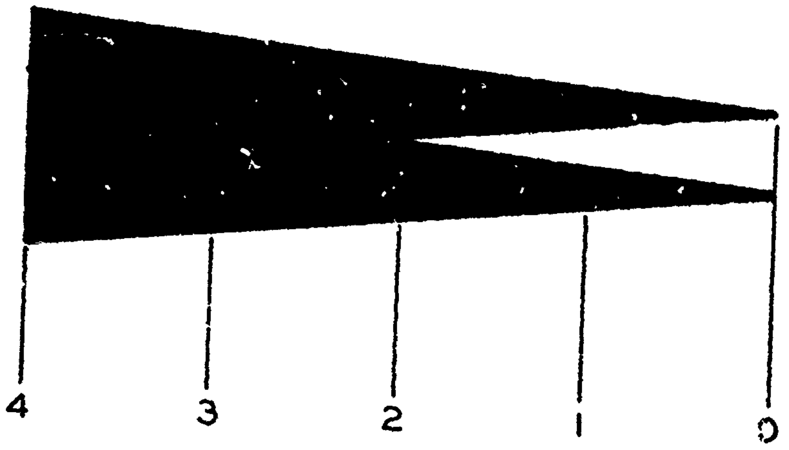
The V-scope or wedge shown in Figure 7 has been used for many years as the "poor man's accelerometer". In its usual use, it is affixed to equipment subject to vibration with its long axis perpendicular to the vibration axis. As the device vibrates, the single wedge is perceived by the observer as a double, overlapping wedge, the degree of apparent separation being equal to the double amplitude. Thus although one cannot measure vertical vibration with a vertical scale, this simple device translates the vertical scale to a horizontal one which can be used in a vertically vibrating mode. Furthermore, by varying the base/length relationship of the wedge, any desired degree of precision can be obtained.

In its usual use the wedge is a vibrating target viewed by a fixed observer. Reversing this relationship, the moving (vibrating) observer could fixate on the stationary wedge, so that any doubling would be a function of the amplitude of the eye movement.

It is possible that rotational and translational movements may be isolated with this procedure. If the wedge is placed at various viewing distances and tests



A. STATIONARY



B. APPARENT SEPARATION IN Gz VIBRATION

FIGURE 7. THE V-SCOPE WEDGE.

indicate that the apparent separation of the perceived wedges is proportional to the test distance, then we must assume that all movement was rotational. If, on the other hand, the apparent separation were a constant, without regard to the viewing distance, then the movement would be purely translational. Separation of the two components if (as might be expected) neither possibility is completely true, might also be possible.

These two methods of evaluating eye movement under vibration stress, one an objective measure and the second a psychophysical measure were used. The important point in both these measures is that they permit free movement of body, head and eyes at all times.

A "run" consisted of testing a subject as outlined below, under each of the vibration parameters, and consumed about an hour and a half.

1. The subject was briefed as to the nature of the experiment, its purpose, what he might experience, what difficulty or discomfort might be involved, the safety precautions, and his task.

2. He was then seated in an aircrew type seat, without cushion, and restrained with lap and shoulder harness. The seat, in turn, is mounted on the M-B C-5 electromagnetic shaker which has the capability of almost perfectly sinusoidal Z axis output from five to ninety Hz, with loads up to 300 pounds.

3. The spectacle-frame-accelerometer was adjusted to the subject who was directed to fixate on a V-scope type wedge 4 meters distant.

4. On signal from the experimenter, the first technician activated the C-5, bringing it "up" to one of the pre-selected seat input loads. Presentation order was randomized to avoid the (unlikely) possibility of contamination from order effects.

5. Approximately ten seconds after the C-5 technician reported "at load", the Sun-Gun was turned on and a photograph was taken of the corneal reflex (Appendix B).

6. At the same time, the oscilloscope display of the accelerometer output was recorded by the Polaroid camera. On these records, the duration of the horizontal time scale is one-half second. The vertical scale indicates acceleration, each division representing 0.25 G (Appendix A).

7. Immediately after the photo-records were made, the Sun-Gun was extinguished and the subject asked to note the extent of "doubling" on the 4 meter wedge, and then on a second wedge placed 0.5 m from his eyes. He then signaled to "come down". When the vibration ceased, the subjects' observations were reported to and recorded by the experimenter.

8. The next "load" was then selected and items 4 through 7 were repeated until all eleven loads had been tested.

All subjects had two runs. The first was for familiarization and was slightly abridged; a second run, a day or two later was used for record. The data obtained on the familiarization run was essentially identical to that obtained in the final run, but because it was incomplete, no attempt to pool the data was made. The experimenter directed procedures and performed one of the photographic operations. One technician operated the C-5 shaker and directly assisted the experimenter. A second technician observed and photographed the output of the spectacle-frame-accelerometer on the oscilloscope. A physician acted as medical monitor to insure the well being of the subject.

To summarize, at each of eleven frequencies tested, five items were recorded.

1. Input to the seat (G units).
2. G load at the head (G units).
3. Eye movement amplitude (linear movement).
4. Wedge separation at 4.0 meters (apparent linear movement).
5. Wedge separation at 0.5 meters (apparent linear movement).

A schematic drawing of the physical arrangement of the experiment is shown on Figure 8.

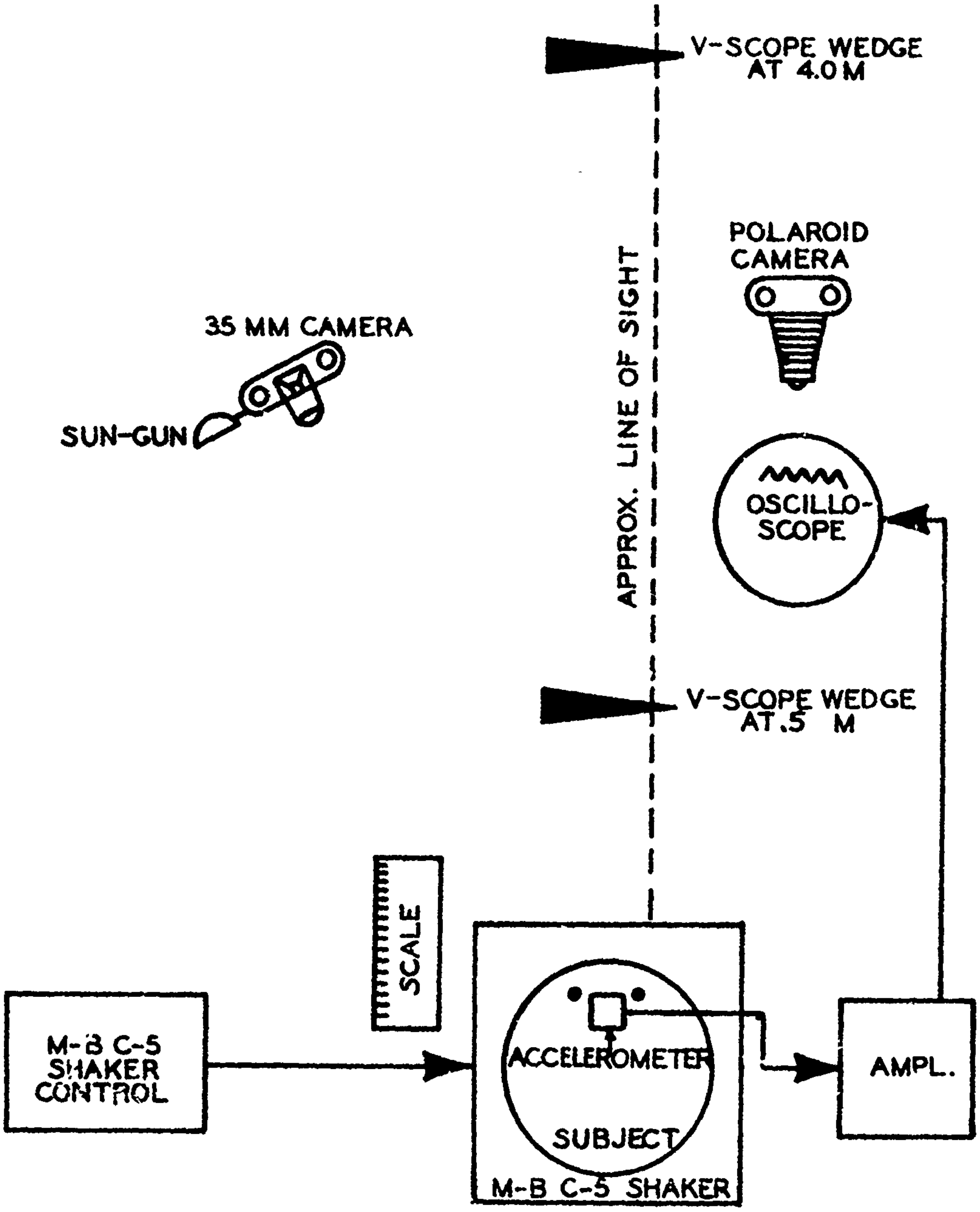


FIGURE 8. SCHEMATIC OF EXPERIMENTAL ARRANGEMENT. C-5 shaker accelerates seat of subject. Head mounted accelerometer feeds through amplifier and oscilloscope to determine head movement. Eye movement is monitored by 35mm camera as subject fixates wedge at 4.0M.

VIII. DATA REDUCTION

Examination of the accelerometer records showed almost perfectly sinusoidal head movement with only minimal distortion at the lower frequencies. Since each vertical division represents 0.25 G it was a simple matter to measure the head movement for each subject at each test frequency in G units. A comparison of this value with the seat input gives the transmission ratio through the body to the head. The frequency at which the value of output/input (G load at the head divided by G load at the seat) is a maximum would represent the whole body resonance to the head.

Eye resonance is determined in a similar manner. However for the eye, head movement (accelerometer record) was considered as the input value and the eye movement (facial photograph) as the output. Since the units do not match, it was necessary first to convert the units of one to the units of the other. The G loads on the accelerometer record were converted to double amplitudes by a simple expedient. The formula relating G load, frequency and amplitude can be solved for double amplitude. When this is done, for any frequency selected, the G load may be multiplied by the appropriate factor to determine the double amplitude in mm (or in any linear unit that may be desired).

A table of the amplitude factors for the frequency spectrum used in the experiment was prepared and is shown in Appendix C.

Individual data tables for each subject relating seat input (frequency and G load), skull movement (G load and double amplitude), eye movement (double amplitude), skull/seat transmission ratio and eye/skull transmission ratio, and the curves of the two transmission ratios are included in Appendix D.

The individual data on transmission ratios were pooled to obtain Tables 1 and 2 and to generate the graphs of Figures 9 and 10.

Individual data regarding apparent separation of the V-scope wedges are included in Appendix E. Mean separation for each test frequency and the two viewing distances were calculated and are presented in Table 3. This table also includes a calculated separation for a constant one G input as well as an adjusted 4.0 M separation divided by eight which will be discussed later.

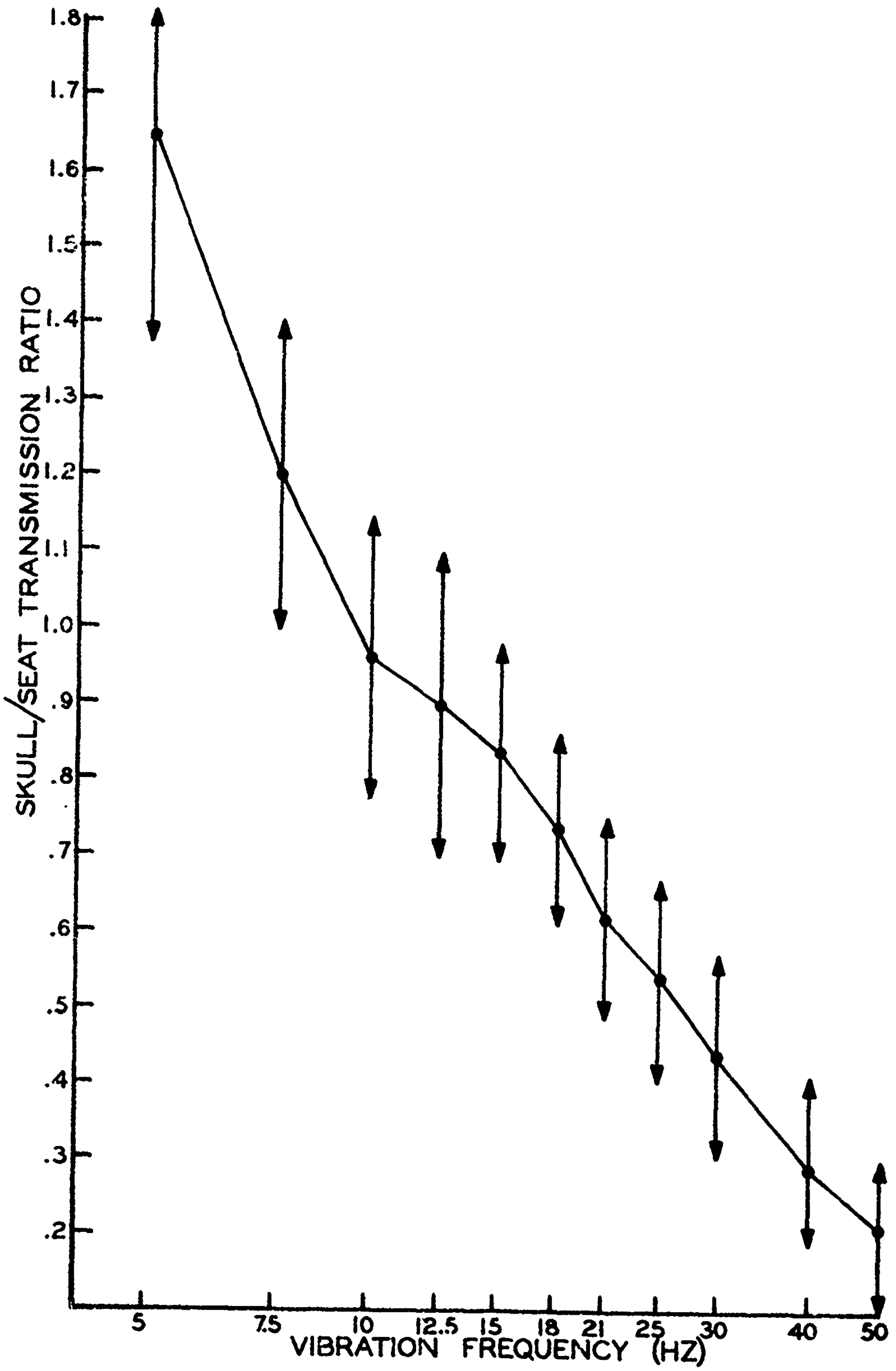


FIGURE 9. SKULL/SEAT TRANSMISSION. Measured G load at the skull divided by the input to the seat.
(arrows indicate standard deviation)

