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The Effect of Low Frequency, High Amplitude, Whole Body, Longitudinal and Transverse Vibration Upon Human Performance

by

Richard J. Hornick, Charles A. Boettcher, and Allison K. Simons

Final Report

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Bostrom Research Laboratories

Division of Bostrom Corporation

Milwaukee, Wisconsin

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Acknowledgements

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Abstract

Two experiments were conducted to determine the effects of horizontal (transverse and longitudinal) vibration upon the seated human being. Such vibration is typically found in ground vehicles.

The transverse (side-to-side) vibration experiment utilized frequencies from 1.5 to 5.5 cps, with intensities of 0.15, 0.25, and 0.35 g. Measures were taken before, during, and following vibration exposure. The longitudinal (fore-aft) vibration experiment utilized the same frequencies with intensities of 0.15, 0.25, and 0.30 g. Measures taken during both experiments were of: compensatory tracking ability, choice reaction time, foot pressure constancy, peripheral vision, visual acuity, body equilibrium, bodily transmissibility, oxygen consumption, breathing rate and total ventilation.

The results indicate that transverse and longitudinal, whole-body vibration does affect tracking ability, choice reaction time, foot pressure constancy, and peripheral vision, with some performance decrements being related to specific frequencies and to intensity increments. Visual acuity and body equilibrium were not affected. Performance decrements, transmissibility, and respiratory effects are related and discussed.

Introduction

When man operates a vehicle or is conveyed in it, he is subjected to oscillations or vibration. The vibration problem is particularly acute in trucks, tanks, personnel carriers, jeeps, helicopters, and high speed, low altitude aircraft. In most of these vehicles, especially ground vehicles, the vibration imparted to human occupants has characteristics of low frequencies and high amplitudes.

Due to terrain, tires or tracks, and suspension systems, most ground vehicles typically possess frequencies from 1 to 7 cps with amplitudes yielding peak acceleration intensities up to 0.50 g's. Occasionally frequency-amplitude combinations beyond 0.50 g intensity exist in a particular vehicle.

The planes of vibration may be defined with reference to the human body in this manner: vertical (up-down), transverse (side-to-side), and longitudinal (fore-aft). Obviously, when a vehicle is under power the occupants experience whole-body vibration in all of these directions.

If man in a vehicle is considered as an integral component of a man-machine system (Hornick, 1961c) the question immediately arises: what are the effects of whole-body, low-frequency, high-amplitude vibration upon the capabilities of the human component?

It is not the purpose of this report to present a lengthy review of vibration studies. Several such reviews already exist; for instance, those of Goldman and von Gierke (1960), Ashe (1960), and Hornick (1961b). Besides, most vibration research has been done in the vertical direction. For representative results of such vertical vibration studies, one may consult, in addition to the review articles, the following: Coermann (undated); Dennis and Elwood (1958); Guignard and Irving (1960); Magid, Coermann, and Zeigenruecker (1960); Riopelle and Hines (1955); Schmitz, Simons, and Boettcher (1960).

In general, low-frequency, vertical vibration may impair or affect visual acuity, peripheral vision, simple reaction time, choice reaction time, compensatory tracking ability, foot pressure constancy, metabolic rate, pulse pressure, oxygen consumption, blood composition, and other physiological and psychomotor behavior. In addition, the resonant frequency of the seated human body to vertical vibration (resonant frequency is that at which input motion is maximally amplified by the body) occurs at 4 to 7 cps (Haack, 1955). Man's tolerance to withstand vertical vibration is also lowest in the range of 4 to 7 cps.

However, statements such as these cannot be made regarding transverse and longitudinal vibration for the elementary reason that few studies of vibration in these directions can be found. Reiher and Meister (1931) evaluated subjective responses of "strong", "annoying", "objectionable", etc. for transverse and longitudinal vibration experienced by standing or prone positioned subjects, and observed that transverse vibration was "soon and intensely felt". In another subjective study, Jacklin (1936) listed transverse vibration as worst (having the lowest threshold for "disturbing" sensations) followed by longitudinal and then vertical vibration.

Regarding transmissibility for transverse vibration, Goldman and von Gierke (1960) state that maximum movement of the hip occurs at 1.5 cps, and the head at 2 cps for the sitting subject. They also report that vertical vibration introduces body resonances at 4 to 6 cps. Dieckmann (1958) indicates maximum body movement to occur below 2 cps for sitting subjects exposed to horizontal vibration.

