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Some Effects of the Vibration of Reading Material upon Visual Performance

J.G. O'Hanlon and M.J. Griffin

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UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN FACTORS RESEARCH UNIT

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ABSTRACT

An investigation has been made of the changes in visual acuity when viewing an object vibrating in the frequency range 5 to 40 Hz. Reading time, error score, and subjective rating of reading difficulty were used as indicators of performance at a Landolt C acuity task.

Three experiments were conducted. The first showed that errors increased with frequency from 5 - 40 Hz and with double amplitude from 0.05 in. to 0.20 in. Two further experiments investigated in more detail

(a) varying amplitude at constant frequency, 16 Hz.

(b) varying frequency at constant double amplitude, 0.1 in.

It was found that error score was proportional to the square root of the amplitude of vibration and that the error score was directly proportional to frequency. A relatively small increase in test object size appreciably reduced errors - a 75% reduction in errors was produced by only a 25% increase in the size of the Landolt C's. The same size increase resulted in up to 20% reduction in the time taken to complete the reading task.

ACKNOWLEDGEMENTS

This study was undertaken in the context of current investigations of the human factor problems associated with operational helicopter flying. Reference is made to Ministry of Defence Agreement No. 70/GEN/9886.

Professor E. E. Zepler and Dr. D. J. Mead have also been connected with this study.

CONTENTS

1. INTRODUCTION

This study arises largely from current involvement in an investigation of the helicopter environment. However, the results are also of relevance to other spheres of interest.

The helicopter is a severe vibration environment with major acceleration components in the frequency range up to 100 Hz. These components are approximately sinusoidal and are largely produced by the out of balance motion of rotating parts. The resultant multi-axial multiple frequency acceleration pattern is transmitted both to the pilot and his instrument panel. Thus, in considering the helicopter environment, both the vibration applied to the pilot and the motion of his instrument panels must be considered.

It is commonly accepted that the eye can pursue the motion of a sinusoidally vibrating object up to about 3 Hz (1, 2). Such pursuit movements are affected by the amplitude of the motion and the size of the target. At slightly higher frequencies the pursuit motion deteriorates rapidly, so that with vibration at frequencies above 5 - 6 Hz the eye is often considered to be stationary. It is primarily this higher frequency range which is relevant to helicopters.

This study has two main intentions. The first is to determine changes of visual acuity produced when viewing a vibrating object and to investigate frequency (with a range 7 to 30 Hz) and amplitude (0.05 to 0.30 ins.) as the major variables. The second intention is to attempt to relate the experimental results to characteristics of the human eye.

A variety of visual test material has been employed in previous studies. In the present study the Landolt C was chosen for measuring visual acuity. This was because common numerals and letters are prone to "re-inforcement" by vibration in certain directions. A sinusoidal vertical motion was employed in this study, since it is necessary to understand the changes involved under these conditions, before investigating the effects of more complex wave forms and multi-axial vibrations.

Throughout this report all references to amplitude of vibration are in terms of the double amplitude (i.e. peak to peak displacement).

1.1 Previous Studies

The field of human response to whole body vibration has been investigated by many researchers. A recent survey on the subject contains no less than 576 pertinent references (3).

In the study of the visibility of vibrating objects the research of Crook has been largely dominant (ref. 4a, b, c, d and e). It is interesting to note that although these reports are among the most well known they are among the most difficult to acquire. For this reason a detailed summary has been prepared.

1.1.1 Crook, M.N. et al.

A. Introduction

The main report (4a) represents the results of three final experiments on the legibility of printed numerals as a function of type size, brightness and amplitude of vibration. In exploratory studies similar experiments were performed and also one on visual thresholds for perceived vibratory movement. An optical (apparent) method of vibrating the object was used throughout since this method was considered to afford greater control over the experimental conditions.

B. Exploratory Experiments

In these experiments the task was a "same or different" judgement of 180 pairs of digits. A vibration frequency of 9 Hz was chosen.

Expt. One. The double amplitude of horizontal linear vibration was varied from .008 to .08 inch and brightness from 1 to 12 ft-Lamberts. There was a significant increase in time, but not error, scores with increasing amplitude. Brightness had no significant effect.

Expt. Two. Vibration amplitude was varied from .008 inch to .024 inch and type size from 6 to 11 point*, at a constant brightness of 14 ft-L. Neither amplitude nor type size had a significant effect on either time or error scores.

Expt. Three. This was a repeat of the conditions of experiment two, but with type inverted. Time and error scores now increased with decreasing type size, while the effects of changes in vibration amplitude did not have a significant effect.

Expt. Four. A combination of unfavourable values of the three variables (e.g. small type size, low illumination and high amplitude vibration) was compared with a favourable combination. There was a significant increase in time and error scores.

A faster motor was then installed, as the experiments had been performed at the "... unrealistically low vibration frequency of 9 Hz...".

Expt. Five. Frequency was varied from 9 to 30 Hz using the same favourable and unfavourable conditions as Expt. Four. Significant increases in time and error scores were noted with an increase of frequency, more so with the unfavourable conditions. The time and error increases were greater from 9 - 15 Hz than 15 - 30 Hz.

Expt. Six (a). Circular, elliptical and linear vibrations were compared at 23 Hz. Form had a small effect on error score, at a lower level of significance than the effect of vibration amplitude.

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* Type size: 1 point = 0.013837 inches.

Expt. Seven. White on black printing was compared with normal type, but no significant difference was found.

Expt. Eight. Type was set close so that overlap of adjacent digits would occur during vibration. The results indicated that vibration overlap is a minor factor compared with, say, brightness.

Expt. Nine. Numerals were set with an increased type density, but avoiding overlap. The results again showed no significant effect.

Expt. Six (b). A mean amplitude threshold in the neighbourhood of .0056 in. was found for perception of vibration at 14 ins. from the eye. This was dependent upon brightness and frequency. The threshold was considerably below the values necessary to produce measurable impairment of legibility under similar conditions.

Crook concludes "... any one of the three aspects studied (amplitude, brightness and type size) could vary over a considerable range without having a significant effect on performance, so long as the other conditions remained favourable". When more than one condition became unfavourable, the performance was significantly impaired.

C. Changes before main experiment.

Crook then concentrated on the effects of brightness, type size and amplitude. In particular lower brightness levels were employed. Frequency was set at 17.5 Hz as being approximately similar to typical propellor speeds. Any increase in frequency was considered not to radically affect performance. An elliptical vibration form was chosen. The "same-different" task was replaced by a simple addition task requiring a "right-or-wrong" reply. No attempt was made to simulate flight conditions, except where it arose when choosing procedures.

All subjects had the equivalent of 20/25 vision or better at 14 inches.

D. Apparatus and Experimental Design.

Apparent vibration was produced by rotation, in a vertical plane, of two pairs of Risley prisms (glass discs with faces cut at a small angle) between the eye and the reading material. By adjustment of the prisms, amplitude and form of vibration could be varied. The situation was similar to looking through a tube 3.75 inches diameter and 4 inches long. A face mask was worn by the subjects to ensure alignment with the visual task.

The amplitude of vibration was claimed to be calibrated to within $\pm$ .0001 ins., frequency to within $\pm$ 2% and illumination to within $\pm$ 3%.

Headlight bulbs provided the illumination and the intensity could be varied by the introduction of evaporated metal film filters supplemented by adjustable crossed polaroids. Room illumination was controllable and always lower than the illumination of the task.

The test cards with the addition task were prepared in 6, 7, 8 and 10 point type. Results of the trials were recorded on a polygraph for later analysis.

Each trial of 100 items took 2 to 6 mins. with an average of 6 trials per hour. Twelve subjects were used and no subject performed more than five sessions. Before the first experimental session, the subject was allowed as much practice as he required, for the remaining experiments only one further practice trial was allowed.

<u>Expt. Ten.</u> Four type sizes and 6 amplitudes up to .03" were chosen, with illumination and frequency constant at 15 ft-L and 17.5 Hz respectively. Only with the highest amplitude and smallest type was there any claimed increase in time or error score and then this was not statistically significant.

<u>Expts. Eleven and Thirteen.</u> These were devised to check particular points and are of no significance to this discussion.

<u>Expt. Twelve.</u> Four amplitudes up to 0.03", four brightnesses 1-14 ft-L. and 6, 8, and 10 point type were used. For 10 and 8 point type and amplitudes up to .02" there was no tendency towards impairment at any brightness level. However, with 6 point type there was a marked deterioration at large vibration amplitudes and the lowest illumination.