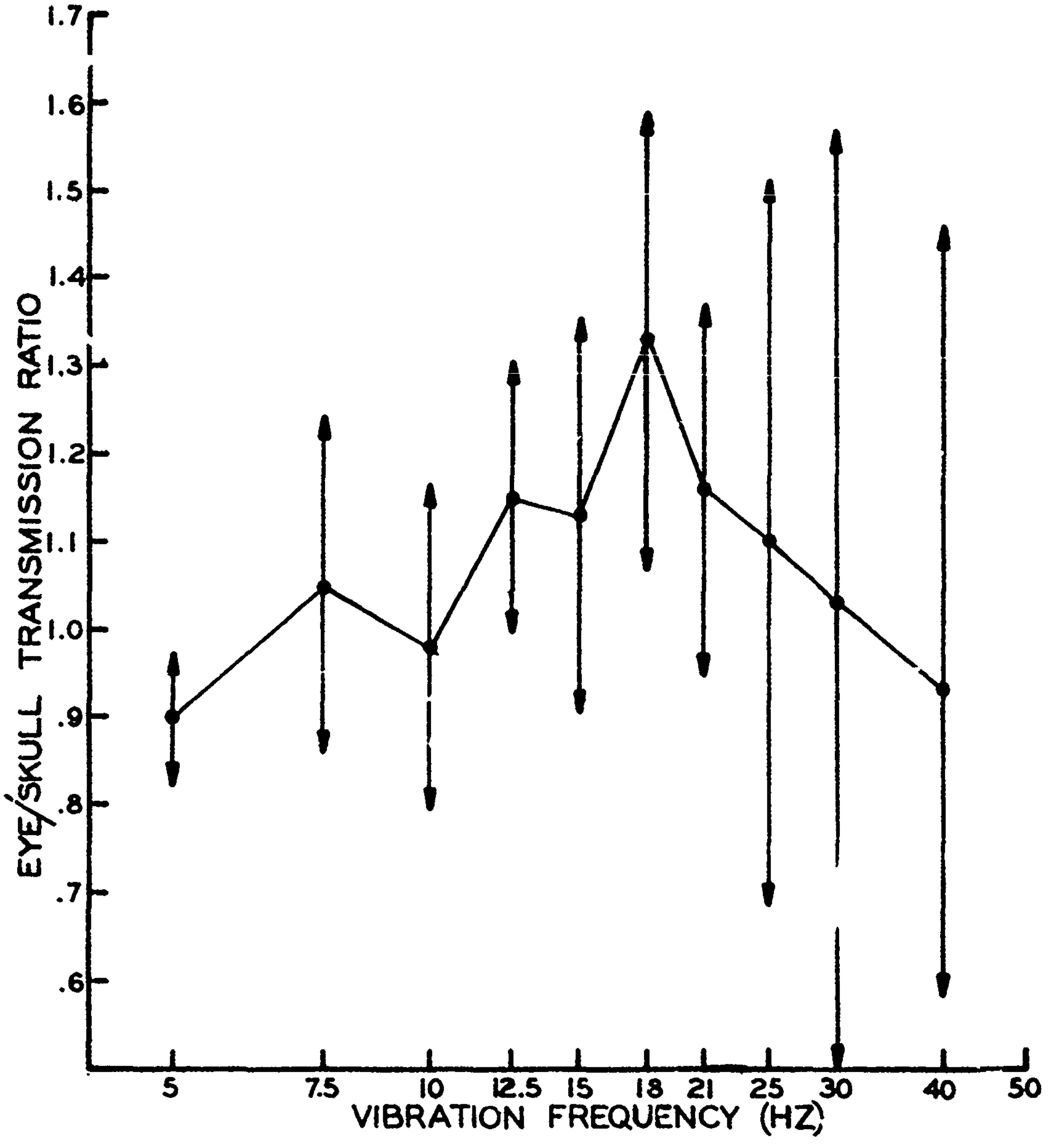


FIGURE 10. EYE/SKULL TRANSMISSION. Measured amplitude of eye movement divided by calculated amplitude of head movement.
(arrows indicate standard deviation)

TABLE 1

SKULL/SEAT TRANSMISSION RATIOS FOR EACH FREQUENCY.

FREQUENCY (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
Subject:											
1	1.4	1.2	.7	.75	.65	.60	.40	.30	.25	.18	.1
2	1.76	1.25	.97	1.0	.90	.75	.70	.70	.58	.35	.26
3	1.4	1.3	.90	1.0	.87	.70	.62	.58	.45	.34	.26
4	1.6	.90	.87	.85	.87	.85	.77	.60	.55	.50	.33
5	1.6	1.1	1.3	1.4	1.2	.90	.80	.58	.57	.57	.32
6	1.4	1.7	1.05	1.1	.93	.82	.62	.50	.49	.20	.13
7	1.25	.96	.98	.72	.82	.72	.48	.42	.35	.20	.15
8	1.76	1.3	.90	.82	.85	.85	.70	.68	.60	.30	.29
9	1.54	1.25	1.1	.95	.85	.70	.60	.43	.35	.19	.13
10	1.76	1.40	.90	.77	.85	.85	.75	.60	.45	.38	.36
11	2.0	1.16	.76	.85	.87	.75	.70	.65	.55	.35	.23
12	1.4	1.16	.90	.64	.60	.48	.42	.37	.25	.19	.15
13	2.2	1.0	1.0	1.1	.88	.78	.65	.70	.45	.29	.25
14	2.0	1.3	1.3	.92	.87	.77	.65	.58	.45	.23	.16
15	1.75	1.0	.70	.62	.65	.55	.48	.35	.20	.08	.08
MEAN	1.65	1.20	.96	.90	.84	.74	.62	.54	.44	.29	.21
STD DEV	.27	.20	.18	.20	.14	.12	.13	.13	.13	.12	.09

TABLE 2

EYE/SKULL TRANSMISSION RATIOS FOR EACH FREQUENCY.

FREQUENCY (Hz)	5	7.5	10	12.5	15	18	21	25	30	40
Subject:										
1	.96	1.25	1.17	1.12	1.15	1.25	1.36	2.5	2.75	1.8
2	.95	1.0	1.04	1.03	.95	.90	.91	1.09	.94	.95
3	.95	1.05	1.26	1.22	1.31	1.61	1.18	1.09	.80	.95
4	.85	1.30	.75	1.0	1.30	1.40	1.10	1.06	.65	.67
5	.83	1.02	.82	.82	1.04	1.25	1.12	.87	.93	.3
6	1.07	.90	.93	1.09	1.0	1.47	1.03	.77	--	.83
7	.88	1.04	.80	1.26	.89	1.25	.75	1.21	1.05	--
8	.85	.89	1.07	1.12	.95	.89	1.17	.76	.91	1.11
9	.96	1.57	.84	.97	.90	1.61	1.21	1.18	1.05	.91
10	.94	.97	.89	1.15	1.0	1.40	.98	.85	.80	.87
11	.89	.98	1.30	1.40	1.50	1.60	1.30	.98	.97	.95
12	.95	1.0	.93	1.24	1.31	1.57	1.09	1.03	--	--
13	.75	.83	1.14	1.40	1.47	1.15	1.13	1.09	.80	1.11
14	.84	.89	.77	1.24	1.30	1.60	1.40	.87	.80	.71
15	.90	1.0	.95	1.16	.86	.96	1.6	1.1	.91	--
MEAN	.905	1.05	.98	1.15	1.13	1.33	1.16	1.10	1.03	.93
STD DEV	.076	.19	.18	.15	.22	.26	.21	.41	.53	.35

TABLE 3

MEAN OBSERVED AND ADJUSTED WEDGE SEPARATIONS.

FREQUENCY (Hz)		5	7.5	10	12.5	15	18	21	25	30	40	50
MEAN SEPARATION OBSERVED (MM)	4.0M	.1	.4	1.6	5.3	4.1	6.3	6.3	5.1	3.5	3.3	2.3
	0.5M	3.4	2.73	2.6	1.9	1.5	1.0	.87	.53	.33	.33	.07
SEPARATION ADJUSTED FOR 1 G CONSTANT INPUT	4.0M	.2	.8	1.6	5.3	4.1	6.3	6.3	5.1	3.5	1.7	1.2
	0.5M	6.8	4.46	2.6	1.9	1.5	1.0	.87	.53	.33	.17	.04
ADJUSTED 4.0M SEPARATION ÷ 8		.016	.1	.2	.67	.51	.79	.79	.64	.44	.21	.15

IX. RESULTS

A. Seat to Head Transmission

The monotonically descending curve of Figure 9 shows the mean skull/seat transmission factor for the subject group. The curve is rather representative since the individual curves (Appendix D) show essentially the same thing. However, the smoothing action of mean determination does camouflage a slight rise or relative rise in most of these curves at around 12.5 to 15 Hz. This should not be considered a resonant peak as such since far greater transmission ratios were shown at 5 Hz in all cases.

On the basis of data presented here, it is not possible to specify the resonant frequency through the whole body to the head. Nevertheless, one may categorically state that it is not greater than 5 Hz and that it is severely attenuated as a function of frequency.

B. Head to Eye Transmission

The pooling of individual eye/skull transmission ratios generates the data and curve of Table 2 and Figure 10.

If one considers approximately ±.1 as a reasonable cutoff value, then it is apparent that between 12 and 25 Hz, amplification of the input G load and eye movement occurs, while at frequencies above and below these points, the globe follows the input in a relatively passive manner. The curve reaches its maximum at 18 Hz, suggesting this to be the approximate value for the ocular resonant frequency.

One must be careful, however, since individual differences may be lost through the expedient of considering means only. Since all subjects did not demonstrate the identical response, it might be appropriate to consider them individually. Examination of the individual eye/skull transmission ratios (Appendix D) shows that eleven subjects had their strongest resonant peaks at (or very near) 18 Hz. Seven of these eleven also showed a secondary peak between 7.5 and 12.5 Hz. The strength of these peaks does register as a small rise at 12.5 Hz on the composite graph of the means (Figure 10).

The other four subjects are more difficult to analyze. Subject #2 shows no strong peaks of transmission ratio. His eye movements apparently represent virtually passive following at all frequencies by the globe of the input to the skull.

Subjects #7 and #8 show the two peaks noted in other subjects, but in addition demonstrate a third peak. It is entirely possible that this third peak represents a harmonic of one of the others (the multiple is correct for a harmonic), nevertheless I am hesitant to consider this as the prime possibility for two reasons. Firstly, the majority of subjects did not demonstrate this phenomenon, and secondly, the magnitude of the peak is too great for a harmonic.

It would be difficult to categorize subject #1, since his data shows a rather unique pattern. What seems to be a resonant peak appears at 30 Hz and is not only at an atypical frequency but the degree of amplification is considerably greater than that found on other subjects.

If one examines only the highest peak demonstrated, and does not consider subjects #1 and #2, the modal as well as median value for ocular resonancy is 18 Hz. Two subjects show resonancy at a slightly higher frequency and two slightly lower.

C. The Wedge Experiment

Considerable variance may be noted between subjects in their perception of the apparent separation of the V-scope. Since the degree of effort expended by the subject in the attempt to visualize the phenomenon has a direct bearing on its magnitude, this is not surprising. Subjects had been directed to establish their own criteria for assessing this effect, and to maintain that same criterion throughout the exercise. Therefore, although each subject gave highly individual responses, leading to large variances in the group data, the constant criteria would be expected to yield far more meaningful information than the raw data would seem to indicate.

At a viewing distance of 0.5 M, wedge separation decreases in a monotonic fashion with increase in frequency. This strongly suggests a dependence upon the eye movement amplitude as the significant underlying variable. At a viewing distance of 4.0 M, this relationship was not observed. Maximum separation of the wedge occurred in the middle of the spectrum, little separation being noted at either end. Moreoever, more than half the subjects introspectively reported that they seemed to be "tracking" the wedge at 5 and 7.5 Hz.

X. DISCUSSION

In an earlier work (Ohlbaum et al 1971), the following mechanism was proposed to account for the viewing distance dependence of the vibration induced visual decrements.

When viewing a nearby target, visual losses occur at all frequencies, but the greatest loss is at the low end of the spectrum. The loss is apparently directly related to the displacement since the curve is reasonably regular and seems to be asymptotic to control level (Figure 1).

At a viewing distance of 4 M, the greatest visual loss occurs near 20 Hz. Lesser decrements may be noted at either end of the experimental spectrum. In the 25 to 50 Hz range, the curve is in close agreement with that obtained at 0.4 M. On the other hand, acuity improves at this distance, as the frequency drops from 20 to 5 Hz, indicating that linear displacement is not the only determinant of acuity loss.

It is impossible to explain these viewing distant dependent differences in the curves on the basis of simple geometry. If the angular amplitude in the target-eye relationship were the only factor, then one might expect a decrement in vision that is inversely proportional to the viewing distance, for a given G load and frequency. Although there is some evidence for this, it cannot explain the essential difference in the shapes of the curves. The geometric factor could not explain the difference between the U-curve obtained at 4.0 M and the monotonic curve obtained at 0.4 M.

Consider that the tracking mechanism of the eye may be capable of maintaining fixation on the oscillating (relative to the eye) target, provided that the movement is predictable and that the changes in direction are small and occur at a low frequency. As an example, if the angular velocity were only 1 degree per second and the total displacement only 1 degree, this movement could be followed perfectly. As these two factors, angular velocity and frequency, increase, a point would be reached at which the tracking mechanism would no longer function adequately and there would be a decrement in visual acuity. Although previous reports indicate that the tracking reflex probably follows sinusoidal movement only to about 2 or 3 Hz (Roth and Teichner 1968), it is entirely possible that the mechanism could function beyond this rate (as long as the oscillations were perfectly predictable) by following alternate changes in direction only. This could be carried further, of course, to allow only every third or fourth oscillation to be "tracked". Although this would not result in perfect performance as when tracking occurred in the 1:1 mode, it would still produce better acuity than in a completely passive, nontracking mode of visual observation.

At close range, the angular amplitude of the target-observer relationship is large and cannot be effectively "tracked". As the distance is extended, although the frequency and linear amplitude are unchanged, the relative amplitude and angular velocity of the subject-target relationship are decreased, permitting at least partial tracking to take place.

At higher frequencies (above 20 or 25 Hz), the eye cannot "track" the moving retinal image, and so the visual loss is directly proportional to the angular amplitude of the moving retinal image. At shorter distances the angular amplitude is too great for tracking to occur, even at low frequency, so that the same principle applies to the extent of the visual loss. However, at greater distances, if the frequency is below 20 Hz, some degree of tracking may occur, so that at 5 Hz vision is only slightly affected, becoming worse towards 20 Hz where all attempts at tracking cease. Beyond this frequency the amplitude is relatively low so that although there is no tracking, the performance degradation follows the pattern established at near, but, of course, reduced in effect because of the reduced angular amplitude.

The only criticism of this hypothesis was based on the fact that actual eye movements and possible resonancy interactions were not considered. Indeed this criticism provoked the current investigation.

If one examines the data presented on Table 1 and Figure 9, it becomes apparent that seat input at high frequencies, is so attenuated through the body that only minimal eye movements and visual disturbances are likely to be observed. At low frequencies, the seat input is not only transmitted but may even be amplified to the skull.

Skull vibration itself is not uniformly transmitted to the eye. In the vicinity of 18 Hz, which I feel to be a reasonable value for human ocular resonance, skull input vibration is amplified more than 30%, while below 12 Hz and above 25 Hz, the eye seems to follow the input passively (Table 2 and Figure 10).

It might be appropriate at this point to compare my two transmission curves with those presented by Lee and King (1971). Substantial agreement regarding skull/seat transmission may be noted. My investigation did not go below 5 Hz (distortion of the low frequency sinusoidal input becomes a problem on the C-5 shaker) and so I cannot confirm the drop in transmission below that frequency. Since this has been considered a reasonable approximation of whole body resonance, their findings are not unreasonable. However, it should be noted that where our endeavors correspond, our data correspond.

This is not true regarding eye/skull transmission. Our curves are compatible only to about 18 Hz. Where my data indicate a drop in transmission at higher frequencies, the Lee and King curve monotonically increases to the unlikely value of 55 at 70 Hz!

This rather serious discrepancy is worthy of further comment. The denominator of the output/input function in this case is the amplitude of the head movement. Since the value of any fraction whose denominator approaches zero, approaches infinity, one must be extremely careful in forming ratios with quite small numerical values for the denominator.

At 50 Hz, Lee and King used a seat input of 1.5 Gz and determined the head/seat transmission to be 0.16. With an input of 2.0 Gz my value was 0.20 indicating no serious disagreement.

Multiplying the 1.5 Gz input by their own 0.16 transmission factor, we note that the G load at the head is only .24 Gz. If we now multiply this by the amplitude factor for 50 Hz which is .203 (Appendix C), we find actual head movement to be less than .05 mm, a very small distance indeed. Since this quantity, 0.05 mm, becomes the denominator of our ratio, it should be apparent that even the smallest overestimation of the eye movement (the numerator of the ratio) will result in an unrealistically large transmission ratio. A small constant error in the measurement of eye movement might have no great effect provided that the head movement were reasonably large, but with head movement in terms of .05 mm, one must be extremely conservative.

I made my measurements in a relatively direct manned being careful to avoid this mathematical pitfall. By utilizing an on-line computer to directly calculate the transmission ratios, Lee and King apparently did not realize the significance of their unrealistically high values.

As we can see from the individual curves, there was only minor variation in the frequency at which ocular resonance appeared. Possibly of greater interest is the existence of smaller peaks in several subjects in the 10 Hz to 12 Hz range. Since, in every case, it was a secondary peak, it cannot represent ocular resonance and since it was at a lower frequency, it cannot represent a harmonic. It must therefore represent the partial resonance of a substructure. One might propose that it derives from the vitreous body, but this would be mere conjecture.