Using animals, Sueda (1937) reported earlier onset of death in rats and rabbits subjected to horizontal as opposed to vertical vibration. Ashe (1960) conducted several experiments using vertical and horizontal vibration on rats which were unrestrained. He reported greater weight loss with vertical vibration, and there was no difference in weight changes between horizontally vibrated and control rats. There was no difference in growth rates between groups of rats which were vibrated in the two planes over a 48-day period. He points out that during horizontal vibration there was a marked increase in heart rate at the onset of vibration with a gradual return to the pre-vibration rate. He interpreted this as being due to an "apprehensive reaction" (Ashe, 1960).

Fraser (1960) reported that human subjects engaged in a tracking task during vibration in each of the three planes revealed no decrement during longitudinal vibration, but significant decrements in transverse and vertical planes.

After examining vibration studies such as these, one is led to several basic conclusions. First, most vibration studies have been conducted with <u>vertical</u> vibration showing physiological as well as performance effects. Second, of the relatively few studies of horizontal vibration--transverse and longitudinal--little has been done in determining the effects of transverse and longitudinal vibration on <u>human performance</u>. At best, only some physiological and mechanical effects are known. Hence, a real need exists for information regarding the effects of horizontal vibration on human performance, especially since subjective indices reveal man's tolerance to be lowest for such vibration.

The experiments reported herein were, therefore, conducted to fill this need. Performance measures were utilized to evaluate the effects of transverse and longitudinal vibration similar to that experienced in typical ground vehicles on man.

Two separate experiments are reported in this study. The first incorporated the use of transverse vibration with frequencies of 1.5, 2.5, 3.5, 4.5, and 5.5 cps; peak acceleration intensities of 0.15, 0.25, and 0.35 g; and measures were taken during a pre-vibration period, during the first 15-minutes of vibration, during the final 15-minutes of vibration, and during a post-vibration period.

The second experiment incorporated the use of longitudinal vibration with the same five frequencies; intensities of 0.15, 0.25, and 0.30 g; and measures during the same four time periods. The longitudinal experiment utilized a maximum g level of 0.30 because a preliminary investigation indicated potential back injury and whiplash of the neck at 0.35 g. To further protect subjects in the longitudinal direction, a lap-type seat belt was worn.

In both experiments subjects were seated on a rigid chair mounted on a shake table.

Performance measures were taken on compensatory tracking ability, choice reaction time, foot pressure constancy, peripheral vision, visual acuity, and body equilibrium. The first four measures were incorporated into a simulated driving task, while visual acuity and body equilibrium were recorded at separate times. In addition, body transmissibility records were taken at the head and belt levels for transverse vibration, and at head, chest, and belt levels during longitudinal vibration.

In order to aid in interpretation of performance results, oxygen consumption, breathing rate, and total ventilation measures were made on several subjects in each direction of motion.

It was hypothesized that A) some frequencies of transverse and longitudinal whole-body vibration would result in decrements in performance; B) the decrements would increase with increases in intensity within a given frequency; C) the resonant frequency of the human body would be below 2.5 cps in each of the horizontal directions, and that greatest performance decrements would occur at or near the resonant frequency; and D) greatest oxygen consumption, breathing rate, and total ventilation would occur at or near resonant frequencies.

Method

Since the methodology of the transverse and longitudinal experiments was very similar the descriptions below apply to both unless otherwise noted.

Subjects

Two different groups of twenty male subjects, ranging in age from 18 to 26 years experienced the conditions in both of the vibration directions. Each subject was given a thorough physical examination before participating.

Design

In the transverse experiment subjects served in all experimental conditions. There were five frequencies (1.5, 2.5, 3.5, 4.5, and 5.5 cps), three levels of intensity (0.15, 0.25, and 0.35 g), and four time periods (pre-, first 15-minutes of, final 15-minutes of, and post-vibration).

The longitudinal experiment employed the same five frequencies and time periods, but the three levels of intensity were 0.15, 0.25, and 0.30 g. Subjects served in all conditions.

In each experiment, therefore, the basic experimental design was a 5 x 4 x 3 x 20 factorial analysis of variance with repeated measures.

Vibration Apparatus

The table used was a multi-directional shake table with a top surface of 36" x 40". The drive mechanism is mechanical with a power source of a 7½ hp. electric motor. A complete description can be found in Schmitz et al. (1960). For each desired experimental combination, frequency and amplitude were pre-set and constantly monitored.

Rigidly mounted on the shake table was a wood chair with a back rest.

Tubular steel legs and supports maintained rigidity of the chair. For protection to the subjects during longitudinal motion, a lap-type seat belt fastened to the chair was used by all subjects.

Performance and Related Apparatus

As mentioned earlier, compensatory tracking, choice reaction time, foot pressure constancy, and peripheral vision measures were combined into a simulated driving situation.