<u>Expt. Fourteen.</u> This was similar to expt. twelve but

with a lower brightness range, .02 ft-L to 0.94 ft-L. Many combinations of brightness and amplitude were exceptionally difficult to see and subjects were allowed to stop if they thought they were going to get no better than chance scores. Progressive impairment as amplitude increased and illumination fell was shown by exceptionally high error and time scores.

E. Significance of results.

Within the realm of 8 and 10 point type size, 1 to 15 ft-L and amplitudes up to .02 inches, no impairment was found at the fixed frequency of 17.5 Hz. Where different experimental conditions overlapped, there was good agreement on error and time scores.

Except for brightness, the effect of any single variable even between extreme conditions is very small. With illumination changes there is a large improvement in performance up to .05 ft-L. The value of such a conclusion about the effect of variables in isolation is limited by the fact that secondary conditions are frequently not optimal. Interactions of brightness and type size, and brightness and amplitude show critical values where an increase of severity of conditions causes a rapid increase in errors and times. A similar effect is found with amplitude and size, for a given brightness, but here small increases of type size rapidly offset any impairment. In the case of all extreme conditions, increases of up to 130% in time and 1100% in error are recorded.

Coerman's work (4) was compared with this experiment. Levels of vibration considered severe under conditions of whole body vibration are well below those of the threshold of object vibration detection. However, a study of the effects on vision of vibrating objects is promoted since the amplitudes of surface vibrations are considerably greater than those experienced, say, through aircraft seating.

The work of Crook and his associates has been long established and is a popular reference. However, it has shortcomings, notably in that the effect of the frequency of vibration is hardly considered either at low frequencies (1 to 5 Hz) where eye pursuit movements are involved, or at higher frequencies (5 to 30 Hz).

1.1.2 Other Studies

The effect of low frequency vibration has been investigated by Drazin (ref. 1) using a dial reading task with optically produced vertical sinusoidal vibrations. Displacement amplitudes were 1, 2 and 4 degrees, with frequencies of 1, 2, 3, 4, 6 and 8 Hz. It was found that as frequency increased, the error score reached a peak of 3 Hz and gradually declined. Below 3 Hz the error score was proportional to the increase in vibration amplitude. At higher frequencies this was reversed, due either to effects produced by partial overlapping of the images or possibly to reduced contrast with the increasing "speed" of the image. Below 3 Hz, eye movements were apparently compulsive when the field of vibration was large. Above 5 Hz there was very little of this compulsion, but some difficulty was recorded in fixating on an intermittent nodal image.

An experiment by Huddleston (ref. 2) is similar to, and in substantial agreement with, the work of Drazin. Movements of subjects' eyes were closely monitored by electro-oculograph techniques, to study further the ability to fixate on a vibrating object and also to investigate the amplitude-phase relationship. It was found that higher vibration amplitudes produced less accurate pursuit with increasing frequency over the range 1 - 3 Hz. High amplitudes were more helpful over the range 5 - 10 Hz, where flickering nodal images of the display could be usefully fixated at excursion extremes. Eye pursuit movements gradually broke down from 1 - 4 Hz, with a decreasing pursuit amplitude and an increasing phase lag. It became easier to fixate on a desired node as frequency increased, particularly above 5 Hz.

Although Dennis (refs. 5,6) was mostly concerned with whole body vibration, he has compared this with the effects of vibrating visual fields. A range of 5 - 27 Hz was investigated, with a constant acceleration of $\frac{1}{2}$ g., and an illumination level of 0.2 ft-L. Significant increases of time and error scores were found only in the range 5 - 10 Hz. Above this frequency the amplitudes had decreased to below the threshold values as determined by Crook and no significant impairment was found. For the same conditions of amplitude and frequency he concluded that below 10 Hz object vibration gave greater impairment than whole body vibration, but above this frequency the converse was true.

Two further experiments were performed, at 6 and 19 Hz to verify his comparison with whole-body vibration. At 6 Hz, with a range of amplitudes .05, .07 and .09 inches all errors and times were greater for object vibration than whole body vibration. However, at 19 Hz, .007 inch head movement produced greater impairment than object vibration of .012 in.

These results in the range 5 - 10 Hz confirm Guignard and Irving's findings (ref. 7) than compensatory eye movements elicited by labyrinthine stimulation during whole-body vibration are more effective than eye pursuit movements of the oscillating target. With vibration of the head, it is suggested that above 10 Hz resonances of facial tissues etc. have an increasing effect on visual performance. However, nodal images (and particularly the reduction in amplitude, at constant acceleration, as frequency is increased) to some extent aid vision of a vibrating field as the frequency is increased.

In a whole body vibration experiment, Rubenstein and Kaplan (ref. 8) looked at target vibration for comparison purposes. No large change of visual acuity was found for vibrating objects in the range 13 - 52 Hz at .03 cms displacement. Within this range the decrement in visual acuity was more marked for head vibration.

The effects of whole body vibration upon visual acuity will be discussed more fully in a later report.

2. EXPERIMENTAL APPARATUS

2.1 Design of the "72" cards

Of the common forms of acuity testing, the Landolt C is one of the least liable to visual interference, or reinforcement, during vibration. Even so, it is necessary for the vibration to be along the top-bottom axis of the C, to avoid the gap appearing as a streak. The test material used consisted of 72 black Landolt C's produced photographically on cards (72 cards) approximately 5 inches square.

The layout of Landolt C's was required to balance the following requirements:-

(a) incorporate as many sizes of test objects as possible;

(b) incorporate a maximum number of test objects;

(c) ensure that under all vibration conditions no image overlap occurred either with other letters or with any boundaries of the card;

(d) that the letters could be grouped to ensure that all subjects could read the card in a variety of prescribed methods.

The form of the card layout is depicted in fig. 1 and shows three sizes of the Landolt C, each arranged in two groups of twelve. Within each group of 24, the directions the gap faced were randomly arranged, with half the gaps facing left and the other half right.

In experiment A the sizes of the Landolt C chosen were

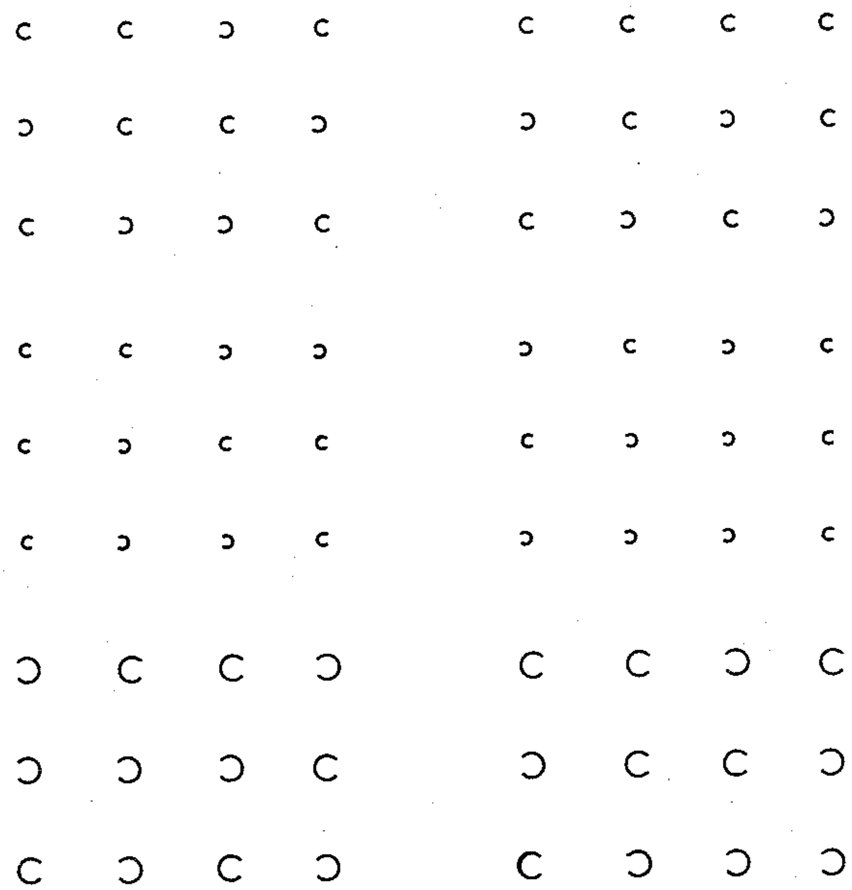

Fig. 1

6/4, 6/6, 6/9 and for the other two, experiments B and C, they were 6/4, 6/5, 6/6. Two different cards were produced for experiment A and four different ones for B and C. The sizes of the gaps in the Landolt C's are shown in Table One.