The 18 Hz that I suggest as an appropriate value for ocular resonancy is quite close to the nadir of visual acuity noted when viewing distant targets.

This does not necessarily indicate that these factors are causally related and so the attempt was made to relate the eye movement data to the visual decrements noted in an earlier investigation (O'Briant and Ohlbaum 1970). Since I had varied the input G load, it was necessary first to equate for a constant value. Mean eye movement double amplitudes at 1.0 Gz were considered for the subject group. For the frequencies of 5, 7.5, 40 and 50 Hz, they were calculated, while for the middle range of frequencies, the measured eye movement was used.

These values were correlated with visual acuity at .4 M, 1 M and 4 M as determined for a similar group of subjects. Indeed, seven of the subjects participated in both experiments. Although minimal differences (7 rather than 7.5 and 20 rather than 21 Hz) exists in two of the test frequencies, it is too trivial to reject the validity of the correlations (Table 4).

TABLE 4

THE CORRELATION BETWEEN EYE MOVEMENT AND VISUAL ACUITY AT SELECTED VIEWING DISTANCES.

FREQUENCY (Hz)	EYE MOVEMENT (MM)	VISUAL ACUITY (SNELLEN DENOMINATOR)		
		4.0M	1.0M	0.4M
5	28.93	19	27	52
7, 7.5	10.73	20	26	44
10	4.95	21	22	36
15	2.09	23	23	30
20, 21	.793	24	21	28
25	.440	25	21	26
30	.231	22	19	23
50	.156	17	17	21
CORRELATION WITH EYE MOVEMENT		.42	.81	.92
"T"		1.15	3.33	5.69

With six degrees of freedom a [illegible] of "T' equal to or greater than 2.45 is significant at the .05 level of confidence. For significance at the .01 level of confidence, 3.71 is required.

With six degrees of freedom, a value of "T" equal to or greater than 2.45 is significant at the .05 level of confidence, while a "T" of 3.71 is significant at the .01 level of confidence.

Thus, for the viewing distance of 0.4 M, one may be better than 99% certain that 85% ($.92^2$) of the visual decrements observed are a function of eye movement alone. Similarly, we are not quite 99% certain that 66% ($.81^2$) of the one meter effects are due to eye movement.

This close interaction does not seem to apply to long range viewing. The low correlation suggests that 18% ($.42^2$) of the visual changes may be due to eye movement, but the low value of "T" makes even this highly questionable.

It is possible to grasp this visually, and intuitively, by examining Figure 12. Eye movement (filled circles) for a constant 1G input (left ordinate) is plotted as a function of frequency. Visual acuity (right ordinate) at three viewing distances is plotted on the same abscissa. One can note the essential similarity in the shapes of the eye movement and 0.4 M acuity curves. There is little resemblance between eye movement and long range visual curves.

Simple translational movements of the eyes and visual axes cannot account for these differences, nor can they account for the differences noted in wedge separation noted at different viewing distances.

A more detailed examination of the psychophysical data obtained with the visual wedge might serve to suggest a mechanism to account for these differences.

Although there is a resemblance between the curve slopes for 4.0 M wedge separation (Figure 11) and that of eye/skull transmission ratio (Figure 10), I suggest that this represents a statistical coincidence. The rather severe attenuation of vibration amplitudes by the torso at the higher frequencies (Figure 9) would more than compensate for the comparatively small amplification noted in the eye/skull transmission ratio at 15-21 Hz.

Any hypothesis which suggests that ocular resonance is the causal factor in frequency or viewing distance dependency of visual acuity must therefore be rejected.

It is entirely possible to derive further information from the wedge experiment. In the event that the eye movement induced were purely translational, then the wedge separation would be independent of viewing distance. Were the movement of a purely rotational nature, the wedge separation would be proportional to the viewing distance.

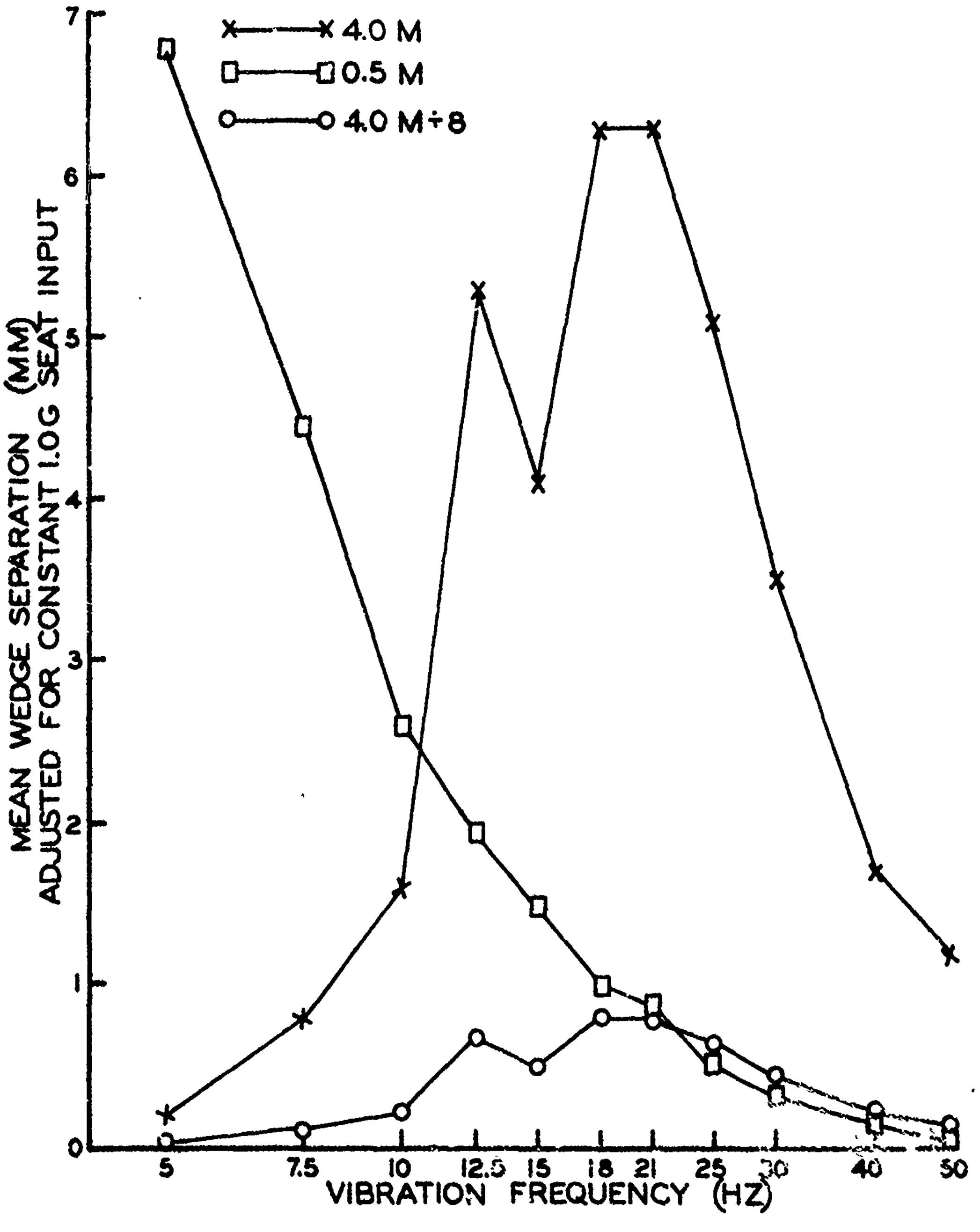


FIGURE 11. PERCEIVED WEDGE SEPARATION. Note similarities in curve shapes to visual acuity. Wedge separation for 0.5M viewing is also similar to eye movement curve (Figure 12).

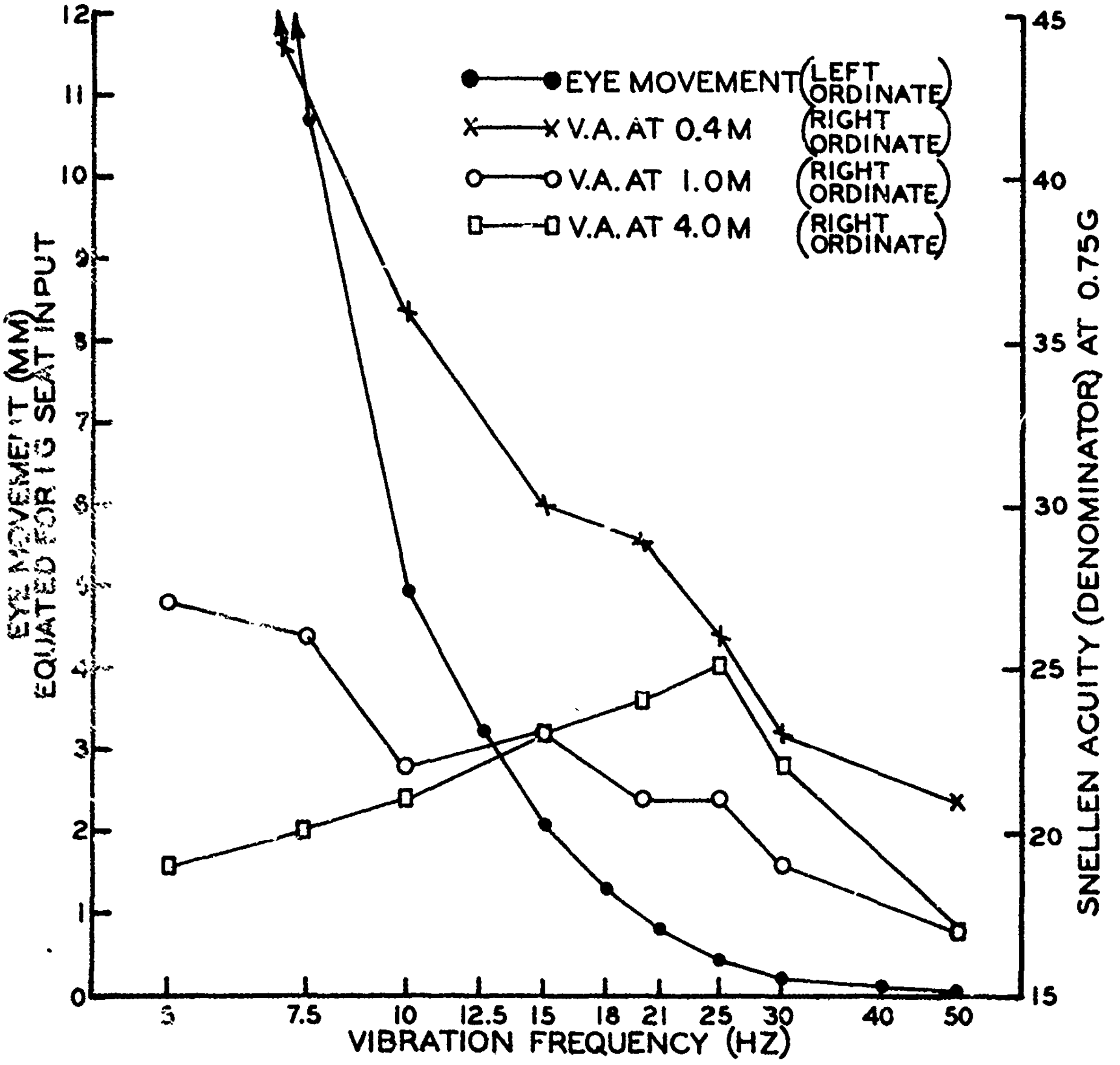


FIGURE 12. THE RELATIONSHIP BETWEEN EYE MOVEMENT AND VISUAL ACUITY. Note essential similarity between eye movement and 0.4M vision. Also see Figure 11.

The viewing distances in the wedge experiment were 0.5 and 4.0 M, in a ratio of 1:8. One-eighth of the apparent wedge separation observed at 4.0 M was calculated (Table 3). The curve generated was then compared to that produced by the .5 M wedge data (Figure 11).

At the high frequency end of the spectrum, from 21 to 50 Hz, the two curves are nearly identical, strongly indicating that the primary eye movement is rotational rather than translational.

Below about 20 Hz, the curves separate. Two factors can account for this separation. The first possibility is that there are two components, one translational, the other rotational, which vary in their phase relationships as a function of frequency. An out-of-phase relationship would result in the nonlinear results noted below 20 Hz.

Although I have rejected the Lee and King data regarding eye/skull transmission, their phase data is most interesting and could be used to support this hypothesis. At the low end of the spectrum, the phase relationship between head movement and eye movement was close to zero indicating very close impedance matching.

As the frequency increases over 15 Hz, considerable lag appears in the phase relationship resulting in nonlinearities in the summation of any torsional and translational components. However at the higher frequencies, the lag is nearly 360° which would effectively be back in phase, and result in the linear relationship noted above 21 Hz.

Such a hypothesis can indeed account for the effects on vision noted in the middle and upper frequency ranges, but does not completely account for the effects noted at the very low frequencies.

In the interest of parsimony as well as the fact that the vast majority of subjects did indeed report that they were "tracking" the wedge at low frequencies, I am inclined to remain with the hypothesis outlined at the beginning of this chapter.

XI. SUMMARY AND CONCLUSIONS

1. The transmission of seat input vibration to the head is not independent of frequency. The degree of attenuation is a monotonic function of frequency with no peaks noted within the 5 to 50 Hz spectrum. Maximum transmission and amplification is at 5 Hz or less. The head/seat transmission data of Lee and King is confirmed.

2. In the 5 to 50 Hz spectrum, the eye follows skull input vibration in a relatively passive manner except in the vicinity of 18 Hz. At this frequency, apparently the resonant frequency of the globe, there is a mean amplification of the input of one-third. There is little variation between subjects with regard to this peak, although some individuals demonstrate secondary peaks at about 12 Hz. Conceivably this could represent substructure resonance effects however this would be only speculation and cannot be confirmed at the present time.

That portion of the Lee and King report regarding eye/head transmission must be rejected. It is unrealistic to consider an amplification factor of 55 in a system as highly damped as the human eye within the orbit. The data of Nickerson et al (1963) suggested a factor of eight, but their methodology, due to the leverage between the jaw (where input was measured) and the eye will obviously overestimate the amplification also.

3. The amplitude of ocular movement correlates very strongly with visual acuity decrements under near viewing conditions. If the visual target is at long range, there is a different relationship between visual acuity and ocular amplitude. The rather strong attenuation by the body of all seat inputs except at the very low frequencies makes the relatively small amplification factor at the eye insignificant by comparison. Although a resonancy has been demonstrated, it can have only minor bearing on the visual acuity decrements noted during vibration.

4. Rather strong evidence has been presented that above 20 Hz the major component of eye movement is rotational rather than translational. If we accept the Lee and King data regarding phase relationships, the changing of phase from about zero at low frequencies to -360° (effectively zero) at high frequencies, we can explain some of the nonlinearities noted in the wedge experiment. These nonlinearities would also help to explain the relationship between eye movement and visual acuity in the middle frequency range.

5. Consistent subjective reports of "tracking" the wedge at 5 and 7.5 Hz lends credence to my earlier hypothesis that at least partial visual tracking may occur at low to moderate frequencies if the angular amplitude is small. This hypothesis can also explain the effects noted at 5 Hz to 10 Hz more easily than the phase hypothesis. In the interests of parsimony, I am inclined to remain with it.

BIBLIOGRAPHY

AGARD, Collected papers of 22nd Aerospace Medical Panel, AGARD-CP-2 (1965).

Bengi, H. and J. G. Thomas, Studies on human ocular tremor, Presentation to AGARD (1972).

Caiger, B., Some effects of vertical vibration on a pilot's head motion and his instrument reading capability, NAEO, Ontario, Canada, LR-463,9400 (1966).

Chaney, R. E. and D. L. Parks, Visual-motor performance during whole-body vibration, Boeing Technical Report D3-3512-5 (1964).

Chiles, W. D. and C. L. Custer, Summaries of research on the human performance effects of vibration, AMRL-TR-67-172 (1963).

Clarke, N. P., H. Taub, H. F. Scherer, W. E. Temple, H. E. Vykukol, and M. Matter, Preliminary study of dial reading performance during sustained acceleration and vibration, AMRL-TR-65-110 (1965).