Compensatory tracking ability was evaluated by requiring the subject to keep a small blip centered on an oscilloscope screen at all times by turning a steering wheel which varied a potentiometer at tho bottom end of the steering shaft. As the blip moved to the left, the wheel had to be turned to the right in order to keep the dot centered, and vice versa. The uncompensated blip moved horizontally across the face of the scope at a frequency of 3.5 cycles per minute, with a total displacement of 2". The variable error (distance from center of scope) was electronically amplified, rectified, and integrated. The integrator was a voltage-to-frequency converter that determined the average frequency over each of four 15-minute periods. The resultant frequency was converted to error with a predetermined calibration factor in terms of inches on the scope. The oscilloscope was placed in a panel at the subject's approximate eye level.

Choice reaction time was recorded with apparatus consisting of three jewel lights (one red, one green, one amber) mounted above the oscilloscope, and a second bank of nine jewel lights (red, green, and amber in a counterbalanced order) below the scope. Subjects were to react by means of a simulated brake pedal when lights of the same color appeared on the upper and lower stationary display banks and were not to respond if dissimilar colors appeared.

During transverse vibration a delay was introduced (from 12 to 40 seconds) between the upper "cue" light and the appearance of the response light. During longitudinal vibration, both lights flashed on simultaneously. A Standard Electric Timer, calibrated in 1/100's of a second, was activated with the flashing of both lights and stopped with pressure on the brake pedal.

For evaluating foot pressure constancy, a Simpson vacuum tube volt meter with a simulated speedometer dial attached to its face was situated next to the oscilloscope. The maximum range of the speedometer needle was 20-60 in simulated miles per hour. The needle indicator of the meter was regulated by the amount of foot pressure exerted on an accelerator pedal. An arm connected to the pedal made contact with a piece of sheet metal on which four strain gauges were mounted, two on the upper surface and two on the lower surface. The amount of strain placed on the sheet metal regulated the movement of the indicator. The subject was instructed to "drive" at 40 miles per hour at all times (the figure 40 was at the center of the dial). Error about this "speed" was amplified and integrated. Average total error for each of four 15-minute periods was the measure used. The amount of torque necessary to maintain center on the meter was 42.3 pound-inches. This task and the instrumentation was the same for both the transverse and longitudinal experiments. See Fig. 1 for the complete visual display.

The last of the simulated driving tasks, peripheral vision, was evaluated by means of dull black standards on either side of the subject at a distance of 55" from the center of the chair. The standards were adjusted to be at each subject's eye level. The standards contained a row of 40

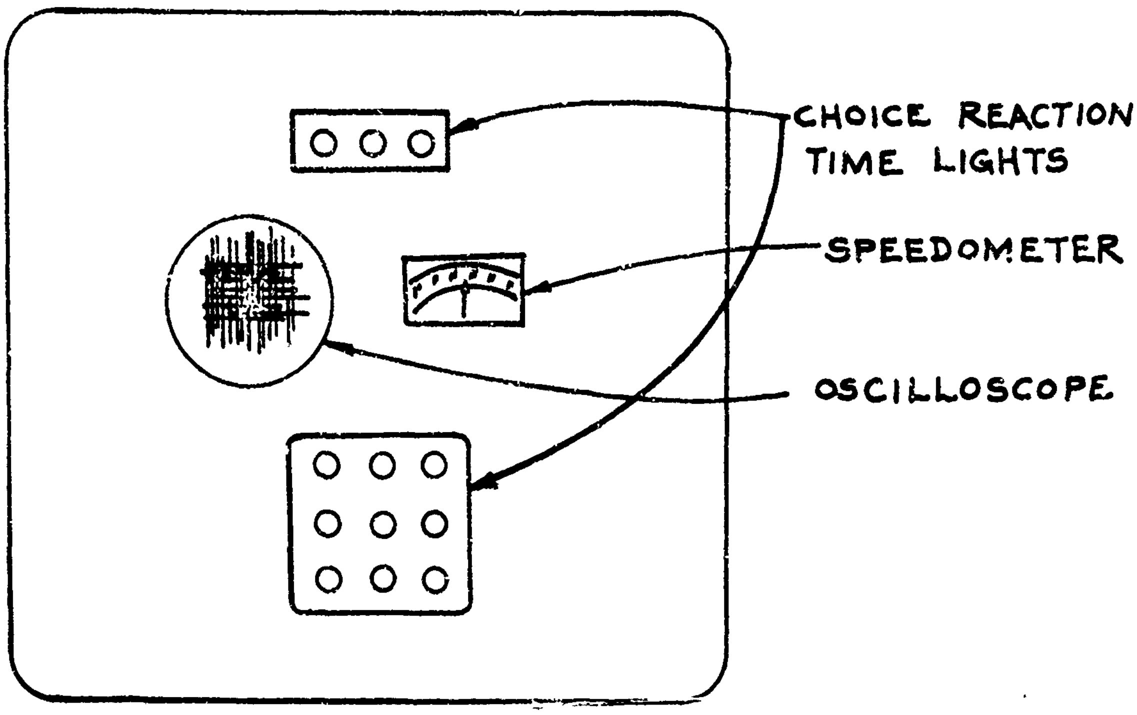

Fig. 1. Visual display. The display was situated approximately 48 inches from seated subject. For compensatory tracking, 1° of steering wheel movement elicited 0.0083 inches blip movement on the scope. For foot pressure, 1° of pedal movement resulted in 6.86 simulated miles per hour variation.