Type of Landolt C	Nominal Size of Gap m.m.	Actual Gap Size m.m.
6/4	0.167 m.m.	0.170 $\pm$ 0.01 m.m.
6/5	0.208 m.m.	0.215 $\pm$ 0.015 m.m.

Table One: Measured size of Landolt 'C' gaps for Experiments B and C.

2.2 The Vibrator

A Derritron VP4 (0.4 inch stroke) electromagnetic vibrator was used. It had a permanent magnetic field and generated a vector force of 24 lbs (11 kg). The vibrator was driven by a combined oscillator and amplifier unit, manufactured by Derritron Electronics Ltd., with 100 watt r.m.s. output.

The oscillator was calibrated at the frequencies to be used during the study by using a self-calibrating stroboscopic light. Settings could be repeated consistently, without stroboscopic aid to within 4% at 5 Hz and 0.6% at 30 Hz. Maximum distortion of the vibrator displacement waveform occurred at 5 Hz and was less than 2%.

2.3 Amplitude measurement

The transducer used to monitor the vibration was mounted on the base of the card holder. It was an Ether BLA-2 accelerometer which is of the cantilever resistive strain gauge type.

The sensing system was calibrated by recording the output when the transducer was turned from upright to the inverted position (i.e. from + 1g to - 1g). This was checked between each group of experiments and once during each. The transducer signal was amplified by a preamplifier having a gain of 33.

During the calibration of the transducer it was determined that the response of the amplifier circuit was effectively flat over the range 5 to 40 Hz.

2.4 The Booth

The main functions of the booth were to reduce the field of view and limit the number of visual distractions. The front of the booth was hardboard with a rectangular viewing aperture approximately 10 ins. x 9 ins. (25 cms. x 23 cms.). A black curtain was suspended from the ceiling, to provide sides and back. Not only did the curtains reflect very little light, but they provided a non-distracting, out-of-focus background to the 72 cards. Curtains near the side of the card were obscured by the aperture. Further black material covered the base of the vibrator. Thus the field of view was limited to the card holder, with a rather diffuse background and no obvious distractions.

The Osram studio lights were mounted inside the booth, pointing at the face of the 72 card at approximately 45° to its plane. A black sidescreen was mounted between subject and experimenter, so that the latter could control the experiment with additional lighting without distracting the subjects.

A headrest was incorporated such that its height could be adjusted to suit individuals and maintain their heads at 1 metre in front the test material. The centre portion of the headrest was padded for comfort.

2.5 Shutter

To ensure that the 72 cards were not seen other than during a trial, a plate shutter was incorporated. It rotated about an axis along its top edge by means of a simple crank mechanism.

Semi-matt paint was applied to the face of the shutter, and on this was fixed the rating scale such that it was visible to the subjects whilst the shutter was closed between conditions.

2.6 Illumination

Illumination levels were determined using a Lightmaster Photometer, manufactured by Evans Electroselenium Ltd. The absolute measurements given may be considered accurate to within about 15%. Measured values of illumination are tabulated below:

Illuminated object	Illumination, lux
"72" card	4,100
Card holder	240 - 1,200
Black curtain	10 - 25
Snellen test card	1,350
Other surrounds	below 10

Table Two: Table of Illumination Values

2.7 Reading distance

Ohlbaum and O'Briant (9) have reported that deterioration of visual acuity under whole body vibration is dependent on viewing distance. Logical considerations suggest that this is also likely to be so of object vibration. For this study, one metre was chosen as representative of instrument to eye distances in many aircraft.

2.8 Timing method

In preliminary trials it was found that there was a pause of two to eight seconds from when the shutter was raised to when the subject started "reading" (i.e. called the direction the gap was facing for the first Landolt C). This pause reduced as the subject became more familiar with the experiment. In order to eliminate this variable it was decided to commence timing at the first call of direction and to finish at the last call.

The time taken was measured using a stopwatch and was recorded to the nearest 0.5 second.

3. EXPERIMENTAL METHOD

3.1 Trials

A trial starts when the reading instructions are given and ends when the subject makes his rating. During a trial the sequence of events was:- method of reading given by experimenter, acknowledged by subject; shutter opened; subject read the twenty-four Landolt C's; shutter closed and subject gave his rating of the task difficulty. There were two trials at each frequency-amplitude combination, one for reading the smallest size of Landolt C, the other for reading the next in size.

3.2 Experimental runs

The complete collection of trials for a single subject is called a run. In Experiment A a run consisted of thirty-six trials for each subject; Experiment B consisted of two runs, each of twelve trials; and Experiment C two runs, each of sixteen trials.

3.3 Experimental design.

The first group of Experiments, A, was conducted to explore the available range of frequencies and amplitudes of vibration, and to determine the changes of visual performance over these ranges. Three amplitudes with six frequencies at each were chosen. From the results of Experiment A it was decided to perform two further experiments. The first of these, Experiment B, investigated the changes of performance with amplitude at a constant frequency of 16 Hz. The second, Experiment C, investigated these changes with frequency at a constant double amplitude of 0.1 inch.

3.3.1 Vibration conditions.

The tables below show the frequency and amplitude combinations used in each of the experiments:-

Experiment A

Double Amplitude, Inches.	Frequency, Hz.					
0.20	5,	7,	10,	12,	15,	20
0.10	7,	10,	12,	15,	20,	30
0.05	10,	12,	15,	20,	30,	40

Experiment B

Frequency, Hz.	Double Amplitude, inches
16	0.05, 0.075, 0.10, 0.15, 0.20, 0.30

Experiment C

Double Amplitude, Inches.	Frequency, Hz.							
0.10	5,	7,	10,	12,	16,	20,	25,	30

Table 3. Frequency and amplitude combinations for all three experiments.

In the second and third experiments, each vibration condition was investigated twice.

3.3.2 Order of presentation.

In all of the experiments the frequency-amplitude combinations were presented in a random order. Each subject was allowed a practice before each experimental run, but to allow for any variations associated with the order of vibration conditions each was given a different practice sequence.

3.3.3 Changes of 72-card.

For Experiment A, the two cards were interchanged after every pair of trials. Four cards were used for Experiments B and C and these were changed in a random order at the same intervals.

3.3.4 Duration of trials.

For any individual setting of amplitude and frequency, two trials were made, one trial reading 6/4 Landolt C's, the other for the 6/5 size. Trials lasted from 13 to 47 seconds with a gap of approximately 20 seconds between them. Resetting the amplitude or frequency and, every second time, changing the test card, took approximately 40 seconds. Thus although the experiment took 30 to 40 minutes there was sufficient time between trials to allow subjects to relax.

3.3.5 The task and the recorded variables.

The subjects' task was to state the direction the gap was facing, left or right, for each C in a group of twenty-four.

The next performance indicator chosen was the time taken to read the twenty-four C's. The time taken to read a group of twenty-four C's with no vibration was considered to be the minimum time required by the subject. Any increase in this time was taken as an indication of the increased difficulty in reading when the test card was vibrating. While, for example, only two C's may give rise to the error score in a trial of twenty-four C's, each of the twenty-four may add to the increase in time.

Subjective rating was chosen as a supporting measurement in order to give some indication of the subjective difficulty of the reading task. A visual display of the rating scale was presented to give subjects a reference for their ratings and thereby help stabilise their assessments.

A numerical scale, in unit steps from 0 to 10, 'no difficulty' to 'extreme difficulty' was chosen. It was displayed on the face of the shutter, so that it was in view

0 1 2 3 4 5 6 7 8 9 10

No Difficulty — Extreme Difficulty

Fig. 2. The rating scale

immediately after each trial, when a rating of that trial was required.

3.3.6 Subjects

In the preliminary Experiment A, six subjects were used. For the second and third experiments four of the original and four further subjects were used, making a total of eight subjects for both Experiments B and C.

Subject	Experiment			Male/ Female	Age	Status	Snellen Acuity		Colour Test	Maddox wing	
	A	B	C				Left Eye	Right Eye		Horiz.	Vert.
B.M.		X	X	M	19	Student	6/5	6/5	All Satisfactory	0-2	0
M.F.		X	X	M	22	Research	6/4	6/4		2-4	0
D.R.		X	X	M	18	Student	6/4	6/4		0-2	0
E.A.	X	X	X	M	25	Research	6/4	6/4		0-2	0
J.W.	X			M	30	Research	6/5	6/4		2-4	0
R.S.	X			M	26	Research	6/5	6/5		0-2	0
J.G.	X	X	X	M	20	College	6/4	6/4		2	0
A.G.	X	X	X	M	22	Student	6/4	6/5		0-2	0
S.M.	X	X	X	F	19	College	6/5	6/4		0-2	0
P.M.		X	X	F	21	Student	6/4	6/4		0-2	0

Table 4. Subject Details and Preliminary Visual Tests

3.4 Experimental preliminaries.

Every subject was shown the apparatus so as to be familiar with its operation. They were then asked to read the instruction sheet, a copy of which is in Appendix One. Following this they were showed a "72" card similar to the ones to be used during the experiments. The manner of reading the card was carefully explained.