Coermann, R. R., E. B. Magid and K. O. Lange, Human performance under vibrational stress, Human Factors 4:315-324 (1962).

Dennis, J. P., Some effects of vibration upon visual performance, J. Appl. Psychol. 49:245-252 (1965).

Guignard, J. C. and A. Irving, Measurements of eye movements during low frequency vibration, Aerospace Med. 33:1230-1238 (1966).

Harris, C. S., W. D. Chiles and R. M. Touchstone, Human performance as a function of intensity of vibration at 5 cps, AMRL-TR-64-83 (1964).

Harris, C. S. and R. W. Schoenberger, Human performance during vibration, AMRL-TR-65-204 (1965).

Harris, C. S. and R. W. Schoenberger, Effects of frequency of vibration on human performance, J. Eng. Psychol. 5:1-15 (1966).

Hornick, R. J., Problems of vibration research, Human Factors 4:325-330 (1962).

Huddleston, J. H. F., Tracking performance on a visual display apparently vibrating at one to ten Hertz, J. Appl. Psychol. 54:401-408 (1970).

Lange, K. O. and R. Coermann, Visual acuity under vibration, Human Factors 4:291-300 (1962).

Lee, R. A. and A. I. King, Visual vibration response, J. Appl. Physiol. 30:281-286 (1971).

Magid, E. B., R. R. Coermann and G. H. Ziegenruecker, Human tolerance to whole body sinusoidal vibration, Aerospace Med. 31:915-924 (1960).

Mercier, A., La vision dans l'aviation d'aujourd'hui, In AGARD, *Visual Problems in Aviation Medicine* (1962).

Nickerson, J. L., A. Paradijeff and H. S. Feinhandler, *A study of the effects of externally applied sinusoidal forces on the eye*, AMRL-TR-63-120 (1963).

O'Briant, C. R. and M. K. Ohlbaum, Visual acuity decrements associated with whole body Gz vibration stress, *Aerospace Med.* *41*:79-82 (1970).

Ohlbaum, M. K. and C. R. O'Briant, Attenuation and amplification of head vibration by the flight helmet, In Preparation (1970).

Ohlbaum, M. K., C. R. O'Briant and R. E. Van Patten, The effect of viewing distance on the visual decrements associated with Gz vibration, *Am. J. Optom.* *48*:298-306 (1971).

Roth, E. M. and A. N. Chambers, *Compendium of human responses to the aerospace environment*, *8*: *Vibration*, NASA CR-1205 (1968).

Rubenstein, L. and R. Kaplan, *Some effects of Y axis vibration on visual acuity*, AMRL-TR-68-19 (1968).

Rubenstein, L. and H. A. Taub, *Visual acuity during vibration as a function of frequency, amplitude and subject display relationship*, AMRL-TR-66-181 (1967).

Schoenberger, R. W., *Human performance during vibration*, AMRL-TR-65-204 (1965).

Schoenberger, R. W., Effects of vibration on complex psychomotor performance, *Aerospace Med.* *38*: 1264-1268 (1967).

Schoenberger, R. W., *Investigation of the effects of vibration on dial reading performance with a NASA prototype Apollo helmet*, AMRL-TR-67-205 (1968).

Taub, H. A., *The effects of vibration on dial reading performance*, AMRL-TDR-64-70 (1964).

Teare, R. J. and D. L. Parks, *Visual performance during whole body vibration*, Boeing Company Report D3-3512-4, TR4 (1963).

Weisz, A. Z., C. Goddard and R. W. Allen, *Human performance under random and sinusoidal vibration*, AMRL-TR-65-209 (1965).

Wulfeck, J. W., A. Weisz and M. W. Raben, *Vision in military aviation*, WADC-TR-58-339 (1958).

APPENDIX A

ACCELEROMETER RECORD FOR ONE SAMPLE SUBJECT.

This shows the vibration pattern at the skull as measured by the accelerometer. The frequency of each condition is noted. Input G load to the seat was ±0.5 Gz at 5 and 7.5 Hz and ±2.0 Gz at 40 Hz and higher. In the middle range, the input was ±1.0 Gz.

The waveform follows the seat input in frequency, but amplitude is a function of the attenuation or amplification through the torso.

The horizontal axis represents time span, the entire abscissa being 0.5 sec. The ordinate is calibrated in G units of acceleration, each small unit representing .25 G.

These records were made concurrently with those in Appendix B.

Frequencies in Row 1 are 5, 7.5, 10 Hz.

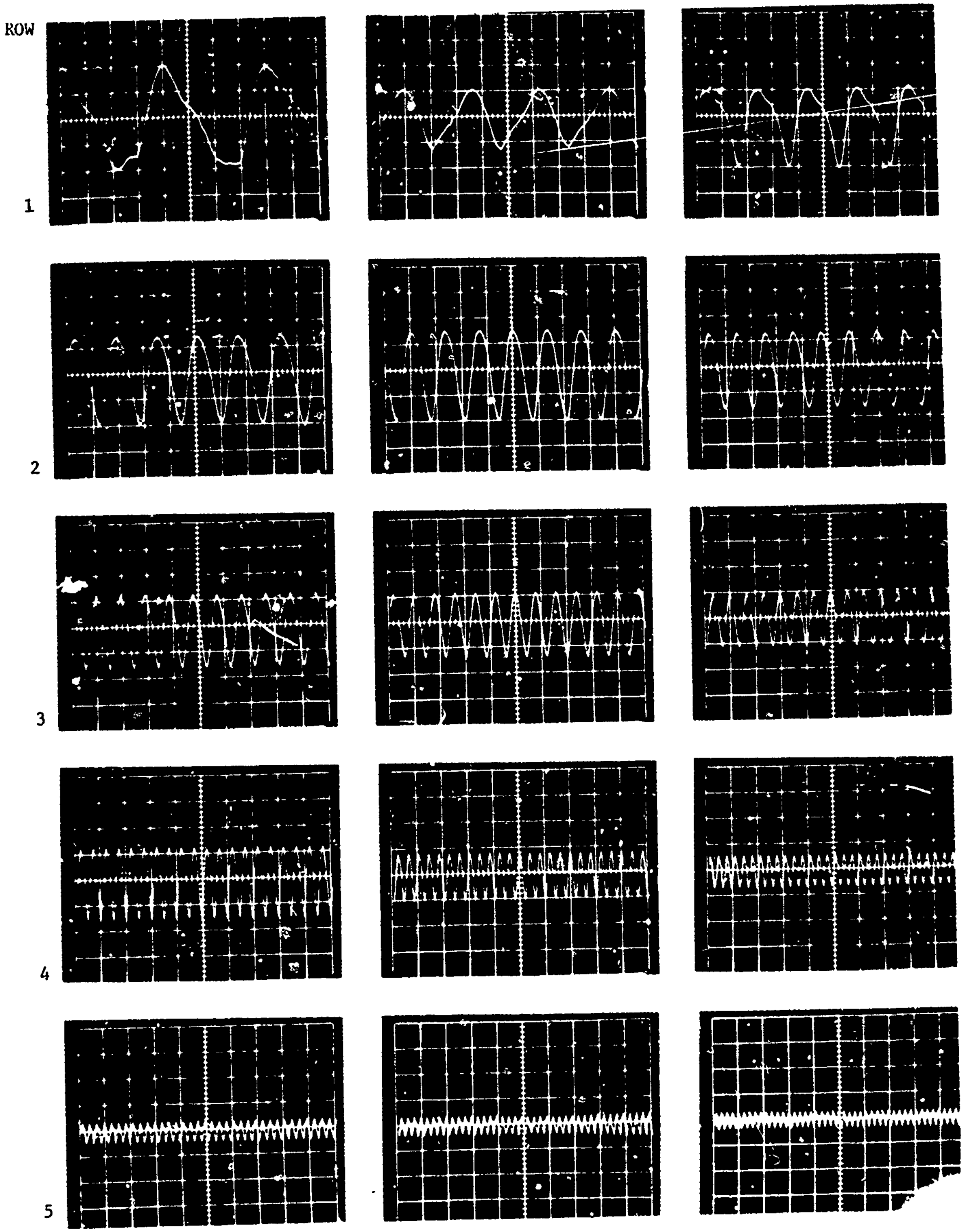
Frequencies in Row 2 are 12.5, 15, 18 Hz.

Frequencies in Row 3 are 21, 25, 30 Hz.

Frequencies in Row 4 are 40, 50, 60 Hz.

Frequencies in Row 5 are 70, 80, 90 Hz.

The last four frequencies were beyond the range of this experiment but one may observe that attenuation of vibration increases at higher frequencies.


ROW
1
2
3
4
5

APPENDIX B

EYE MOVEMENT PHOTOGRAPHS FOR ONE SUBJECT.

The following pages show the face of one subject at each of the eleven seat inputs of the experiment.

Nominal shutter speed was 1/2 second and the extent of the corneal excursion is represented by the reflection. Due to the existence of some non-Z axis output, at the lower frequencies, it is possible to follow each individual cycle. At the higher frequencies only a solid line or band is noted.

The subject is vibrating due to the seat input and the head movement is monitored by an accelerometer rigidly mounted in an epoxy reinforced spectacle frame which is tightly adjusted to the subject. The metric scale is at the same focal plane as the eyes of the subject and is not vibrating. Test frequency is indicated by the upper number adjacent to the ruler.


5
17


7½
17


10
17


12½
17


15
17


18
17


21
17


2.5


30
17


40
17


50
7

APPENDIX C

THE PARAMETERS OF VIBRATION.

Analysis of the magnitude of the various components of vibration is dependent upon the time history of the motion which produces the vibration. In the field of aerospace medicine, the most commonly used vibration tests are based upon the assumption of simple harmonic motion, i.e., the time history of the displacement is described by a sine wave. With this assumption the equations for velocity and acceleration are developed by successive differentiations of the displacement equation.

Assuming sinusoidal motion let:

X = instantaneous displacement (cm)

$dX/dt = \dot{X}$ = instantaneous velocity (cm/sec)

$d^2X/dt^2 = \ddot{X}$ = instantaneous acceleration (cm/sec^2)

x_o = the magnitude of the displacement either direction from the zero position. This is usually referred to as the "half-amplitude" and is expressed in mm, cm or any other appropriate units.

t = time (sec)

f = frequency (cps or Hertz)

then:

$$X = x_o \sin 2\pi ft$$

$$\dot{X} = x_o (2\pi f) \cos 2\pi ft$$

$$\ddot{X} = -x_o (2\pi f)^2 \sin 2\pi ft$$

If only the maximum values of X, $\dot{X}$, and $\ddot{X}$ are of interest, as is usually the case, these expressions are simplified by the fact that the maximum values of the sine and cosine functions are equal to unity.

Therefore:

$$\text{Xmax} = x_o$$

$$\dot{\text{X}}\text{max} = x_o\ (2\pi f)$$

$$\ddot{\text{X}}\text{max} = x_o\ (2\pi f)^2$$

The negative sign on x_o in the acceleration equation is neglected here since it merely represents the phase difference between the acceleration and the displacement and the velocity.

Accordingly, if any two factors are known, the third may be calculated. For example, assume that frequency and acceleration are known and it is desired to determine the displacement. Assume the frequency to be 10 Hz, and the acceleration to be one G (980 cm/sec^2), then:

$$\ddot{X} = x_o\ (2\pi f)^2 \text{ and}$$

$$x_o = \ddot{X}/(2\pi f)^2 = 980\ \text{cm/sec}^2/(2 \times 3.14 \times 10)^2\ \text{sec}^{-2}$$

$$x_o \approx 0.24\ \text{cm} = 24\ \text{cm}$$

Similar manipulations may be performed with any other combination of parameters.

Thus it can be seen that acceleration is proportional to amplitude and to frequency squared, and that the two latter factors must maintain an inverse relationship if acceleration is to be kept constant. An inadequate grasp of this relationship has led to considerable confusion in the literature since each investigator has chosen to vary a different factor and the reader is frequently at a loss to reconcile the various experiments.

When working at specific frequencies, it is frequently desirable to convert acceleration to double amplitude. If one solves the acceleration equations for each frequency desired, it is possible to derive a table of amplitude factors. In this manner, to determine the double amplitude (in the units desired) one multiplies the acceleration (in the units desired) by the amplitude factor for the appropriate frequency.

The following table indicates the double amplitude factors to be used when acceleration is in G units and the amplitude is desired in millimeters.

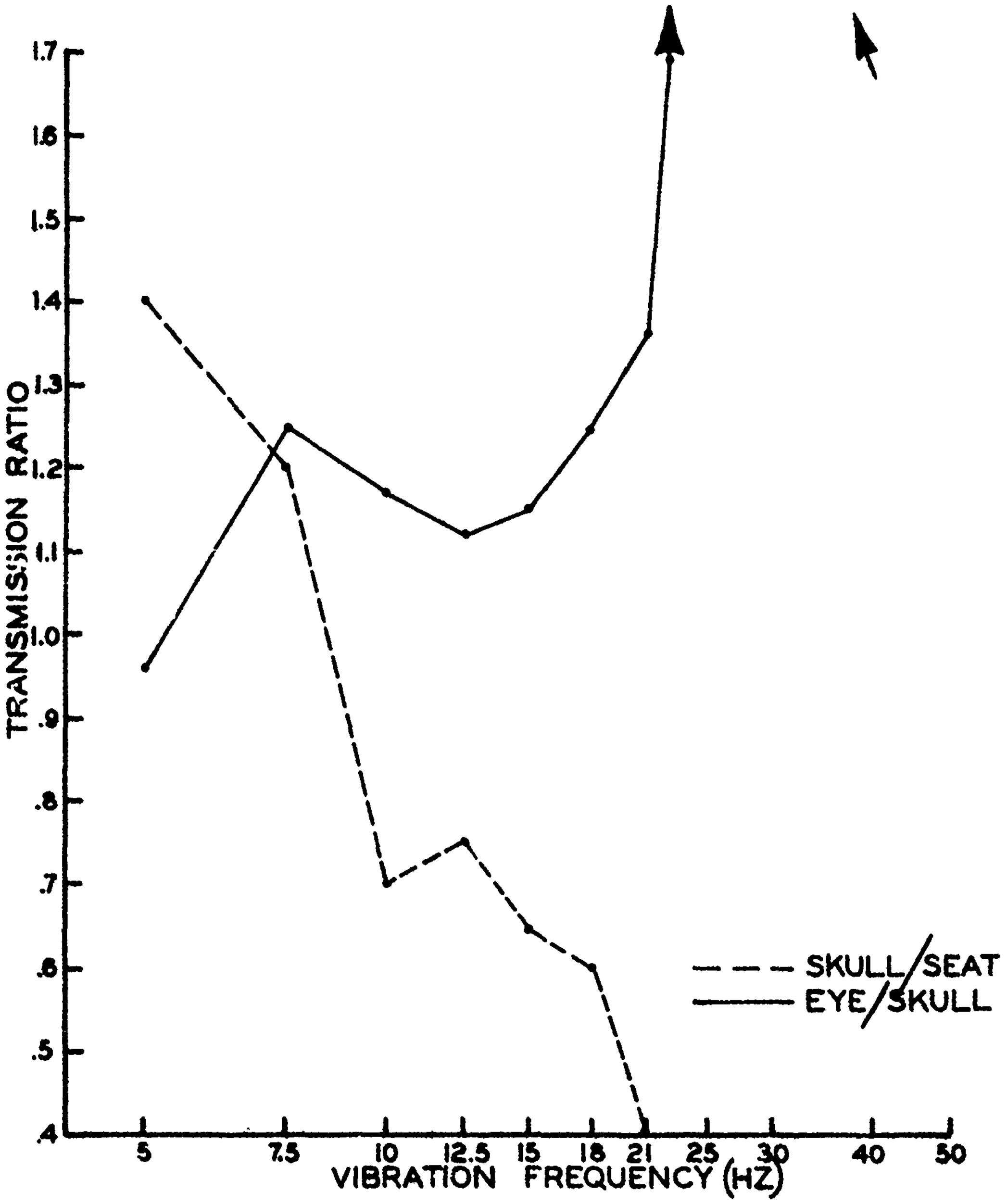
FREQUENCY	5	7.5	10	12.5	15	18	21	25	30	40	50
FACTOR	19.5	8.62	5.08	3.15	2.18	1.33	1.1	.785	.557	.304	.203

APPENDIX D

TRANSMISSION DATA FOR EACH SUBJECT.