countersunk GE #47 lights. A multiple contact switch was used as a scanning device which lit each light in succession beginning with the first (beyond the subject's field of peripheral vision) and ending when the subject pressed a button (mounted on the wheel in place of the horn button) which switched off the light and stopped the scanner indicating the number of the light which the subject first saw. For each subject the standards were placed so that specific lights maintained calibrated peripheral vision angles in all conditions.

The visual acuity test utilized Landolt C's as targets. A black partition with a small sliding door was placed 12' 8" from the subject at eye level as he sat on the vibration table. A 200 watt lamp was placed approximately 10 inches in front of the partition and focused on the sliding door. Cards on which the Landolt C's were printed could be inserted in a frame behind the sliding door so that the gap in the C was up, down, left or right. The reflected light from these targets was measured as 100 foot Lamberts.

Body sway was recorded before and after each vibration condition. The apparatus consisted of a wall mount adjustable to the height of each subject, a flexible brass rod 19" long which was fastened to the mount and vertically suspended from it, and a head piece adjustable to head size. Strain gauges were mounted to the rod so that transverse and longitudinal movements were detected. In this way, body sway in any plane through the axis of the rod could be recorded. Strain gauge signals were amplified by two Brush amplifiers and recorded on the two channels of standard Brush oscillograph chart paper. The sway in each plane was measured by means of a compensating polar planimeter in terms of peak to peak area.

Each subject was also measured for his mechanical body response, or transmissibility, to each of the vibration conditions. Two accelerometers were used to obtain this measure. One accelerometer, (Statham A5Aa-5-350) was fastened to the table to measure input. A second accelerometer (Statham A52-5-300), was firmly fastened to a 3½" x 2½" piece of thin plywood; the plywood was then attached to a 2½" wide strip of nylon backed vinyl material. The material with the accelerometer attached could be firmly tied around the subject at his belt line, around his chest or around his head. The table input was compared to the motion recorded at the head, chest, or belt level for the transmissibility measure.

Respiratory parameters and oxygen consumption were measured with conventional techniques using a Collins 13½ L Respirometer. Metabolic rate was calculated from the mean oxygen consumption during 6 minutes of vibration. It was based on an assumption of an R.Q. of 0.82, resulting in 4.825 Cal/L O_2. Breathing frequency was counted from the spirogram. The ventilograph pen was used to calculate total minute ventilation, calculated as the mean L/minute for the 6 minute period. Control (no vibration) periods were run at the beginning of each experiment and after each 5 exposures to vibration. The mean value for all "no vibration" periods was used as the reference point, to which changes were referred.

Procedure

All subjects experienced a complete practice session of one hour duration.

A description of a typical experimental session is presented here for clarification. The frequency and amplitude was pre-set into the table for the desired frequency-intensity combination. For any one subject, of course, these combinations were experienced in a random order.

The subject began by having his pre-vibration body sway recorded. He then sat on the chair of the shake table for 15-minutes of no vibration (PRE) during which time his performance on the simulated driving tasks was obtained. He controlled the oscilloscope blip by means of the steering wheel. He attempted to maintain the simulated 40 miles per hour on the speedometer display by means of the accelerator pedal. These two tasks were continuous. At random intervals the choice reaction time lights were presented, the subject reacting as quickly as possible by striking the simulated brake pedal. Again at random intervals, and in a left-right random order, the peripheral vision lights moved into his field of vision, the subject pressing the horn button as soon as he noticed the light. During this PRE period, a tape recording of the table noise was played in order to control for the table noise during vibration conditions.

The same procedure was followed during the next one-half hour in which the shake table was vibrating while the performance measures were recorded. The half-hour was electronically divided into two 15-minute periods (V_1 and V_2). Subjects were not aware of this division.

Following the half-hour of vibration, the subject again was stationary while the recorded table noise was played. Measures following vibration (POST) were then obtained for 15-minutes.

After this, the subject's body sway was again recorded.

In order to measure visual acuity, each of the 15 frequency-intensity combinations was experienced while the subject attempted to locate gaps in the Landolt C rings. A control condition (without vibration) was randomly interspersed among the 15 conditions. Visual acuity limit was defined as the visual angle represented on the C where the subject made four errors out of eight possibilities.