Three checks on eyesight were made before the experiment to check each subject's suitability for the experiment. The items checked were visual acuity at 6 metres, muscle balance and colour blindness. These three were the minimum suggested by The Eye Hospital, Southampton (10).

Preliminary vision tests

Snellen acuity test. A two-sided Snellen chart was used for testing each of the subjects' eyes in turn. The chart was well illuminated, such that it had a luminance of 1350 lux and was placed 6 metres in front of subjects.

Ishihara colour vision test. A shortened form of the Ishihara test for colour blindness was used. This was intended as a check rather than for diagnosis, and would only detect the commonest form of colour blindness, red-green blindness (xanthocyanopsia).

Maddox wing test. The extrinsic muscles of the eye act in pairs, the most used are the internal and external rectus pairs for changes of convergence from far to near objects. If they are not in complete balance then, when the number of visual clues are reduced, the eyes may have difficulty in converging on an object. This is called exophoria, and is best demonstrated by the Maddox wing test. Up to five units of exophoria is generally allowed before correction. The same test can be applied vertically, and one unit out-of-balance then requires attention.

After satisfactory completion of the preliminary checks, the subject was seated in front of the booth. During each trial he was required to rest his forehead against the padded portion of the head rest, such that the distance from the card to his eyes was one metre. When he was not reading the "72" card, the subject could relax and sit back.

3.5 Experimental Environment.

The background noise level in the experimental situation was generally low. Although asked during the experiment, none of the subjects thought any of the noises to be distracting.

The laboratory was part of a centrally heated building and the normal room temperature was approximately 20°C. No subject reported feeling any vibration transmitted to his body.

4. RESULTS

4.1 Experiment A

The first experiment was intended solely to explore the vibration frequency and amplitude ranges. Each experimental value was convered once for each of six subjects. As such the results will be discussed briefly.

Error and frequency.

For each of the three amplitudes the error score increased with frequency.

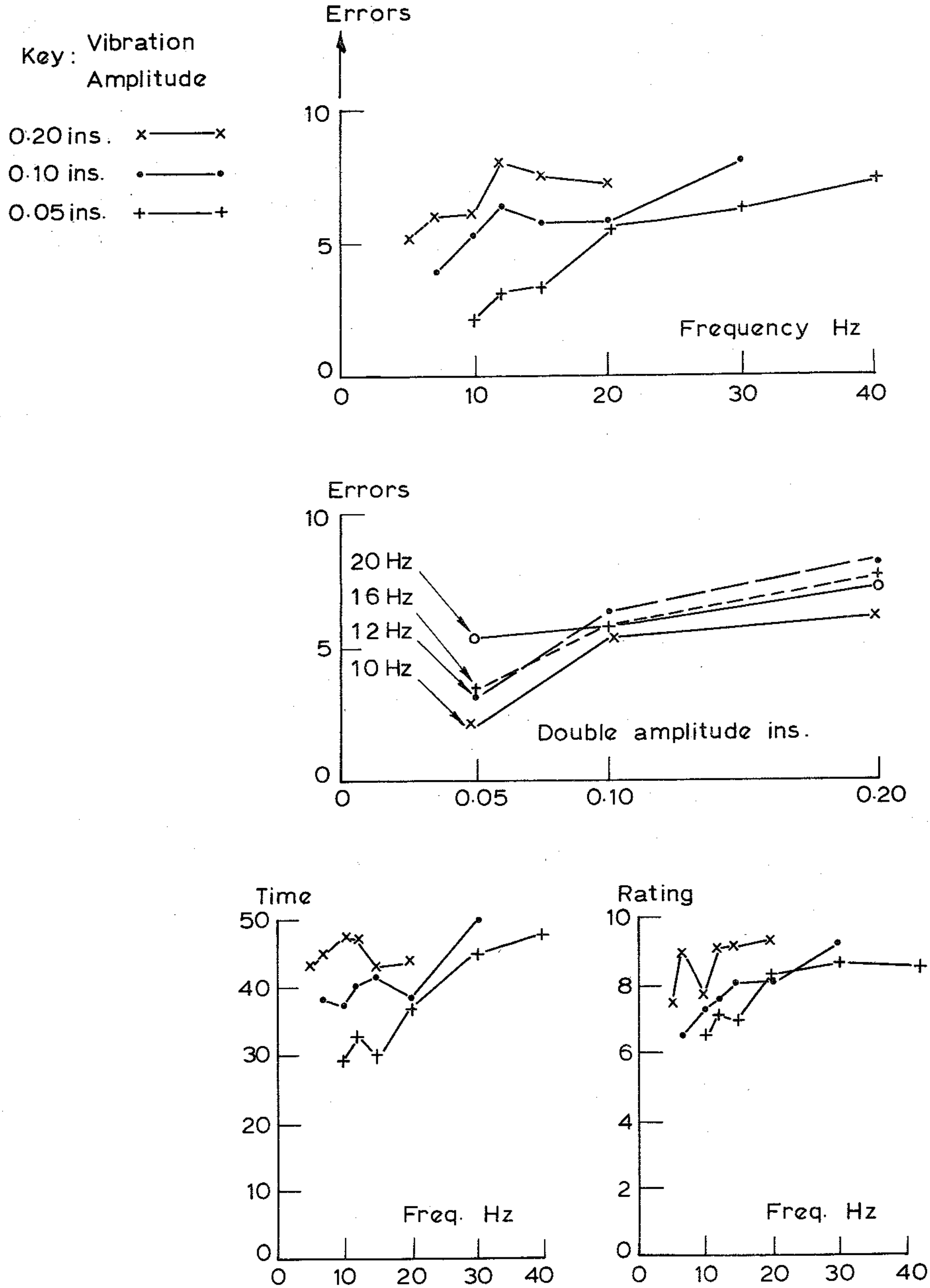

Fig. 3 Experiment A, Summary graphs.

Error and amplitude.

The relationship between error and vibration amplitude was considered using the four common frequencies (10, 12, 15 and 20 Hz). It appeared that error increased with amplitude for a constant frequency.

Reading time

For the two smaller vibration amplitudes time increased with increasing frequency. There was no such trend for the 0.20 in amplitude. Generally, a longer time was taken for the larger vibration amplitudes.

Rating

In all cases the subjective rating of difficulty increased with frequency and was generally higher for the larger vibration amplitudes.

Comparison between 6/4 and 6/6 scores.

In all cases the error scores were greatly reduced with the larger test object, as were times and ratings. The effects of frequency and vibration amplitude were similar, although the overall changes were reduced. The results for 6/6 are not shown.

4.2 Experiment B

The second experiment studied the effect of double amplitude (0.05 to 0.30 in.) at the constant frequency of 16 Hz for 8 subjects.

Error and amplitude.

A linear plot of error against amplitude gave a smooth curve. Using the method of least squares it was determined that error score, E, was proportional to the square root of the double amplitude, a; more precisely:

$$E = 15.7 \sqrt{a} + 0.45$$

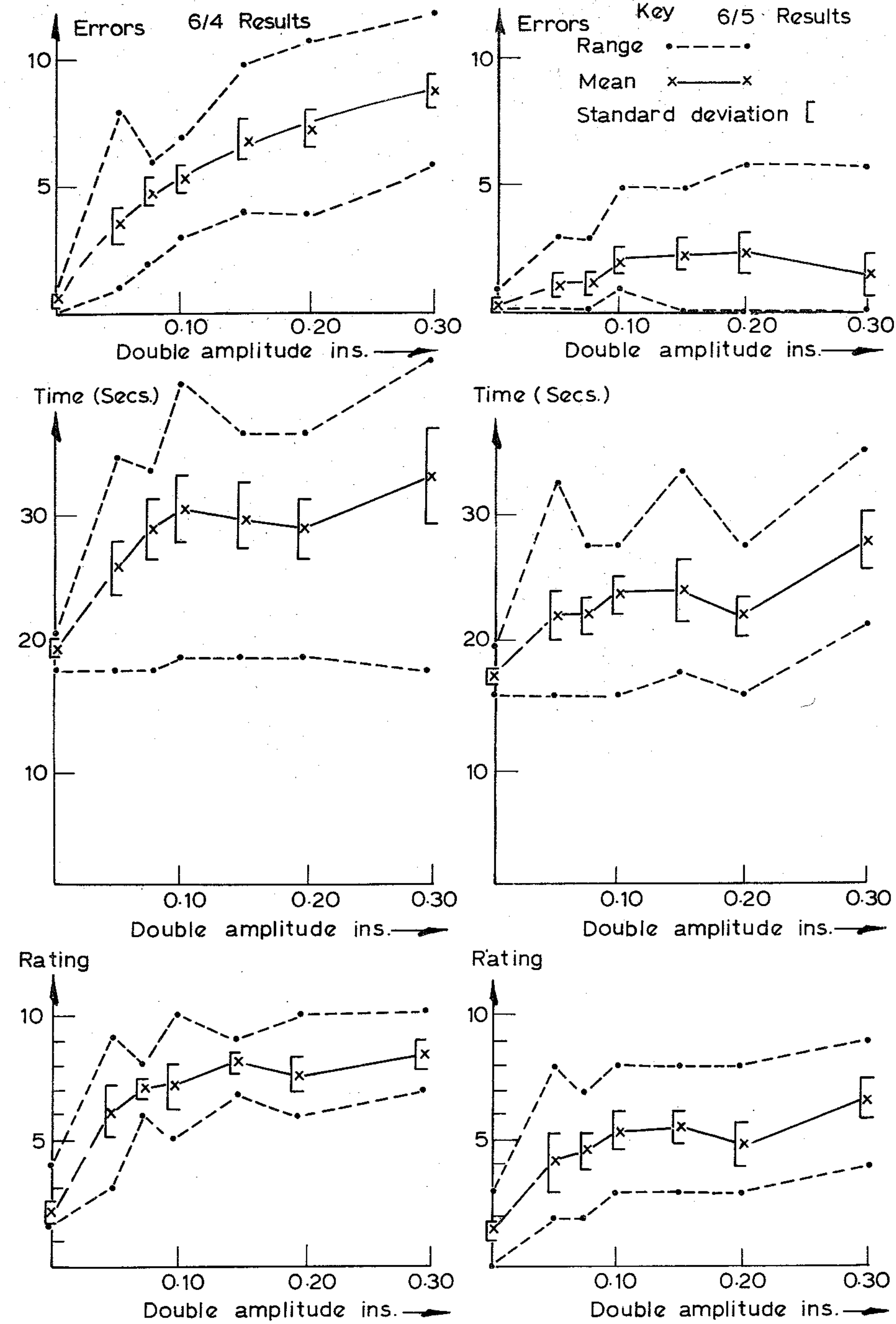

Fig. 4 Experiment B - Means, ranges and standard deviations of errors, time, ratings.

A linear regression analysis was performed on the data and gave a correlation co-efficient of 0.995. The intercept of this line with the zero vibration condition was at 0.45 errors, whereas the experimental value was 0.62. This point was not included in either of the statistical calculations since at lower vibration amplitudes the nodal images of the Landolt C will overlap, which could effect the detection of the gap. Also Crook (4e) has demonstrated that there is a vibration perception threshold and that this threshold is considerably below the value necessary to produce measurable impairment of legibility.

There was no observed trend in the range of error scores recorded at each amplitude but there was a slight rise in the standard deviations as amplitude and error score increased.

For the larger Landolt C's (6/5) the error scores were considerably reduced. Generally they were 30 to 50% of the error score of the 6/4 size for the same condition. Thus, a marked improvement was shown for only a 25% increase of gap size. The results from 0.05 in. to 0.20 in. followed the same trend as the 6/4 results, but at 0.30 in. the error score dropped noticeably. The standard deviations of error scores for the 6/5 size were of a similar magnitude to the error scores themselves. With such a large scatter, calculation of a least squares straight line would have been of little value.

Reading Time and Amplitude

There was a steady increase in the reading time except at 0.20 in. where there was a reduction of about three seconds, about 15%. This dip was also reflected in the subjective ratings at this point, but not in the error scores.

The greatest increase in time was from zero vibration to 0.05 in., this being of the same magnitude as the time increase from 0.05 in. to 0.30 in. This was also reflected in the rating scores. Thus even small amplitudes of vibration at 16 Hz would appear to have slowed the reading task. Again there was no trend in the ranges of reading time, but there was an overall increase in their standard deviations, with increasing amplitude.

A very similar trend was shown for nearly all the points for the 6/5 results, but the times were reduced by an average of two to four seconds. Again, the dip in time and rating scores was noted at 0.20 in.

Rating and Amplitude

Again there was a steady increase in the difficulty-rating score with the larger amplitudes. This was marred only by the dip at 0.20 in. Both ranges and standard deviations decreased with increasing vibration amplitude. This is probably a characteristic of the fixed ceiling to the rating system. It will be recalled that time scores increased most from the zero vibration condition. This increase was more marked with ratings where the initial jump was much larger than the change of rating between the lowest and highest amplitudes.

The above trends are reflected in the 6/5 scores, which were two to three units lower on the difficulty-rating scale. Again the largest increase was from the static condition to 0.05 in. amplitude.

4.3 Experiment C

The third experiment studied the effect of frequency (5 to 30 Hz) at the constant double amplitude of 0.1 in, for 8 subjects.

Error and Frequency

A linear plot of error against frequency gave a straight line so a linear relationship was assumed. The exact value was found

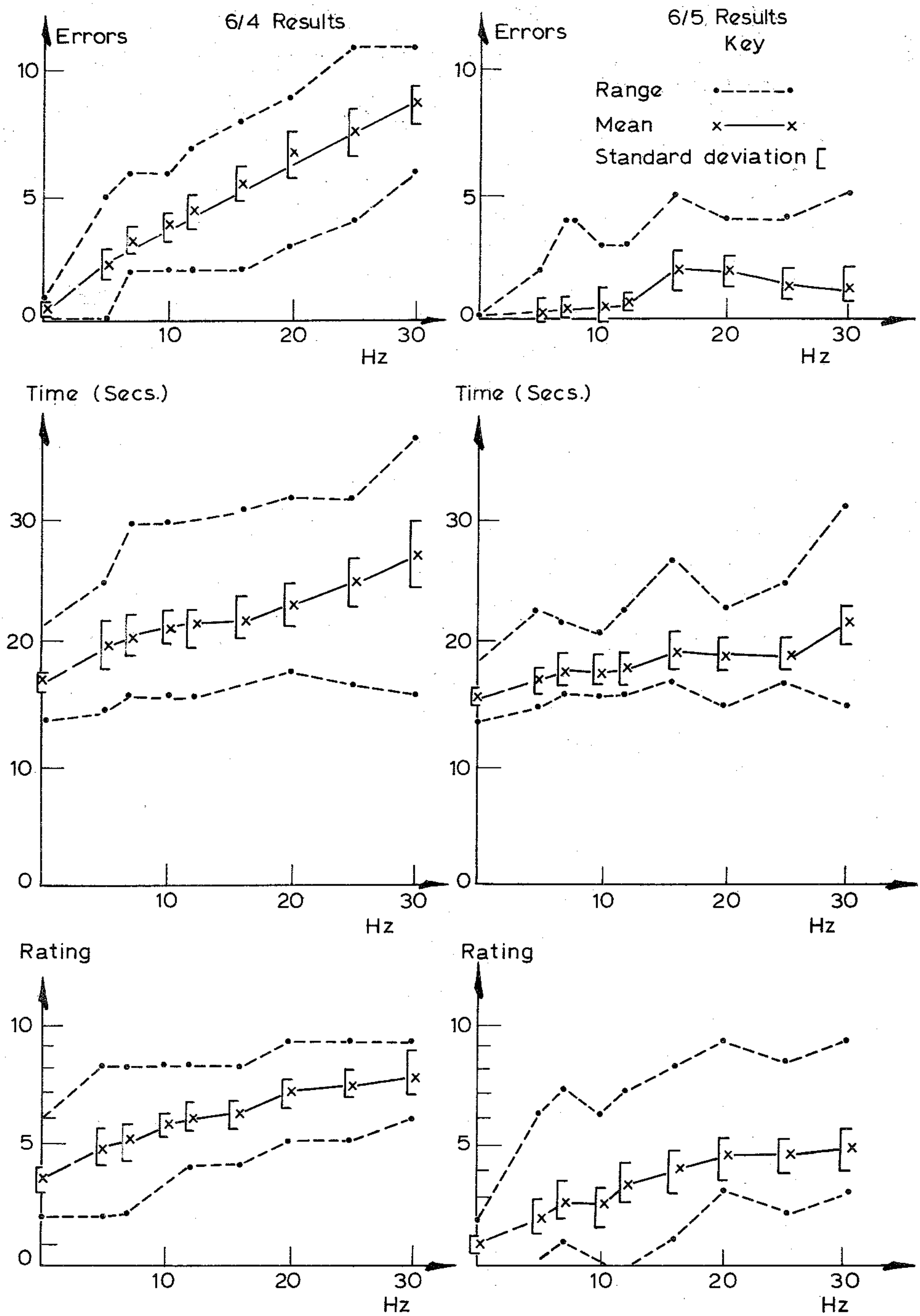

Fig. 5 Experiment C - Means, ranges and standard deviations for errors, time and rating.

by the method of least squares:

$$E = 0.25 f + 1.36$$

where 'f' is the frequency of vibration. The correlation coefficient was 0.98. As before, the static condition was not included in the calculation, since below 5 Hz the situation will change when it is possible for the eye to follow the moving object.