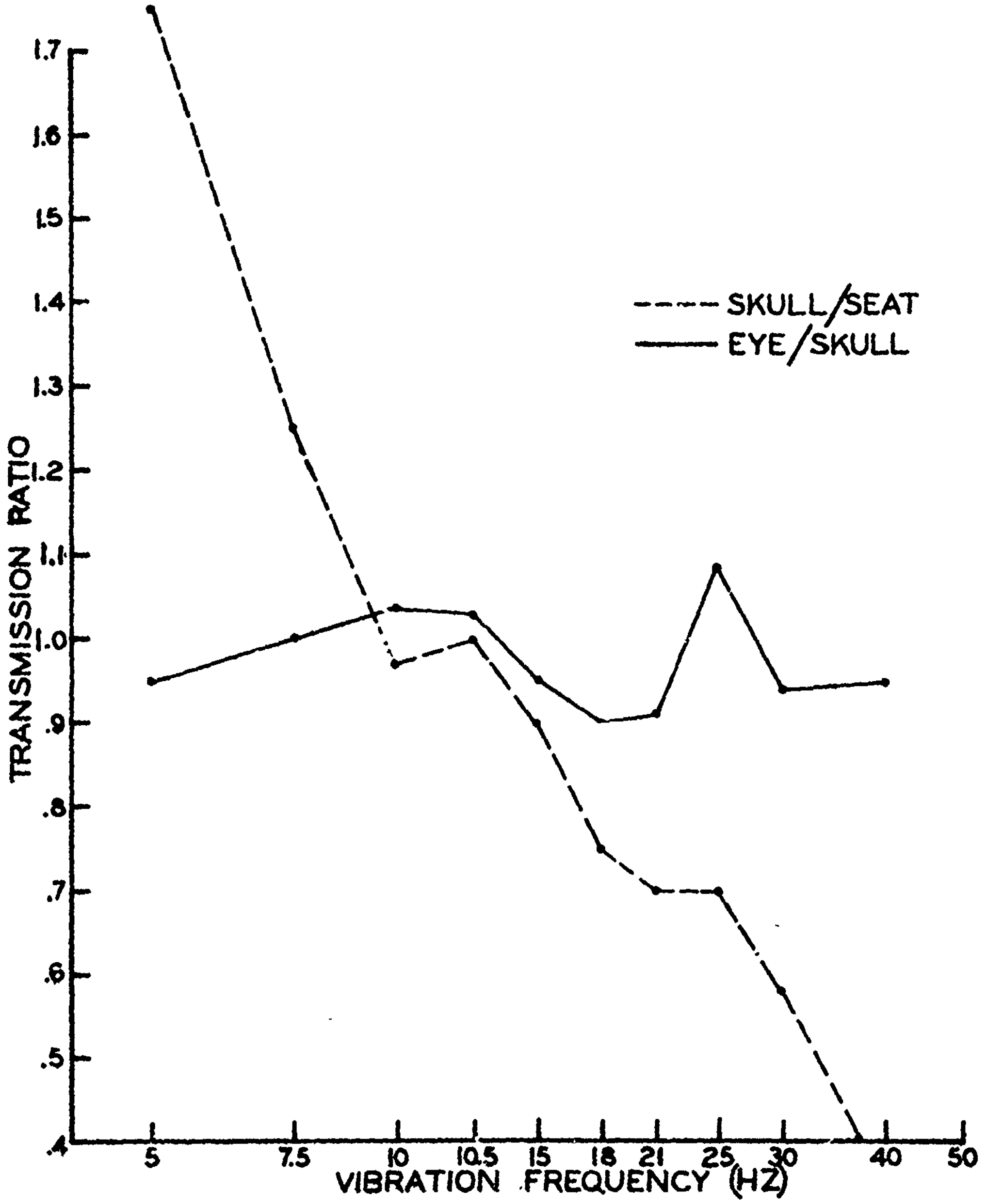
The following pages indicate the seat, head and eye movement for each subject as well as the calculated transmission ratios at each test frequency.

The solid graph shows the cause of eye/skull transmission while the dotted curve represents skull/seat transmission.



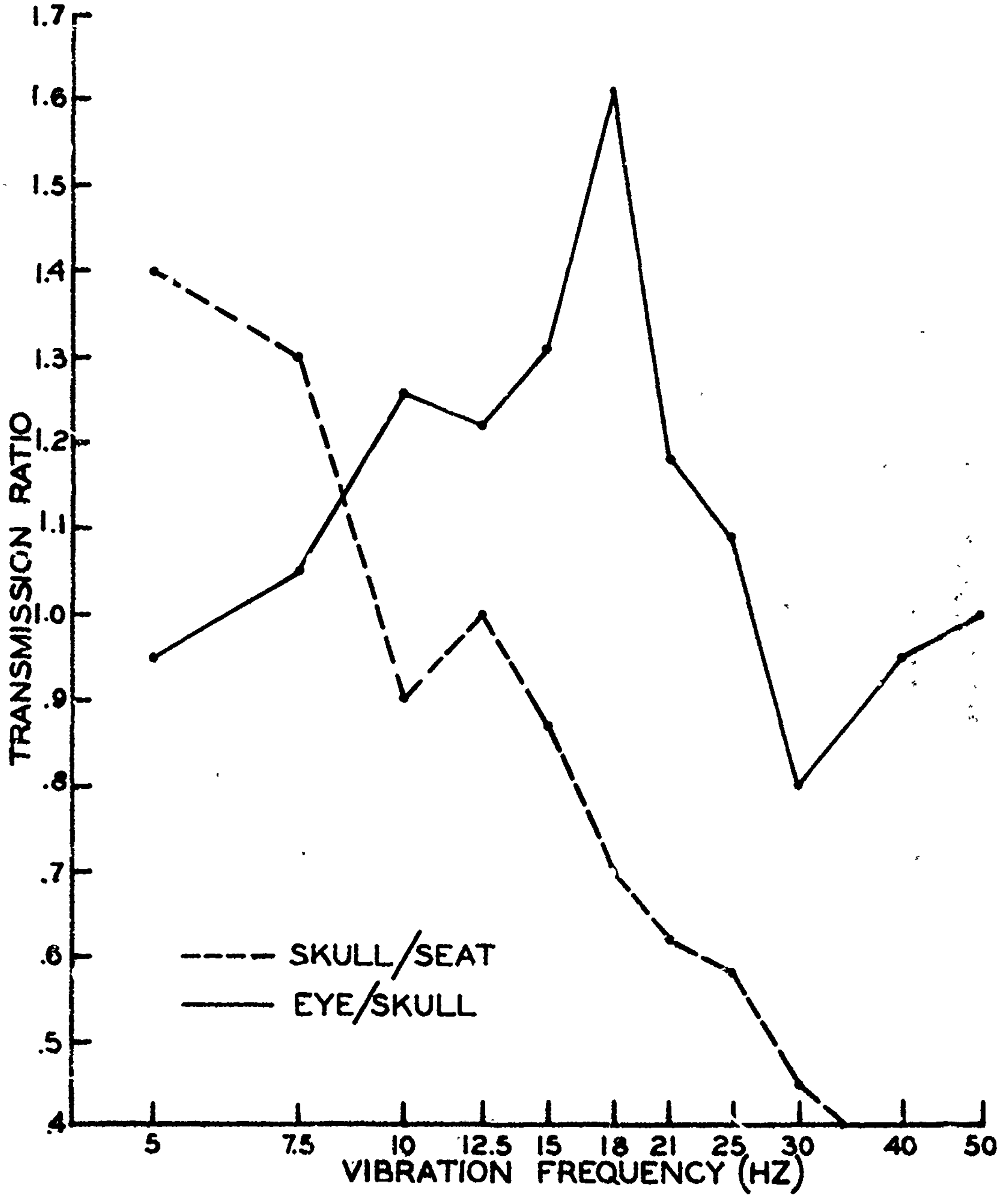
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.7	.6	.7	.75	.65	.60	.40	.30	.25	.35	.20
SK/ST TRANS	1.4	1.2	.70	.75	.65	.60	.40	.30	.25	.18	.10
SKULL (MM)	15.0	5.3	5.6	3.0	1.9	.93	.66	.34	.19	.11	.053
EYE (MM)	14.4	8.3	4.7	2.9	1.7	1.6	.8	.4	.2	.1	--
EYE/SK TRANS	.96	1.57	.84	.97	.9	1.61	1.21	1.18	1.05	.91	--

TRANSMISSION DATA FOR SUBJECT #1



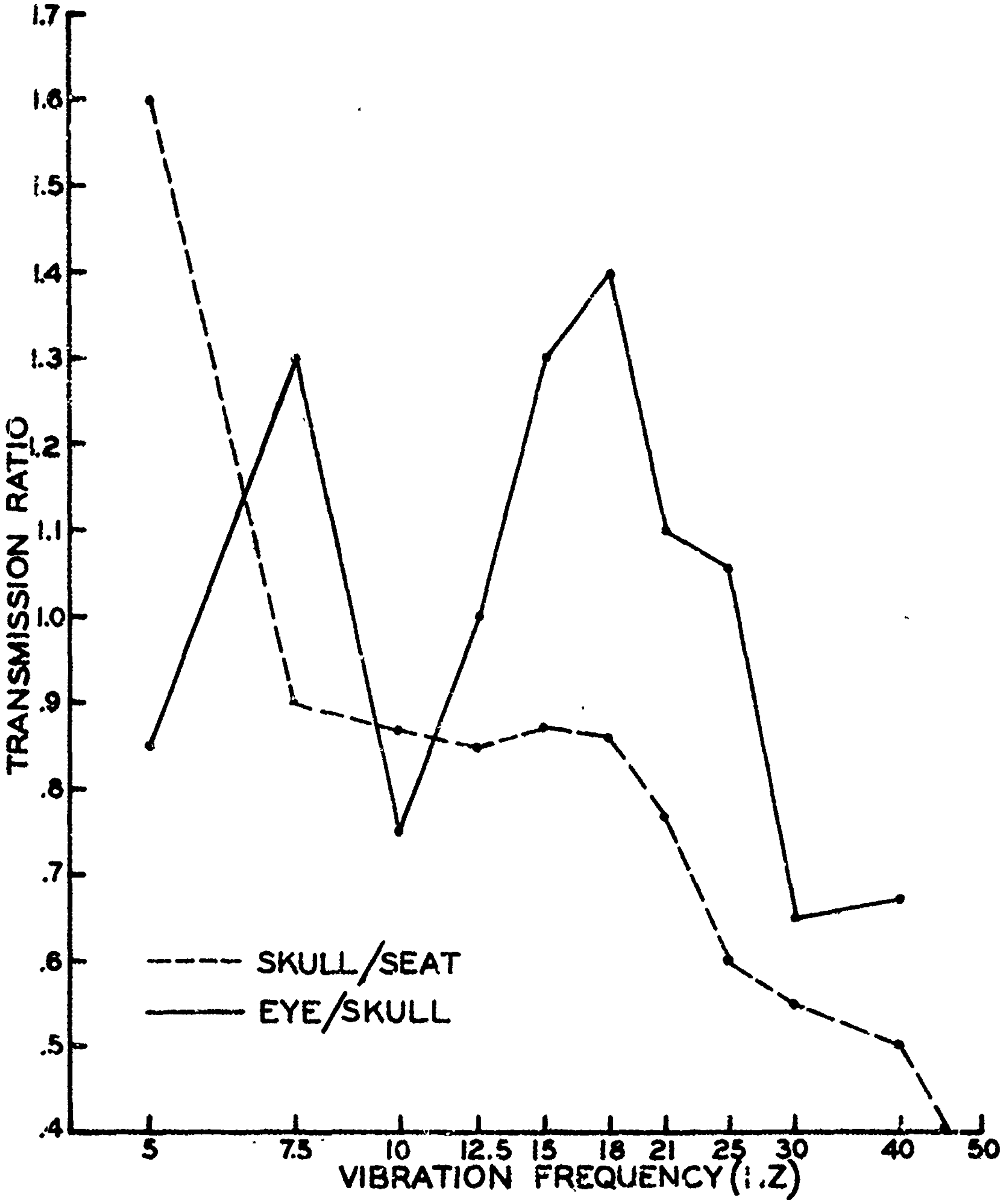
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.0
SKULL (G)	.88	.62	.97	1.0	.90	.75	.70	.70	.58	.70	.45
SK/ST TRANS	1.76	1.25	.97	1.0	.90	.75	.70	.70	.58	.35	.26
SKULL (MM)	17.2	5.3	4.9	3.2	2.0	1.0	.77	.55	.32	.21	.092
EYE (MM)	16.3	5.3	5.1	3.3	1.9	.90	.70	.60	.3	.2	--
EYE/SK TRANS	.95	1.0	1.04	1.03	.95	.90	.91	1.09	.94	95	--

TRANSMISSION DATA FOR SUBJECT #2



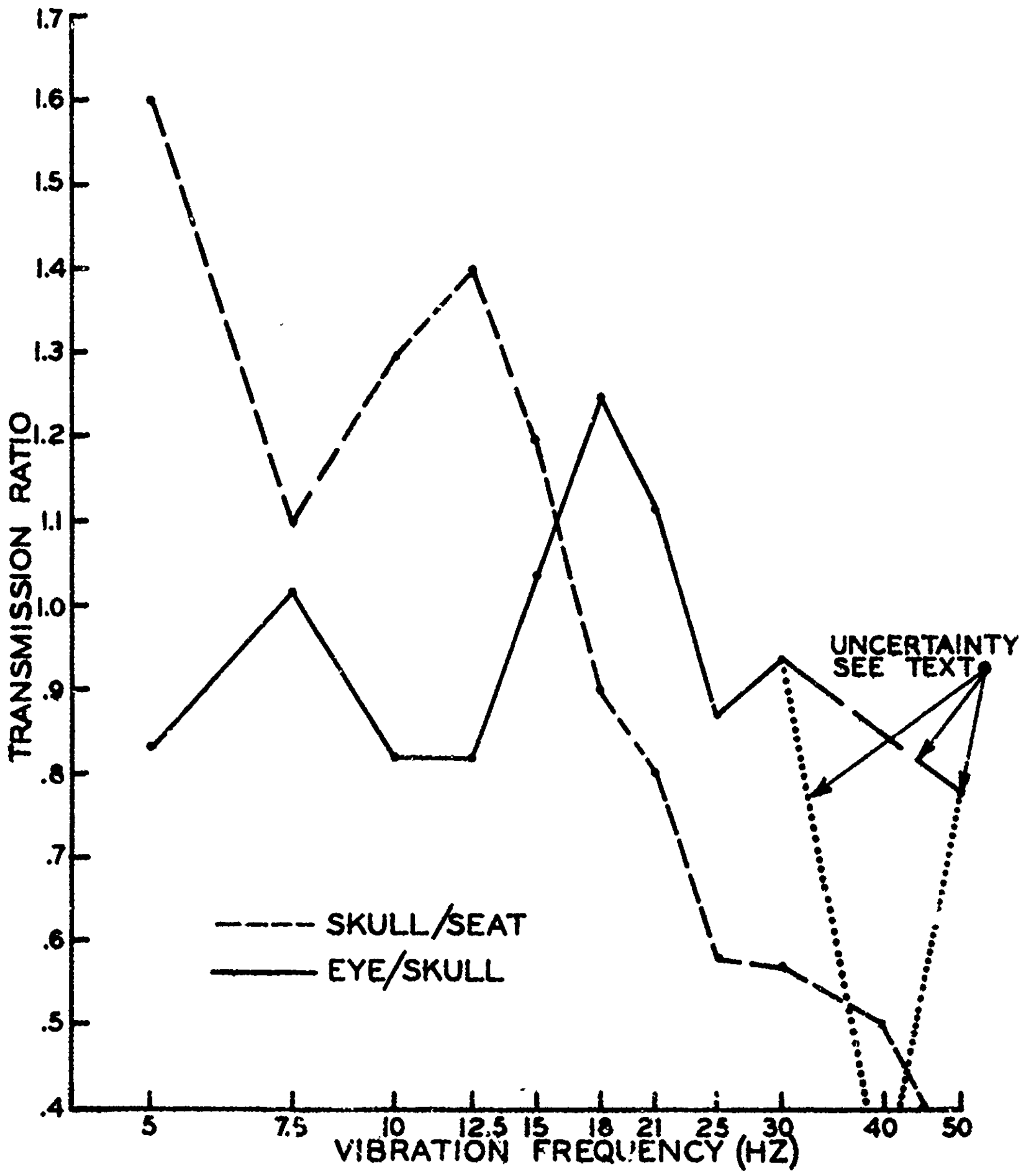
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.7	.65	.9	1.0	.87	.70	.62	.58	.45	.68	.52
SK/ST TRANS	1.4	1.3	.9	1.0	.87	.70	.62	.58	.45	.34	.26
SKULL (MM)	13.7	5.6	4.6	3.2	1.9	.93	.68	.46	.25	.21	.106
EYE (MM)	13.0	5.9	5.8	3.9	2.5	1.5	.80	.50	.20	.20	.10
EYE/SK TRANS	.95	1.05	1.26	1.22	1.31	1.61	1.18	1.09	.80	.95	1.0