Human body mechanical response was obtained in additional sessions. All frequency-intensity combinations were again reproduced while accelerometers were placed on the table and at head, chest, or belt levels. Peak-to-peak acceleration recorded on the body was divided by the peak-to-peak table acceleration giving a ratio measure of transmissibility at each point.

Separate sessions again were used for three subjects in the transverse and five subjects in the longitudinal direction for the respiration measures.

Results

(Transverse Vibration)

Compensatory Tracking

The summary analysis of variance for tracking ability appears in Table 1. Data shown in Figs. 2, 3, and 4 indicate that decrement in this ability is greatest below 2.5 cps. Within a frequency, increments in intensity result in greater decrements. There is a trend for tracking error to increase as time of exposure increases and there is not complete recovery of tracking ability during 15-minutes following exposure to transverse vibration.

Choice Reaction Time

The summary analysis of variance for reaction time appears in Table 2. The summary and Fig. 5 reveal that the time period is the only significant factor. Frequency and intensity of vibration have no effect, but choice reaction time is significantly impaired following exposure to transverse vibration.

Foot Pressure Constancy

Table 3 and Figs. 6, 7, and 8 show that foot pressure constancy suffers greatest decrement at 1.5 and 2.5 cps during vibration; increasing intensity incrsases decrement; decrement is immediate with the onset of vibration and shows no trends during exposure; recovery is virtually complete following exposure.

Peripheral Vision

The summary analysis of variance for peripheral vision appears in Table 4. As seen in Fig. 9, peripheral vision is impaired only at 1.5 and 2.5 cps, and only during the initial 15-minutes of transverse vibration.

Table 1

Summary Analysis of Variance for Compensatory Tracking
During Transverse Vibration

Source	SS	df	MS	F	
Between Subjects	1.147	19	0.060		
Within Subjects					
Frequency	0.057	4	0.014	7	.01
Intensity	0.060	2	0.030	15	.01
Time	0.112	3	0.037	18.5	.01
F x I	0.030	8	0.004	2	.05
F x T	0.044	12	0.004	2	.05
I x T	0.026	6	0.004	2	N.S.
F x I x T	0.033	24	0.001	0.5	N.S.
Residual	1.852	1121	0.002		
Total	3.361	1199			