From 7 to 30 Hz there was a gradual increase in the range of scores and their standard deviations. Both of these increased noticeably at 5 Hz. At this frequency some subjects commented that they felt something urging them to follow the C at which they were looking.

The trend of the6/5 error scores followed the pattern as for 6/4 up to 20 Hz. Above 20 Hz the errors reduced noticeably. This will be discussed later.

Where the vibration conditions of experiments B and C intersect,at 0.1 in. and 16 Hz, and at the static condition there is close agreement both for the 6/4 and 6/5 error scores. Additionally, at the points where they may be related, the error scores of Experiment A come close to those for B and C.

Reading Time and Frequency

A very steady increase of reading time with increasing frequency was noted. Standard deviations and, to a limited extent, the ranges of times increased with frequency.

Again the trends of the 6/5 results follows those for the 6/4 times, but the times were four to six seconds quicker.

Between Experiments A and B there was a drop of from eight to ten seconds in the reading times. A similar drop was observed (at 0.1 in. and 16 Hz) between Experiments B and C. Individual times showed no marked change between the first and second runs within either experiment. It was assumed then that subjects had approached the final experiment with less "foreboding" than previous ones. When approached later none of them recalled having consciously gone faster. This trend was also reflected in the rating scores. The time and rating scores in these experiments must not then be used out of context.

Rating and Frequency

Again a steady increase in the difficulty-rating was noted with increasing frequency. Standard deviations reduced very slightly, and ranges considerably as frequency increased. This again indicates the effect of a fixed maximum value of the rating.

The trends of 6/4 results is followed by those for the 6/5 ratings.

When Experiments B and C intersect (at 0.1 in. and 16 Hz) the ratings were slightly lower for C. However, the main interest is not with the magnitude of the rating, but with the way this changes with the experimental conditions.

4.4 Inter-relationships of reading time, error and rating.

Graphs of time and error; rating and error; and time and rating were constructed. Although each of them showed a band of results (Fig. 6a and 6b) the following trends for 6/4 and 6/5 values in Experiments B and C were noted.

Time and error: As errors increased so did the time taken.

Rating and error: As errors increased so did the difficulty rating given.

Time and rating: As time increases so did the ratings. This was expected since the harder the task appears to the subject the slower he would go.

Two examples of these graphs are shown in Figs. 6a and 6b.

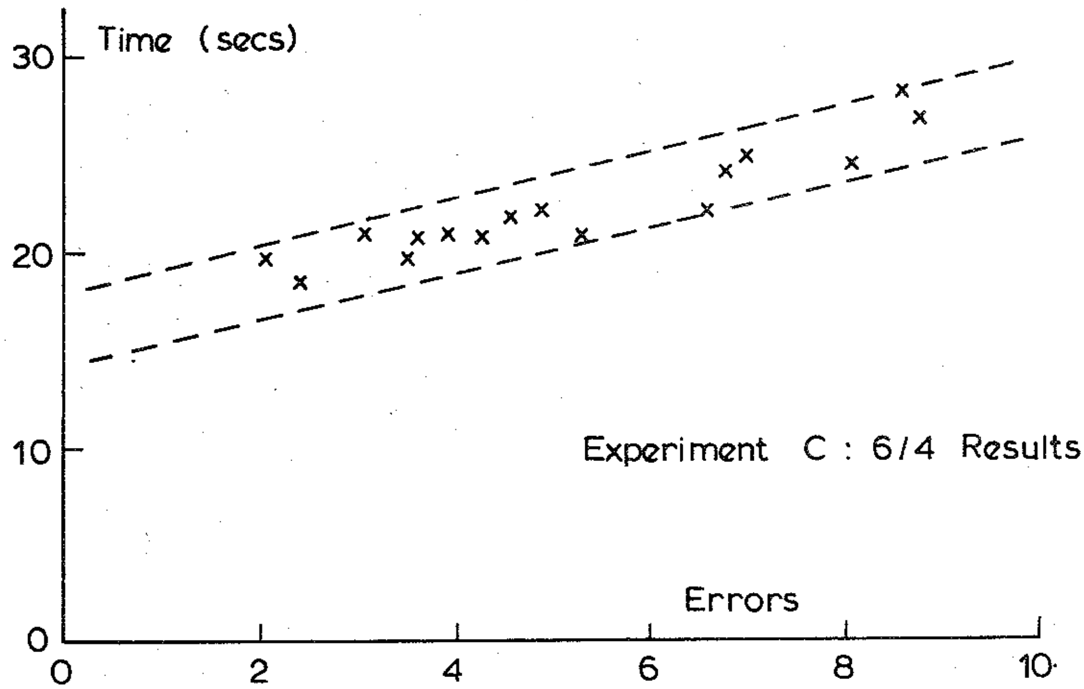

Fig 6a

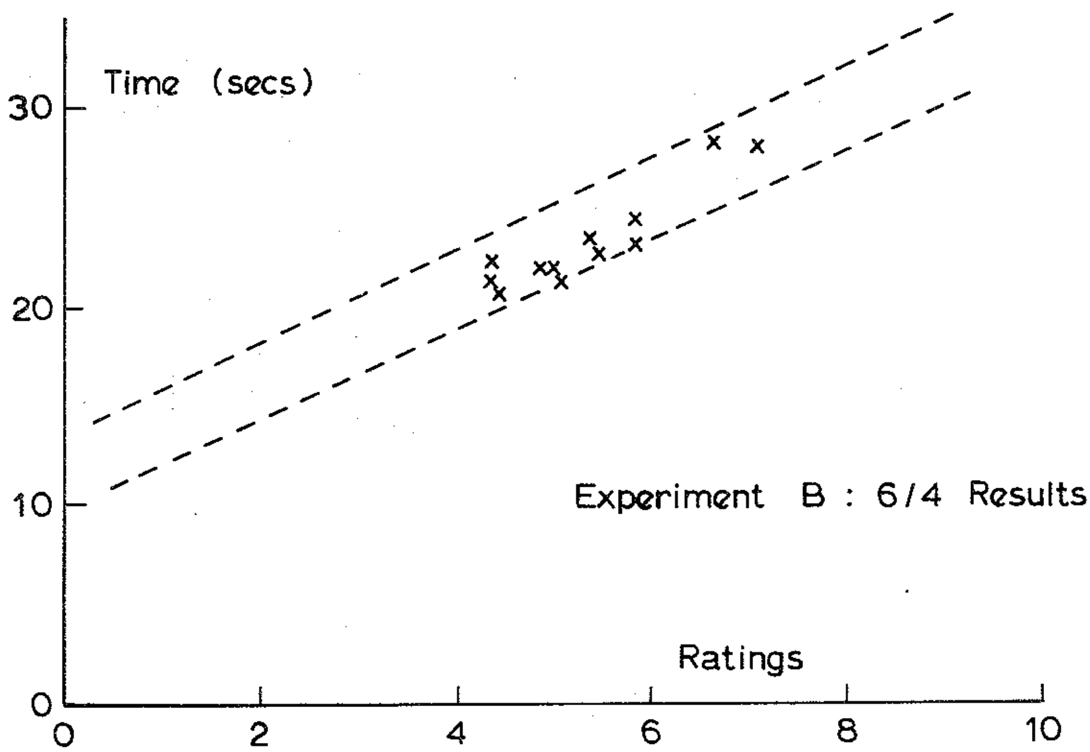

Fig 6b Time, error and rating relationships

It is significant to note that points on the error curves for 6/5 values which showed a marked deviation (at high frequencies and amplitudes) were in normal positions on the time and rating scales, and vice versa. It would appear that when the vibration appeared to be more severe the subject took longer and rated higher, whilst in fact making fewer errors. It would require detailed investigation however to show the real significance of this behaviour. When subjects are allowed to pace themselves it does therefore appear that it is necessary to monitor, as well as possible, the three parts of the scoring system:

(a) the accuracy of performance;

(b) the speed of the performance;

(c) the subject's impression of task difficulty.