TRANSMISSION DATA FOR SUBJECT #3



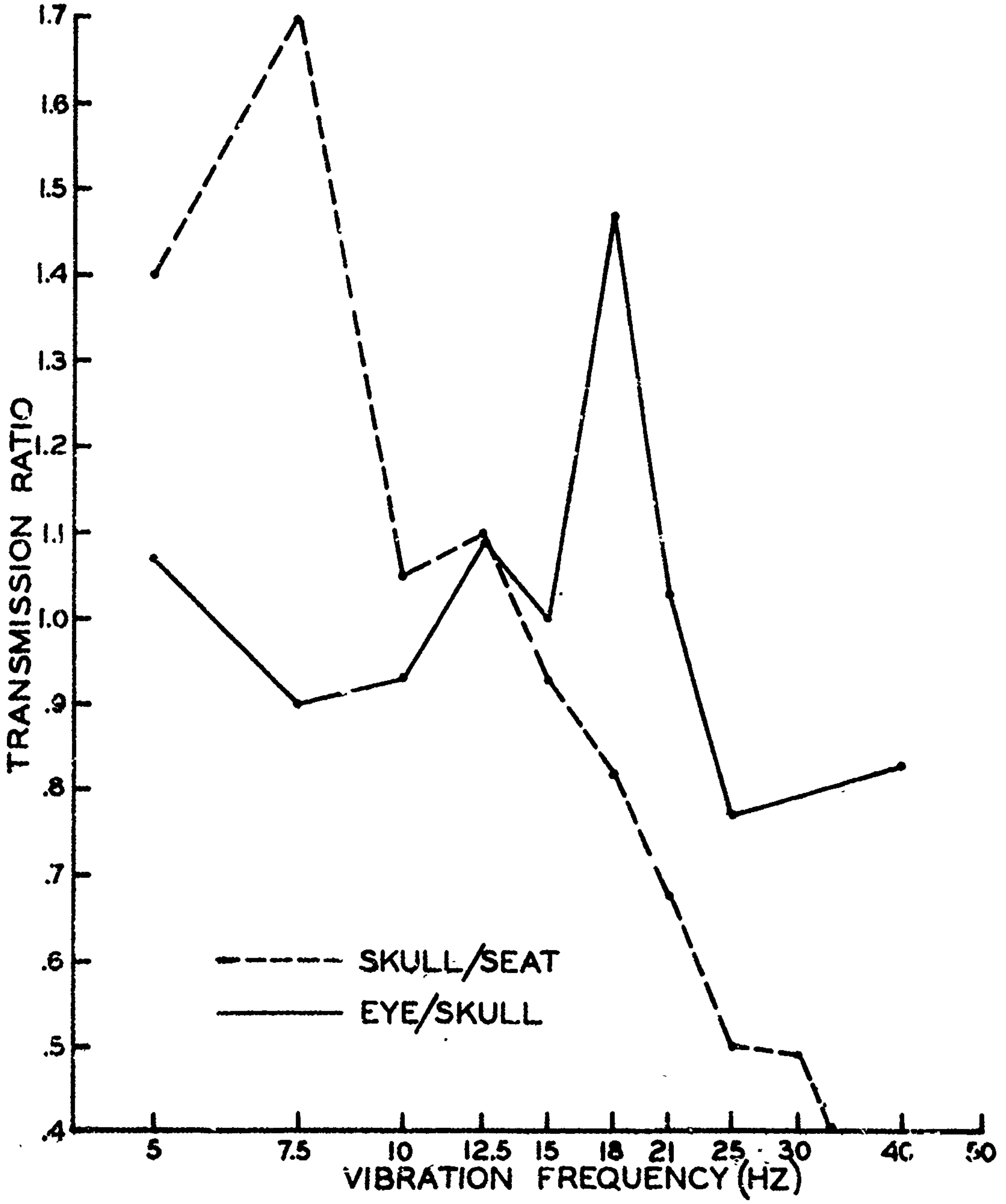
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.8	.45	.87	.85	.87	.85	.77	.60	.55	1.0	.65
SK/ST TRANS	1.6	.90	.87	.85	.87	.85	.77	.60	.55	.50	.33
SKULL (MM)	15.6	3.9	4.8	2.7	1.9	1.13	.85	.47	.31	.30	.13
EYE (MM)	13.2	5.2	3.6	2.8	2.5	1.6	.9	.5	.2	.2	--
EYE/SK TRANS	.85	1.3	.75	1.0	1.3	1.4	1.1	1.06	.65	.67	--

TRANSMISSION DATA FOR SUBJECT #4



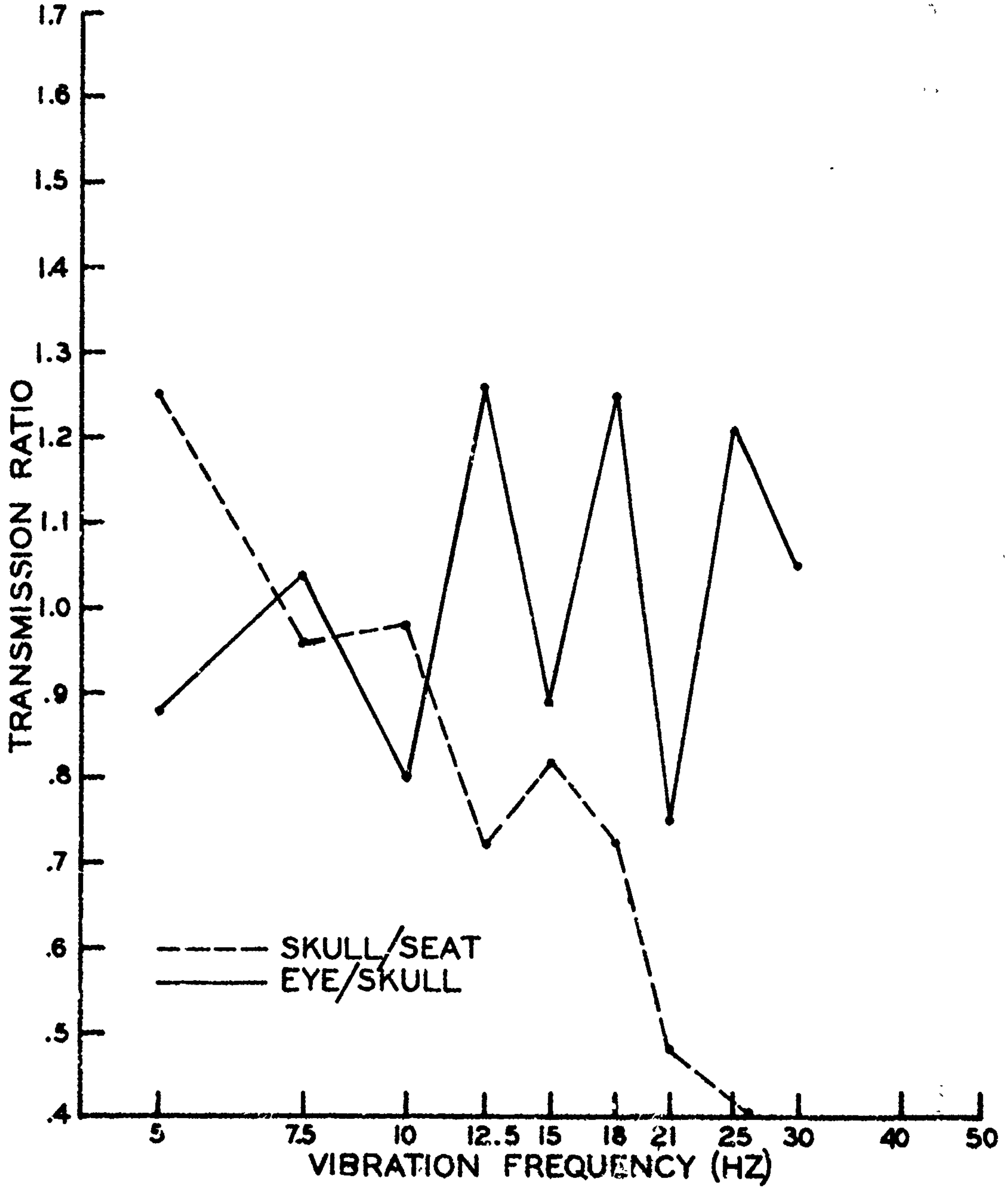
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.8	.55	1.3	1.4	1.2	.9	.8	.58	.57	1.08	.63
SK/ST TRANS	1.6	1.1	1.3	1.4	1.2	.9	.8	.58	.57	.50	.32
SKULL (MM)	15.6	4.8	6.6	4.4	2.6	1.2	.88	.46	.32	.33	.128
EYE (MM)	13.0	4.9	5.4	3.6	2.7	1.5	.9	.4	.3	.1	.1
EYE/SK TRANS	.83	1.02	.82	.82	1.04	1.25	1.12	.87	.94	.3	.78

TRANSMISSION DATA FOR SUBJECT #5



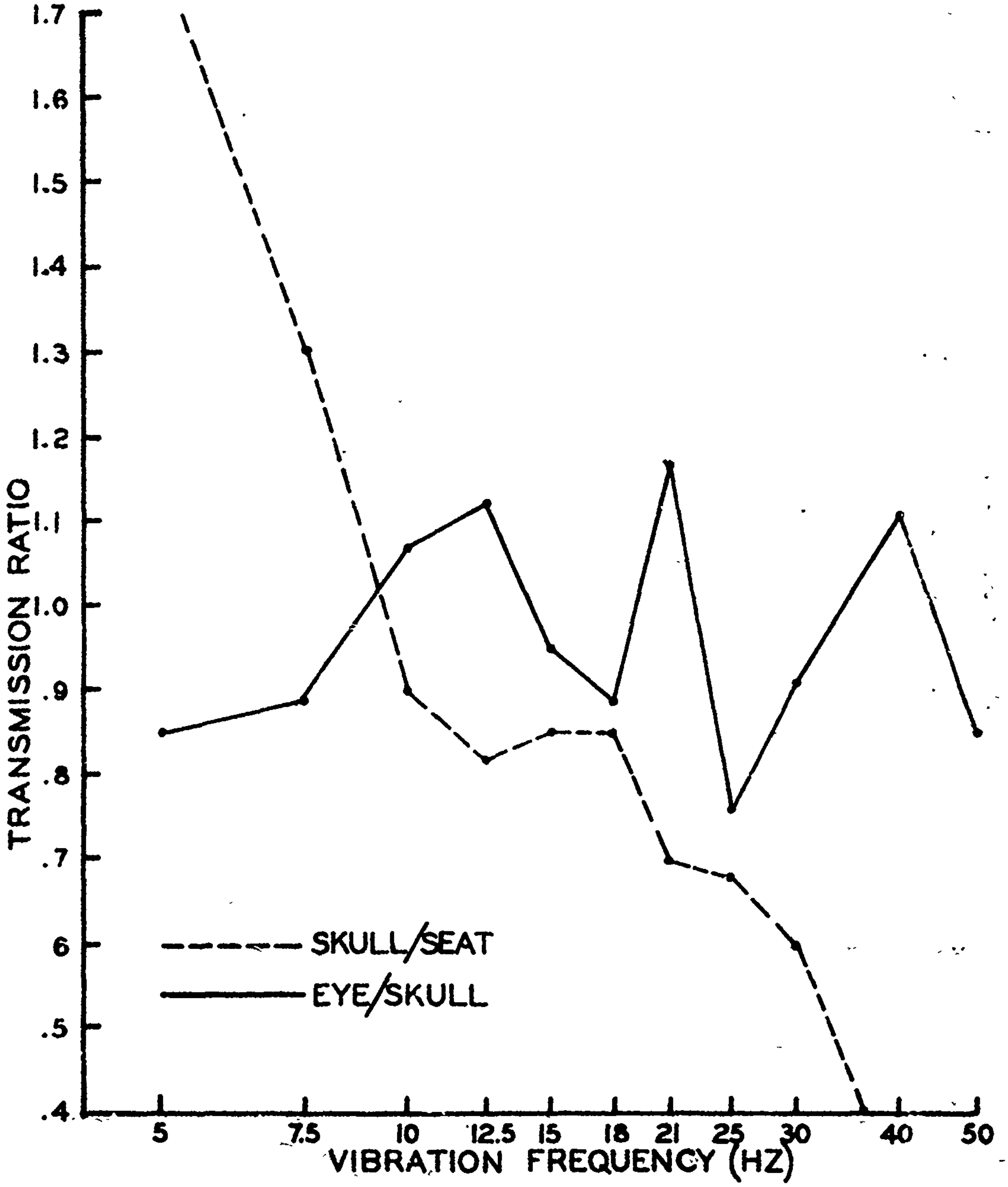
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.7	.85	1.05	1.1	.93	.82	.68	.50	.49	.40	.25
SK/ST TRANS	1.4	1.7	1.05	1.1	.93	.82	.68	.50	.49	.20	.13
SKULL (MM)	13.7	7.3	5.4	3.5	2.0	1.09	.75	.39	.27	.12	.051
EYE (MM)	14.6	6.6	5.0	3.8	2.0	1.6	.8	.3	--	.1	--
EYE/SK TRANS	1.07	.9	.93	1.09	1.0	1.47	1.03	.77	--	.83	--