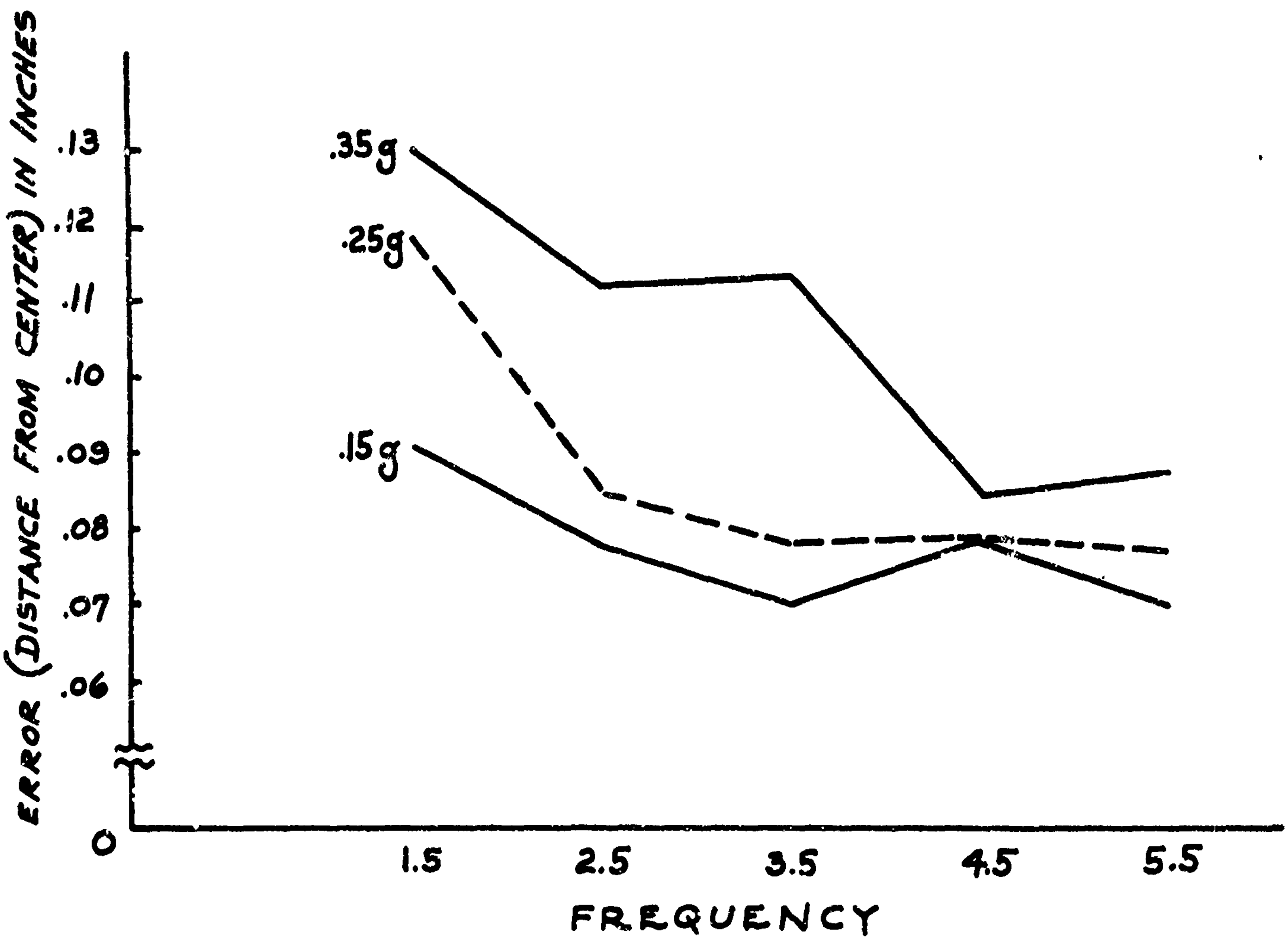

Fig. 2. Compensatory tracking as a function of frequency and intensity of transverse vibration.