4.5 Individual Behaviour

Only two subjects showed any general tendency to trade accuracy against time taken during Experiment B. One subject took longer (PM) whilst being more accurate, the other (JG) took the opposite alternative. The same two subjects repeated their approach in C. Subject BM gave consistently higher than average ratings in both experiments. Very low times were recorded by MF for both experiments.

Experiment B:- Three subjects showed a marked dip in both time and rating at 0.20 in. There was little or no dip in their corresponding error scores. This dip was also witnessed in their 6/5 scores for both time and ratings. There was no other common variation.

Experiment C:- There was no common variation of the sort found above.

5. DISCUSSION

5.1 Model of the viewing mechanism

The eye is considered to be stationary when viewing an object vibrating at a frequency above 7 Hz. When the eye is determining the position of the gap in the Landolt C it "looks" first at one side and then the other. In this search the main area of interest is reduced to a very small area in the centre of the fovea; say, a circle of diameter 'd' (Fig. 7a). The image on the retina of the 6/4 size C covers an area about 8 to 10 cone units across and so 'd' is about 3 to 4 cones. In Fig. 7 the eye is looking at the top nodal image of the C vibrating at frequency 'f', and the area G is stationary (i.e. the eye is not moving). The passage of the C into the area, stopping and then passing out may be represented on a simple harmonic motion model (Fig. 7b). The diameter of the area G is 'd', and 'h' is the single amplitude of motion of the image on the retina (and hence directly related to amplitude of motion of the vibrating object). The arc CAD is that associated with 'd', and 'p' is the enclosed angle.

It is proposed that the ability of the eye to distinguish the presence of the gap is related to the time taken for the gap to pass through the area G. From Fig. 7b the time for the gap to pass through G is:

$$T' = \frac{1}{f} \times \frac{2p}{2\pi} \qquad \ldots (i)$$

Geometrically, $\cos p = 1 - \frac{d}{h}$

But using the algebraic expression for $\cos \theta$

$$\cos p \simeq 1 - \frac{p^2}{2} \quad \text{if } p \text{ is small}$$

and so $$\frac{d}{h} \simeq \frac{p^2}{2}$$

Subst. into (i) $T' \approx \dfrac{1}{\pi f} \; \dfrac{\sqrt{2d}}{\sqrt{h}}$

thus $T' \propto \{ \dfrac{1}{f} , \dfrac{1}{\sqrt{h}} \}$ for small d in relation to h.

If then, this time and the error are related inversely (i.e. as the time is reduced and the chance of seeing the gap is also reduced, with a linear relationship between these two, then the error would be increased) then:-

$$\text{Error} \propto \{ f , \sqrt{h} \}$$

This is demonstrated by the relationships given earlier (sections 4.2 and 4.3), but for several reasons the hypothesis is very tentative and certainly in need of further investigation.

5.2 <u>Consideration of flicker</u>

A diagramatic representation of the passage of the image of the Landolt C over one cone, near to the nodal position of the image, is shown in Fig. 7c. The response of the cone, signalling white or black, during this part of the cycle is also illustrated. Thus the passage of the black and white interfaces over the cone will give a flicker sensation. The speed of this flicker depends not only on the speed of the gap over the cone, but also the time represented by length KL. This in turn is governed by the size of the 'C' (by both the gap size and the curvature).

The example has been presented referring to only one cone. A similar effect would be recorded over neighbouring cones, although for differing durations and intensities.

There is a point when the frequency associated with the passage of the black-white interfaces equals the maximum signal transmission rate.

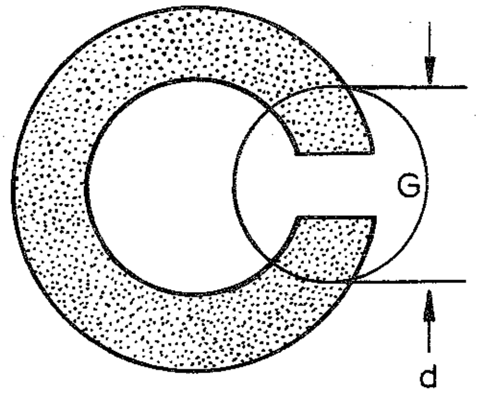

Fig 7a

Gap of landolt C passing through area G at top nodal image

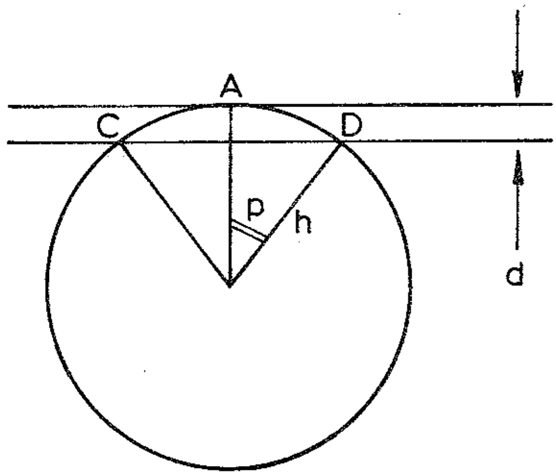

Fig 7b

Simple harmonic representation of fig 7a

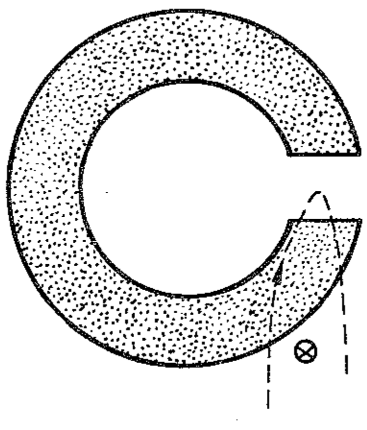

Fig 7c

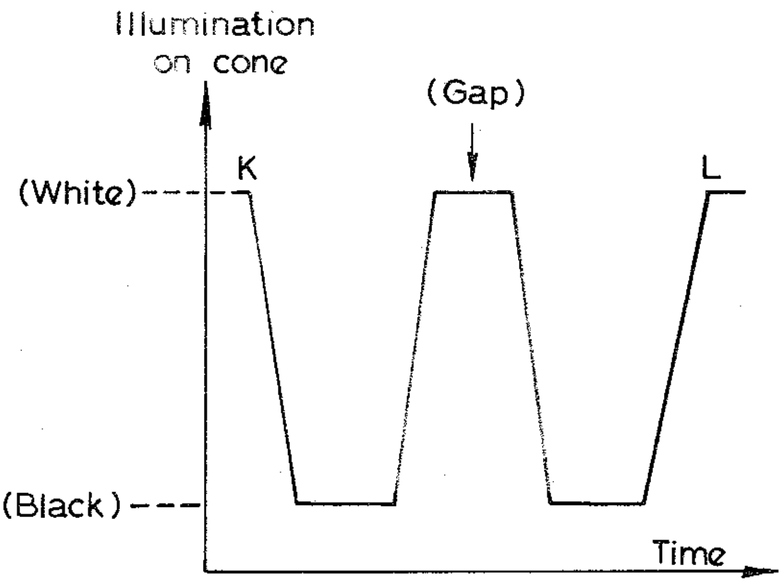

Fig 7d

Fig 7 Gap of landolt C passing over one cone (Top nodal image)

Well below this frequency, the passage of each interface will be observable. The Landolt C can then be observed to be vibrating without the help of other sensory clues. Above this frequency, however, the demanded signal rate is greater than that available. Consequently a time-averaging process will show areas of differing brightness, or contrasts, and the vibrating C will appear much the same as in a long exposure photograph.

It has already been stated that the 6/5 results follow a similar trend to those for 6/4 and that this trend breaks down at both high amplitude and high frequency. This could be due to a complex inter-action of frequency, size, illumination and amplitude resulting in a variable critical fusion frequency (C.F.F.). If this be so it would appear from both 6/4 and 6/5 results that the associated C.F.F. rises with reduced size. This may be a function of the viewing criterion employed, namely detecting the presence of the gap in the C. In other objects, such as printed numerals, these effects may be reduced, or enhanced.

5.3 Frequency ranges

It would appear that there are three regimes in the frequency domain, with three different viewing mechanisms.

Up to about 3 to 5 Hz - fig. 8a

The eye is capable of following the moving object. As the frequency is increased, at a given amplitude, so the errors increase (1). Below 3 Hz pursuit movements are compulsive. From say 3 to 5 Hz this mechanism breaks down with a resultant reduction in the number of errors.