TRANSMISSION DATA FOR SUBJECT #6



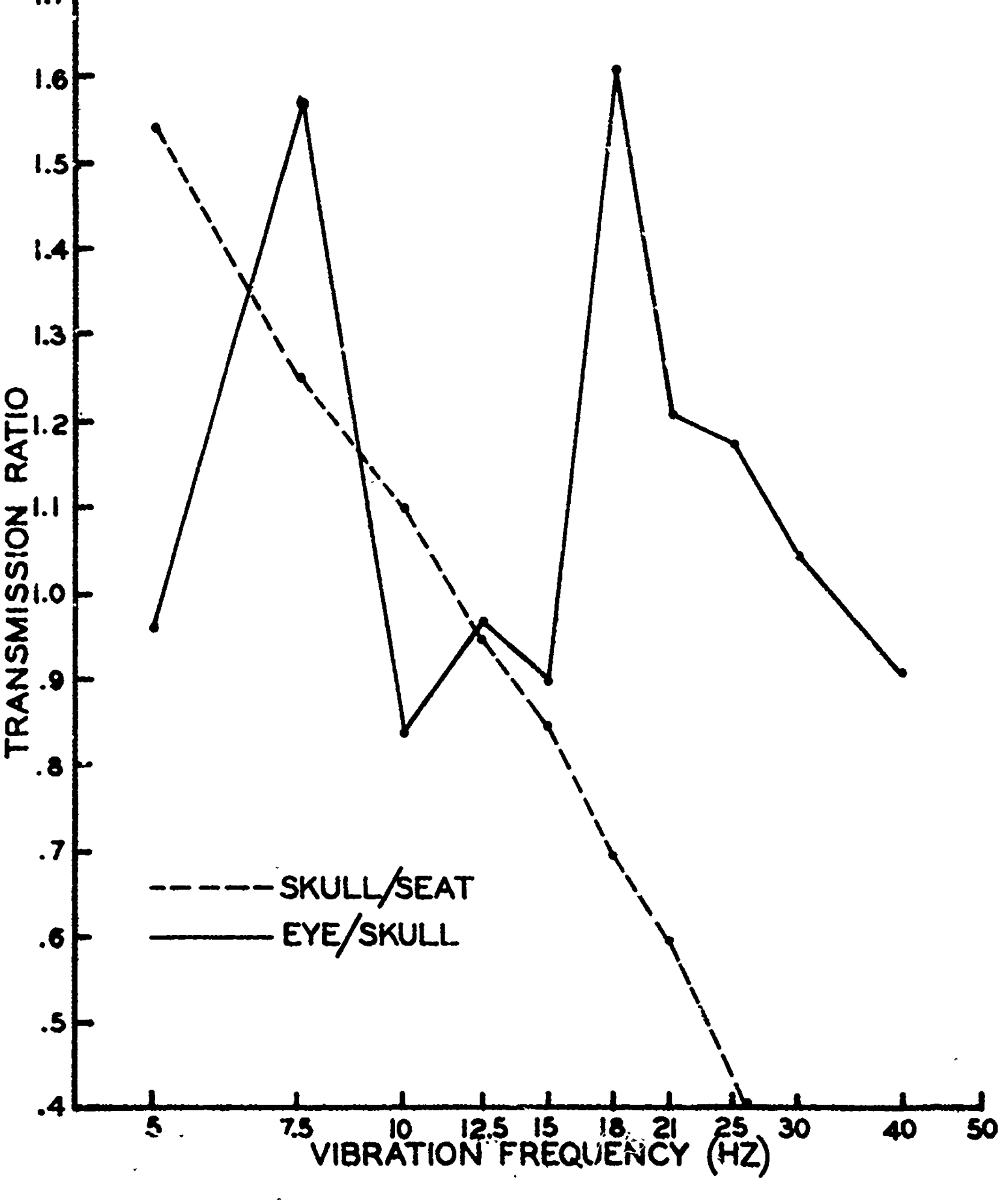
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.62	.48	.98	.72	.82	.72	.48	.42	.35	.40	.30
SK/ST TRANS	1.25	.96	.98	.72	.82	.72	.48	.42	.35	.20	.15
SKULL (MM)	12.1	4.1	5.0	2.3	1.8	.96	.53	.33	.19	.12	.061
EYE (MM)	10.6	4.3	4.0	2.9	1.6	1.2	.4	.4	.2	--	--
EYE/SK TRANS	.88	1.04	.8	1.26	.89	1.25	.75	1.21	1.05	--	--

TRANSMISSION DATA FOR SUBJECT #7



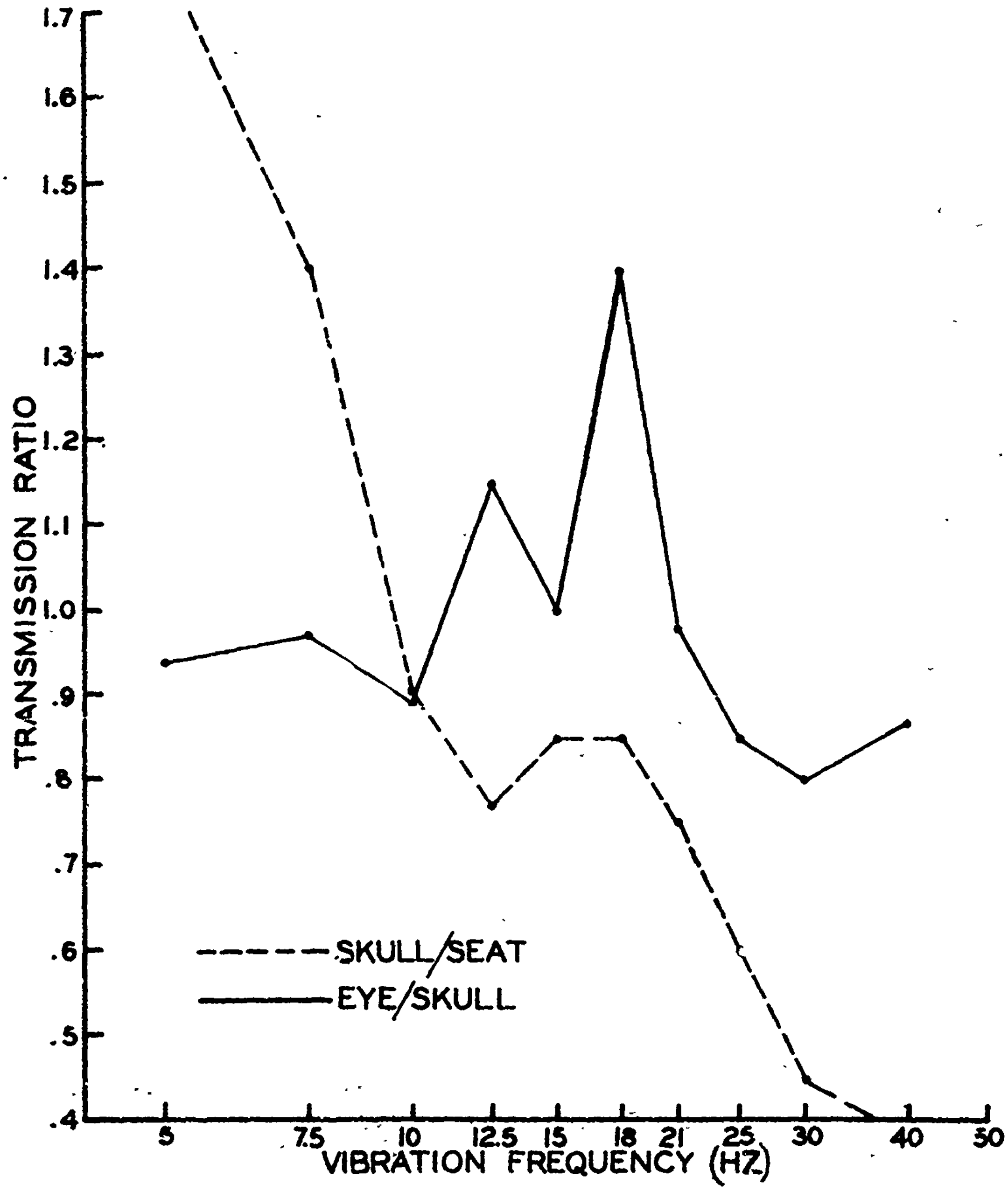
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.88	.65	.90	.82	.85	.85	.70	.68	.60	.60	.58
SK/ST TRANS	1.76	1.30	.90	.82	.85	.85	.70	.68	.60	.30	.29
SKULL (MM)	17.2	5.6	4.6	2.6	1.9	1.13	.77	.53	.33	.18	.118
EYE (MM)	14.6	5.0	4.9	2.9	1.8	1.0	.9	.4	.3	.2	.1
EYE/SK TRANS	.85	.89	1.07	1.12	.95	.89	1.17	.76	.91	1.11	.85

TRANSMISSION DATA FOR SUBJECT #8



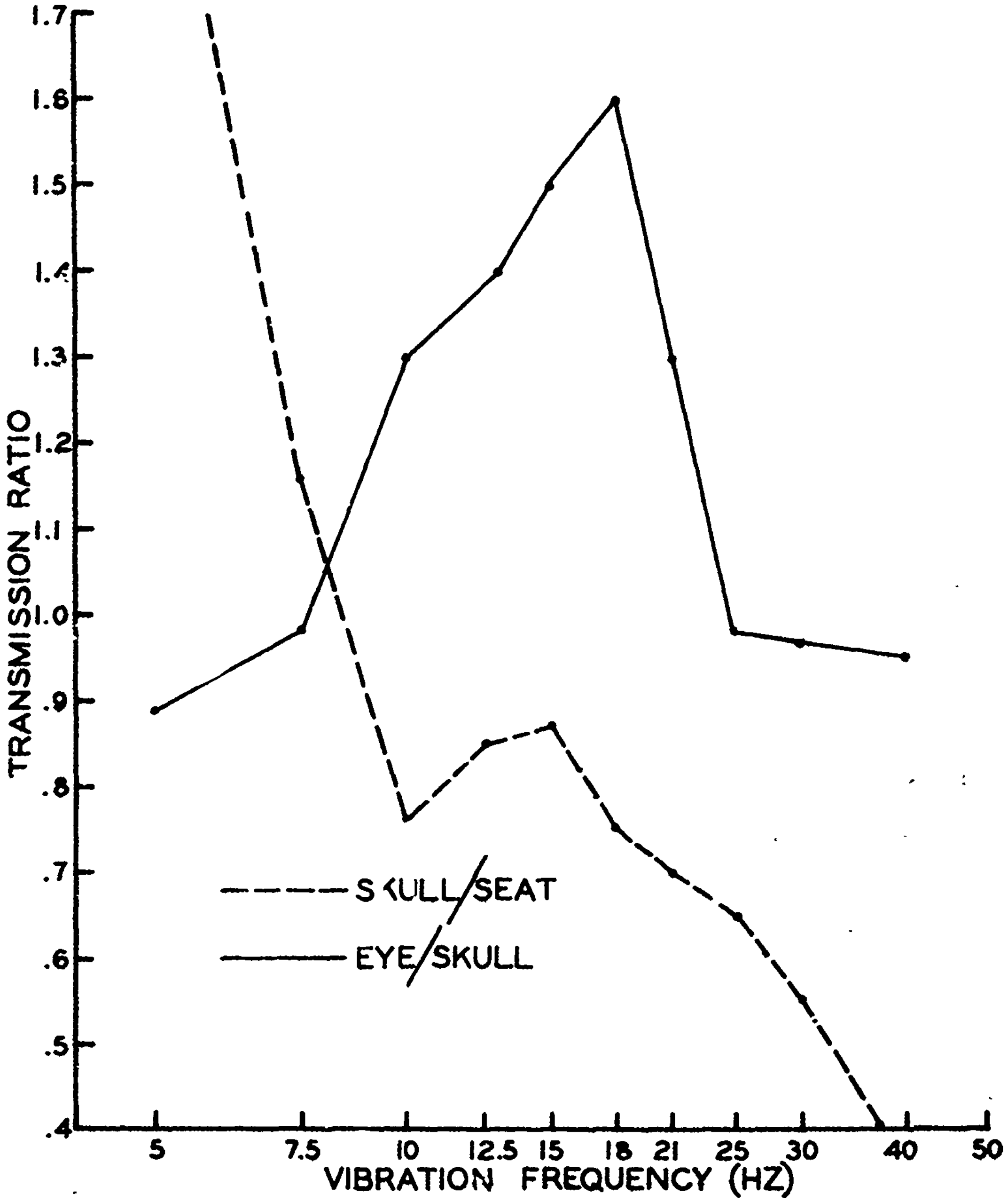
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	77	.62	1.1	.95	.85	.70	.60	.43	.35	.37	.26
SK/ST TRANS	1.54	1.25	1.1	.95	.85	.70	.60	.43	.35	.19	.13
SKULL (MM)	15.0	5.3	5.6	3.0	1.9	.93	.66	.34	.19	.11	.053
EYE (MM)	14.4	8.3	4.7	2.9	1.7	1.60	.80	.4	.2	.1	--
EYE/SK TRANS	.96	1.57	.84	.97	.9	1.61	1.21	1.18	1.05	.91	--

TRANSMISSION DATA FOR SUBJECT #9



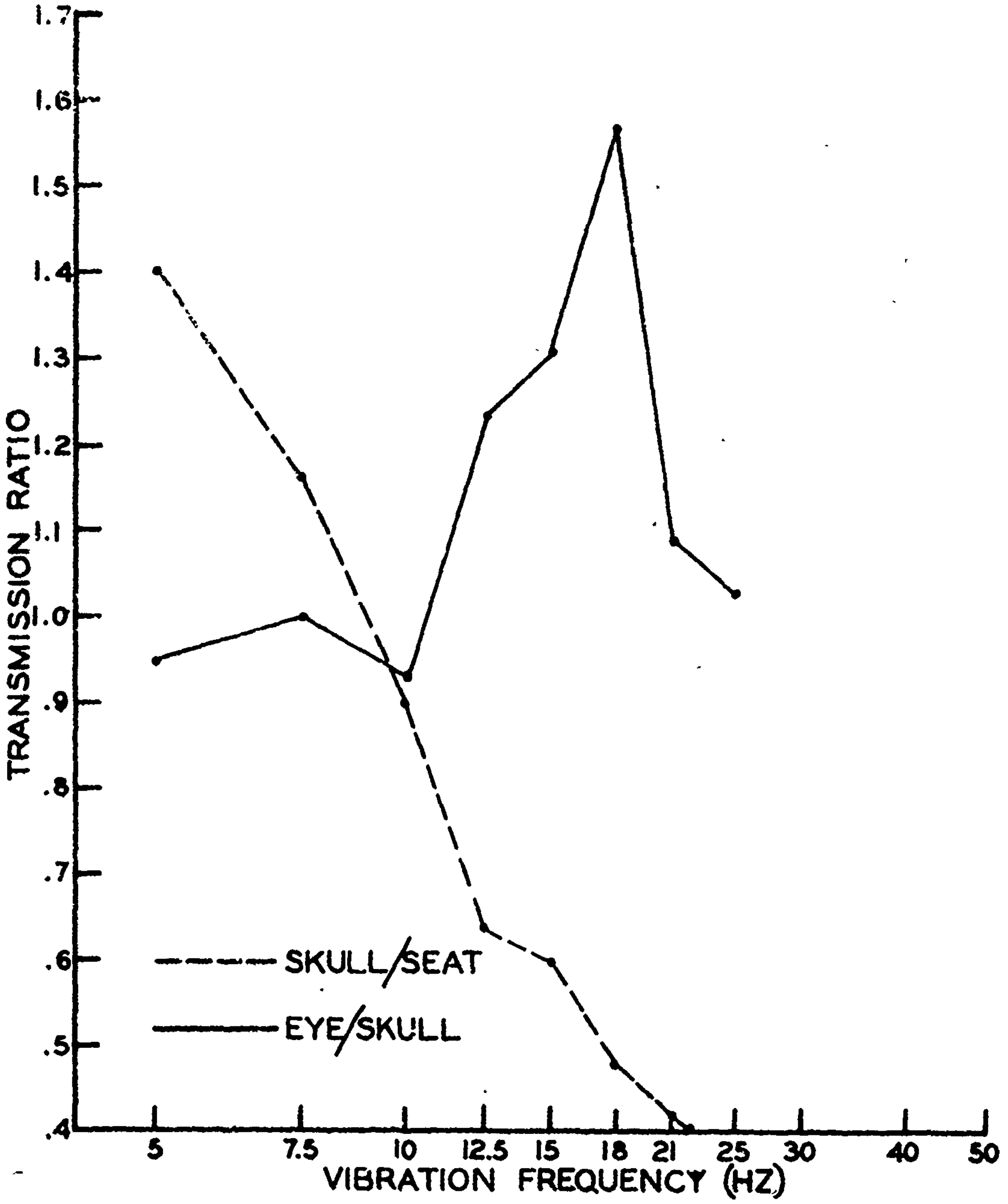
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.88	.70	.90	.77	.85	.85	.75	.60	.45	.75	.72
SK/ST TRANS	1.76	1.40	.90	.77	.85	.85	.75	.60	.45	.38	.36
SKULL (MM)	17.2	6.0	4.6	2.43	1.9	1.13	.82	.47	.25	.23	.147
EYE (MM)	16.2	5.8	4.1	2.8	1.9	1.6	.80	.4	.2	.2	--
EYE/SK TRANS	.94	.97	.89	1.15	1.0	1.4	.98	.85	.8	.87	--