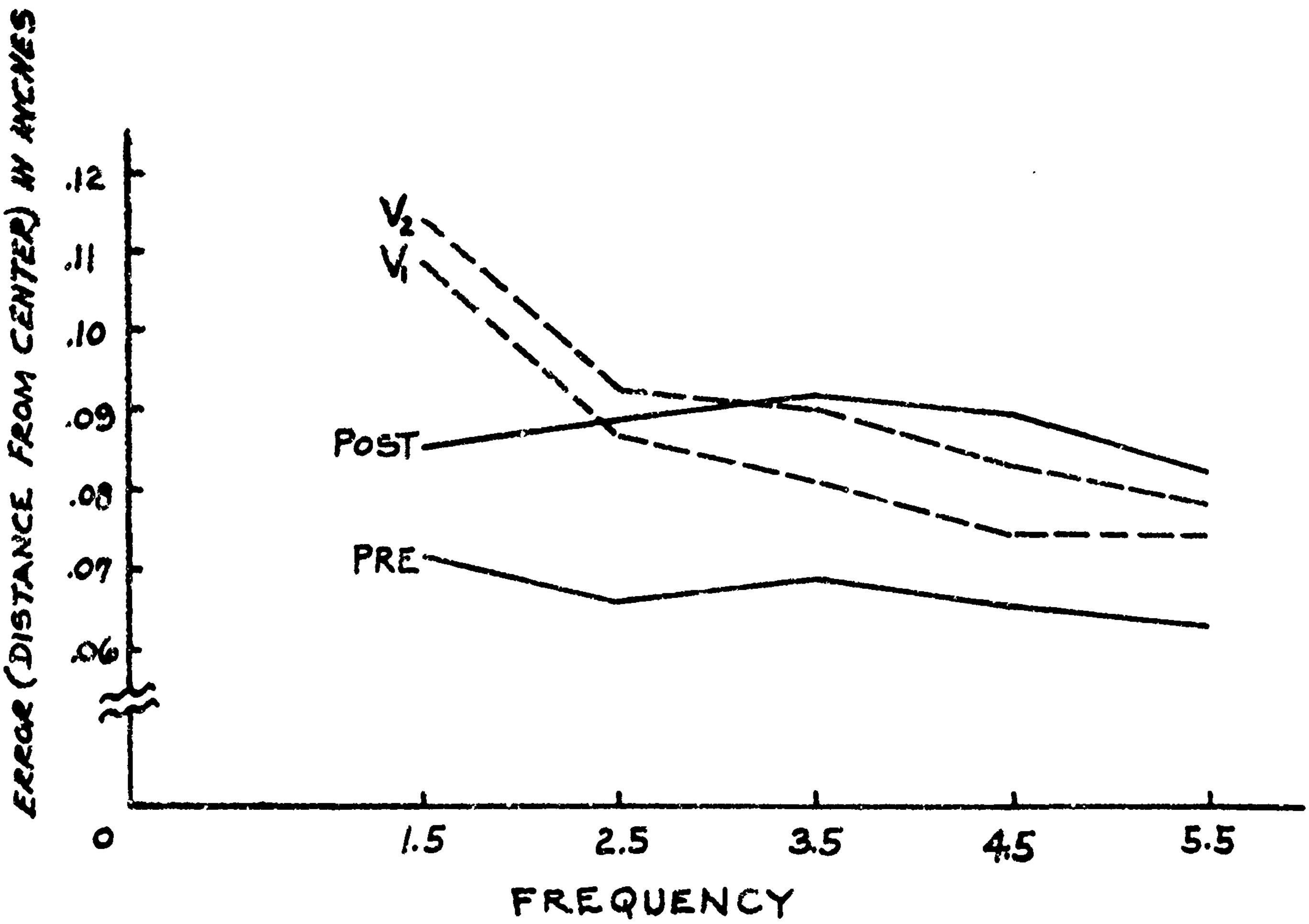

Fig. 3. Compensatory tracking as a function of frequency and time period for transverse vibration.

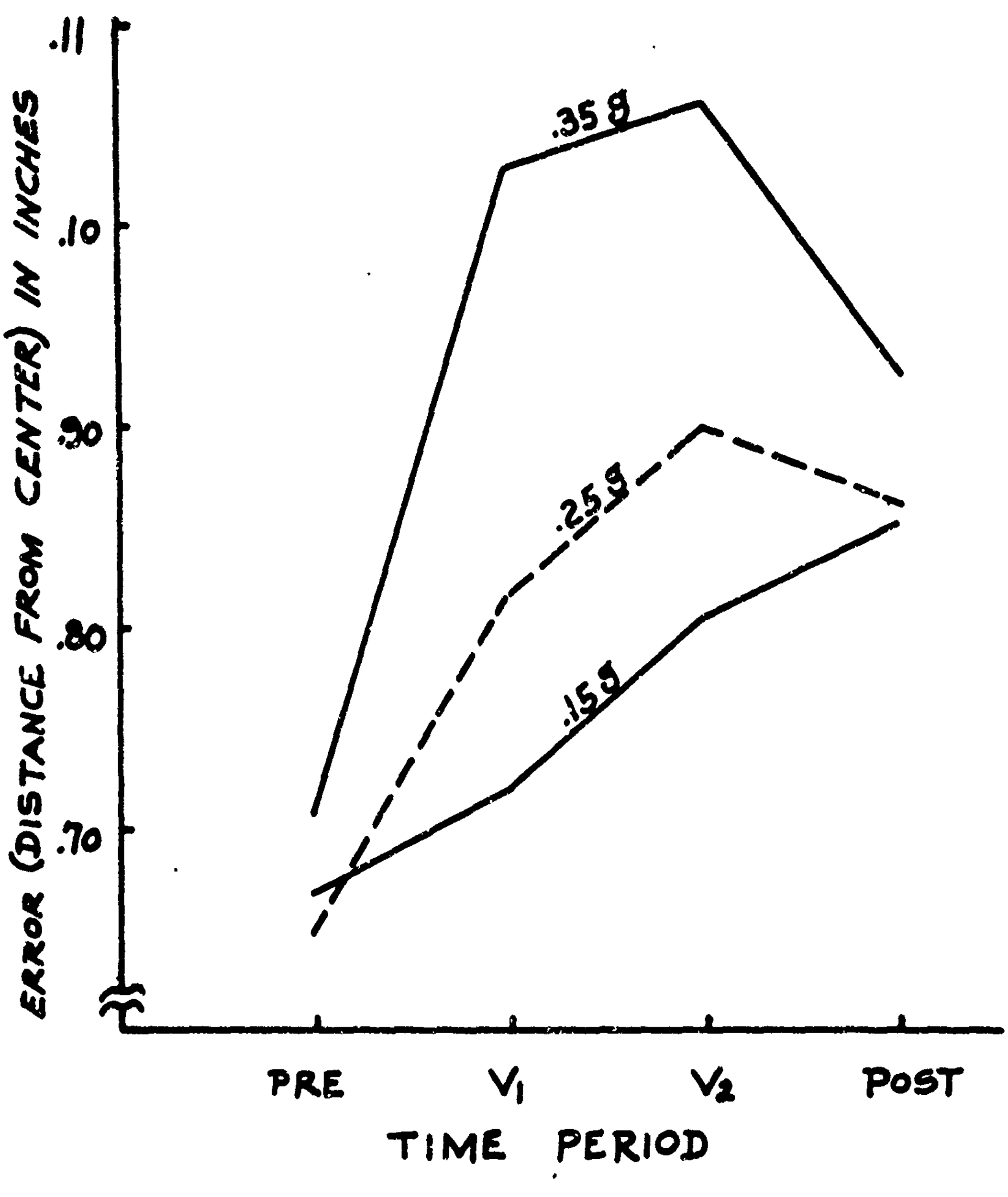

Fig. 4. Compensatory tracking as a function of intensity and time period for transverse vibration.