From 3 Hz to approximately 30 Hz - fig. 8b

Above 5 Hz the eye is considered to be stationary. In the range 5 to 30 Hz it has been shown that errors are directly

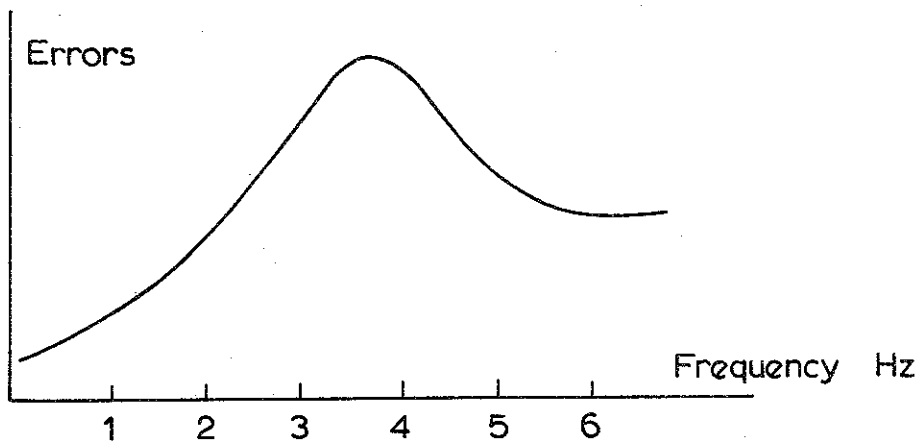

Fig 8a Errors against frequency 0-5 Hz

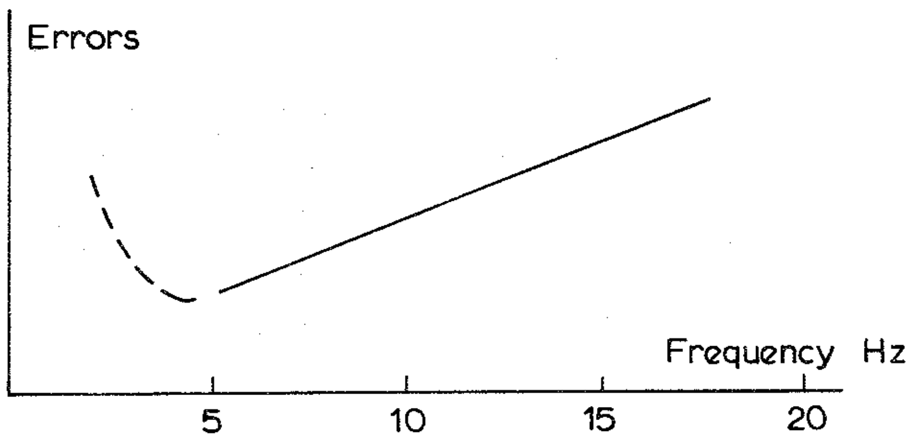

Fig 8b Errors against frequency 5-20 Hz (This study)

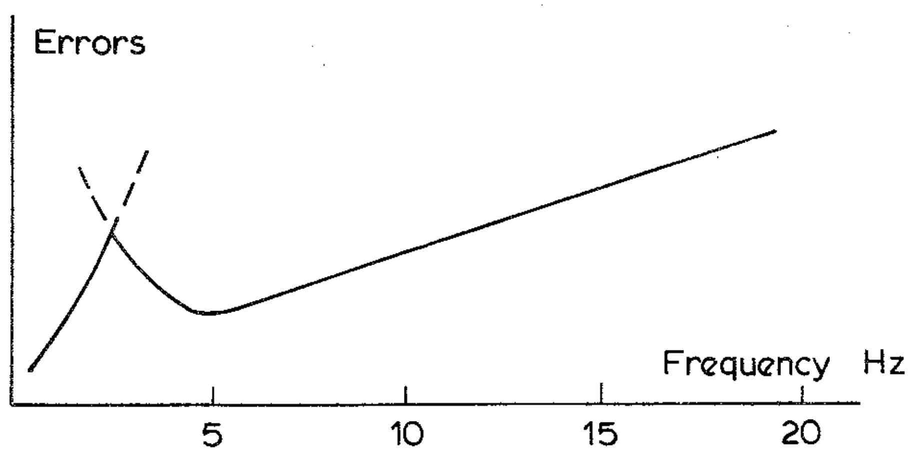

Fig 8c Figs 8a and 8b combined

(Shapes will be dependent on experimental conditions) proportional to frequency for one particular task. Below 5 Hz the time between the images being seen at the nodes increases and so an increase of difficulty in seeing nodal images would be expected. A borderline region where one mechanism supercedes the other must exist, giving a result of the form in Fig. 8c.

30 Hz has been assigned as the approximate upper limit of this range of viewing, since the boundary at the upper end is the C.F.F. The value of the C.F.F. will obviously vary according to conditions.

Above approximately 30 Hz.

This is the region where the nodal images of the Landolt C's have fused and the object is seen as a blur. The viewing criterion is not whether the gap itself is seen or not, but whether the blur on one side of the C appears different to that on the other. Both sets of 6/5 results would indicate that there is a reduction of errors from the flickering, to the blur regime.

6. CONCLUSION

Over the experimental range, changes of acuity were found to be too small to be quoted in normal terms (i.e. a change from say 6/6 to 6/9) and so changes in error scores for 6/4 and 6/5 sizes were found.

It was found that the 6/4 error score was directly proportional to the frequency and to the square root of the amplitude of vibration. Statistical tests showed the relationships to be highly significant. The 6/5 error scores showed a similar trend to the 6/4 results over a limited range of frequencies and amplitudes. The reading time and subjective ratings also increased with both frequency and amplitude for both sizes of Landolt C.

In both of the main experiments the error scores, reading times and ratings were higher for reading the 6/4 than the 6/5 size. This indicated that although the errors increased with increasing frequency and amplitude, the increase was easily offset by a relatively small increase in the size of the object.

It is proposed that in the frequency domain there are three overlapping ranges of viewing mechanisms. The low frequency range gives rise to pursuit movements of the eyes and has been well investigated. There is a high (and variable) frequency above which the object is seen only as a blur by a stationary eye. Between these there is a middle range where the eye is effectively stationary, but it is possible to see the object vibrating.

A simple model for the mechanism for seeing the gap in the intermediate frequency range has been proposed. From this model two relationships were developed and confirmed by the experimental results.

7. RECOMMENDATIONS

7.1 Further Research

The results of any investigation employing a visual task will depend greatly on the nature of the particular task employed. It is therefore desirable to re-establish the results of this study with other commonly encountered visual tasks.

The effects of changing the brightness of the test card, and also the contrast between the object and its background, should be investigated. Additionally, since a significant increase in the difficulty of the task would be expected when the stable nodal images have been eliminated, the effect of multiple frequency and other motions should be investigated.

The results which have been presented should be considered complimentary to current research on visual acuity during whole-body vibration.

7.2 Application of Results

In a situation where a vibration component in the frequency range 5 to 30 Hz is presenting a visual problem, it would be beneficial to reduce both the frequency and amplitude of the vibration. However, this experiment has indicated that a relatively small increase in the size of the visual material will often be a more effective method of reducing the interference.

The vibration of aircraft instruments and dials is rarely either a single axis or single frequency movement. There is as yet no experimental evidence to show how current knowledge is to be modified to fit such situations.

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APPENDIX ONE

SUBJECT INSTRUCTIONS

This experiment is designed to investigate the changes of visual acuity when viewing a vibrating object.

Your acuity will be determined using a standard chart, then a check will be made for muscle balance and absence of colour blindness.

The test cards used during the experiment have groups of Landolt C's arranged on them, each facing left or right. A similar card will be shown to you.

Each section of the experiment will proceed thus:- You will be told which group of C's to read, and the order to read them, e.g. "middle group, starting left hand block". The shutter will lift. Will you then call the direction that the gap faces in each successive C, doing so as quickly and accurately as possible. When you have finished the shutter will close. Will you then "rate" the difficulty of the task using the scale on the shutter face.

There will be a short practice session during which you will be shown some of the conditions to expect and you will be given a chance to practice at reading and rating the task. Please ask any questions at the end of this session.

During the main experiment, several different amplitudes and frequencies will be chosen, and each time you will be asked to read a group of C's as described above. It is important that you do call a direction, even if you are not quite sure.

Before the experiment you will be asked to complete a short questionnaire.

Thank you for participating in this research.

Are there any questions?