TRANSMISSION DATA FOR SUBJECT #10



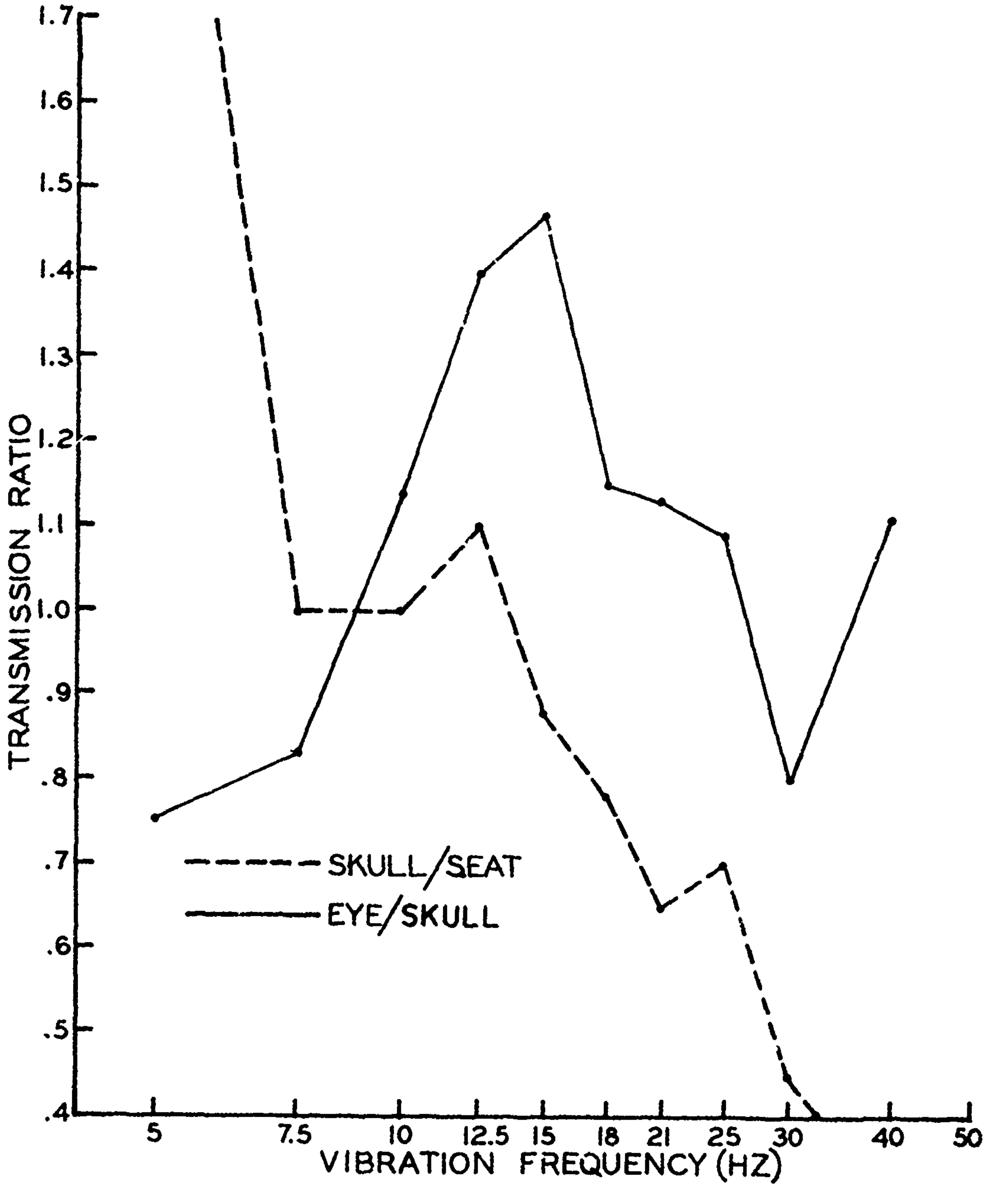
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	1.0	.58	.76	.85	.87	.75	.70	.65	.55	.70	.45
SK/ST TRANS	2.0	1.16	.76	.85	.87	.75	.70	.65	.55	.35	.23
SKULL (MM)	19.5	5.0	3.9	2.7	1.9	1.0	.77	.51	.31	.21	.092
EYE (MM)	17.2	4.9	5.0	3.8	2.9	1.6	1.0	.5	.3	.2	--
EYE/SK TRANS	.89	.98	1.3	1.4	1.5	1.6	1.3	.98	.97	.95	--

TRANSMISSION DATA FOR SUBJECT #11



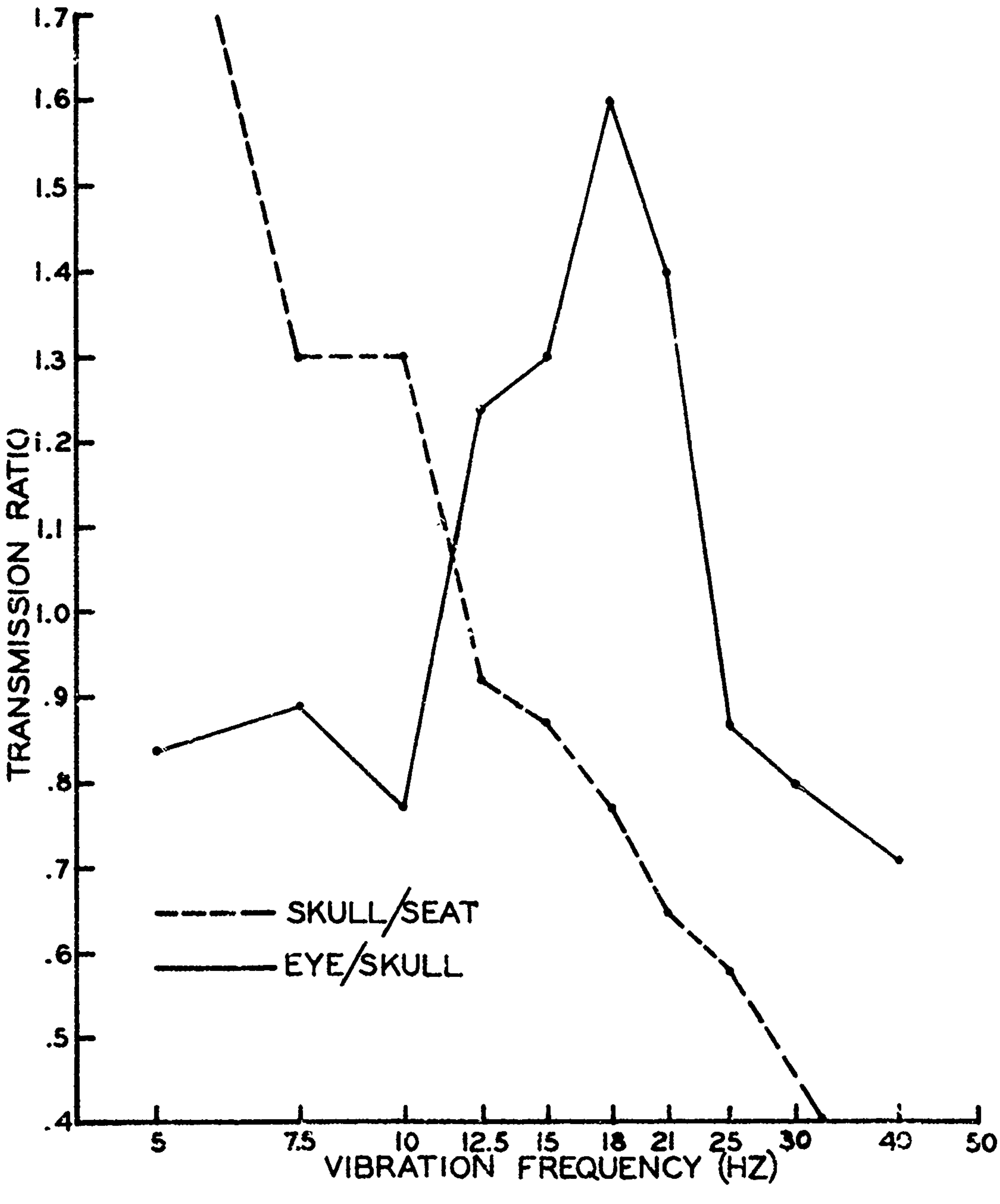
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.70	.58	.90	.64	.60	.48	.42	.37	.25	.37	.30
SK/ST TRANS	1.40	1.16	.90	.64	.60	.48	.42	.37	.25	.19	.15
SKULL (MM)	13.6	5.0	4.6	2.1	1.3	.64	.46	.29	.14	.11	.061
EYE (MM)	12.9	5.0	4.2	2.6	1.7	1.0	.5	.3	--	--	--
EYE/SK TRANS	.95	1.0	.93	1.24	1.31	1.57	1.09	1.03	--	--	--

TRANSMISSION DATA FOR SUBJECT #12



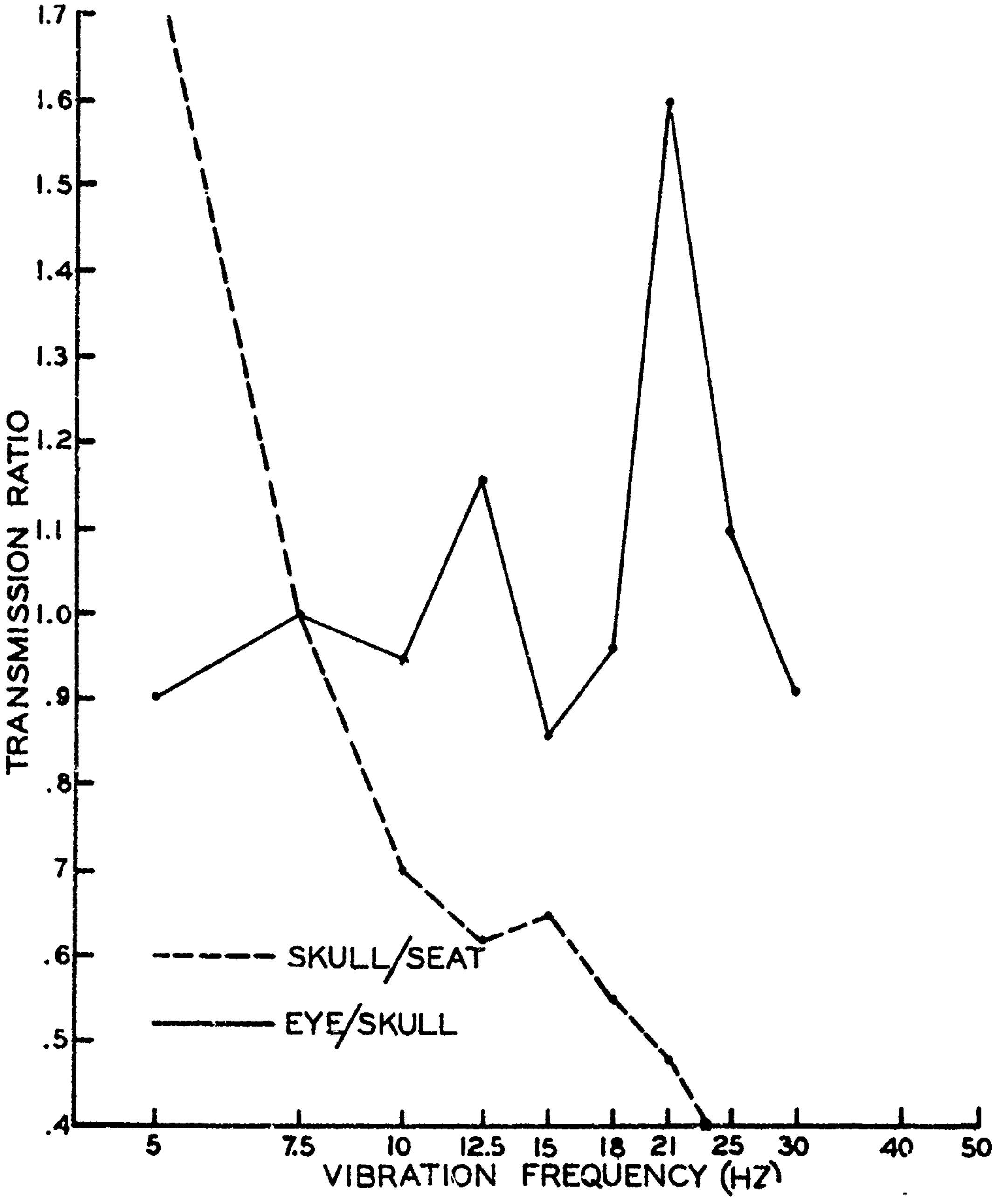
FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	1.1	.5	1.0	1.1	.88	.78	.65	.70	.45	.58	.50
SK/ST TRANS	2.2	1.0	1.0	1.1	.88	.78	.65	.7	.45	.29	.25
SKULL (MM)	21.5	4.3	5.1	3.5	1.9	1.04	.71	.55	.25	.18	.10
EYE (MM)	16.1	3.5	5.8	4.9	2.8	1.2	.8	.6	.2	.2	--
EYE/SK TRANS	.75	.83	1.14	1.40	1.47	1.15	1.13	1.09	.80	1.11	--

TRANSMISSION DATA FOR SUBJECT #13



FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50.
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	1.0	.65	1.3	.92	.87	.77	.65	.58	.45	.45	.32
SK/ST TRANS	2.0	1.3	1.3	.92	.87	.77	.65	.58	.45	.23	.16
SKULL (MM)	19.5	5.6	6.6	2.9	1.9	1.02	.71	.46	.25	.14	.065
EYE (MM)	16.4	5.0	5.1	3.6	2.5	1.6	1.0	.4	.2	.1	--
EYE/SK TRANS	.84	.89	.77	1.24	1.3	1.6	1.4	.87	.8	.71	--

TRANSMISSION DATA FOR SUBJECT #14



FREQ (Hz)	5	7.5	10	12.5	15	18	21	25	30	40	50
SEAT INPUT (G)	.5	.5	1	1	1	1	1	1	1	2	2
SKULL (G)	.87	.50	.70	.62	.65	.55	.48	.35	.20	.15	.15
SK/ST TRANS	1.75	1.0	.70	.62	.65	.55	.48	.35	.20	.08	.08
SKULL (MM)	17.0	4.3	3.6	1.9	1.4	.73	.53	.27	.11	.045	.031
EYE (MM)	15.3	4.3	3.4	2.2	1.2	.7	1.0	.3	.1	--	--
EYE/SK TRANS	.90	1.0	.95	1.16	.86	.96	1.6	1.1	.91	--	--

TRANSMISSION DATA FOR SUBJECT #15

APPENDIX E

WEDGE SEPARATION DATA FOR EACH SUBJECT

I. Apparent Separation in MM of V-Scope Wedge at Each Test Frequency. Viewing Distance is 4.0 M.

FREQUENCY	5	7.5	10	12.5	15	18	21	25	30	40	50
Subject:											
1	.5	2	3	10	6	1	1	0	0	0	0
2	0	0	0	3	2	2	1	1	1	1	1
3	.5	3	6	16	16	14	14	12	10	9	6
4	0	0	0	1	1	10	6	10	8	5	3
5	0	0	0	2	3	3	4	1	2	4	5
6	0	0	4	7	6	6	6	4	4	3	1
7	0	0	3	12	6	4	0	0	0	0	0
8	0	0	0	1	1	1	1	0	0	4	8
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	1	0	8	0	10	4	5	0
11	[illegible]	0		8	22	34	32	24	14	12	2
12	0	0	0	0	[illegible]	2	2	2	1	1	1
13	.5	[illegible]	2	7	7	6	10	4	1	1	2
14	0	0	3	9	4	2	5	5	5	3	3
15	0	0	1	3	3	3	3	3	2	2	2
MEAN	0.1	0.4	1.6	5.3	4.1	6.3	6.3	5.1	3.5	3.3	2.3

II. Apparent Separation in MM of V-Scope Wedge at Each Test Frequency. Viewing Distance is 0.5 M.

FREQUENCY	5	7.5	10	12.5	15	18	21	25	30	40	50
Subject:											
1	8	4	3	2	2	1	1	1	0	0	0
2	6	3	4	3	2	1	1	0	0	0	0
3	10	8	6	5	4	3	3	2	1	2	1
4	0	0	0	0	0	0	0	0	0	0	0
5	3	2	3	2	0	0	0	0	0	0	0
6	7	6	6	4	4	1	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0
8	0	3	1	1	1	1	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	1	0	0	0	0	0	0	0
11	0	0	2	2	2	6	6	4	3	3	0
12	0	4	4	1	1	1	1	1	1	0	0
13	0	0	3	3	4	2	1	0	0	0	0
14	9	5	6	4	3	0	0	0	0	0	0
15	8	6	1	1	0	0	0	0	0	0	0
MEAN	3.4	2.73	2.6	1.9	1.5	1.0	.87	.53	.33	.33	.07

☆ U. S. GOVERNMENT PRINTING OFFICE· 1976 — 657-6[illegible]/990