Table 2

Summary Analysis of Variance for Choice Reaction Time
During Transverse Vibration

Source	SS	df	MS	F	
Between Subjects	25.382	19	1.336		
Within Subjects					
Frequency	.090	4	.023	1.53	N.S.
Intensity	.023	2	.012	0.80	N.S.
Time	.385	3	.128	8.53	.01
F x I	.026	8	.003	0.20	N.S.
F x T	.284	12	.024	1.60	N.S.
I x T	.037	6	.006	0.40	N.S.
F x I x T	.342	24	.014	0.93	N.S.
Residual	17.295	1121	.015		
Total	43.864	1199			

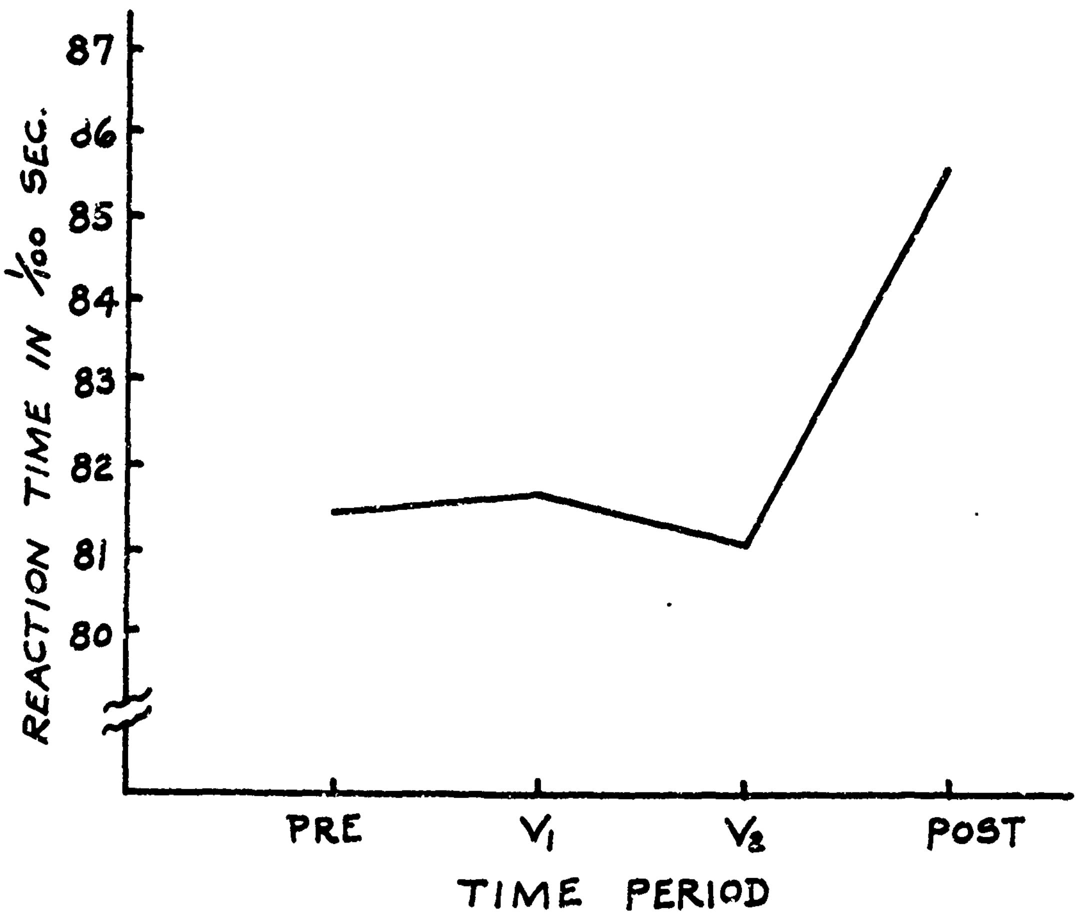

Fig. 5. Choice reaction time in each of the 15-minute time periods for transverse vibration.

Table 3

Summary Analysis of Variance for Foot Pressure Constancy
During Transverse Vibration

Source	SS	df	MS	F	
Between Subjects	315.343	19	16.597		
Within Subjects					
Frequency	39.724	4	9.931	20.18	.01
Intensity	31.666	2	15.833	32.18	.01
Time	54.024	3	18.008	36.60	.01
F x I	21.026	8	2.628	5.34	.01
F x T	41.927	12	3.494	7.10	.01
I x T	14.782	6	2.464	5.00	.01
F x I x T	12.748	24	0.531	1.08	N.S.
Residual	551.879	1121	0.492		
Total	1083.119	1199			

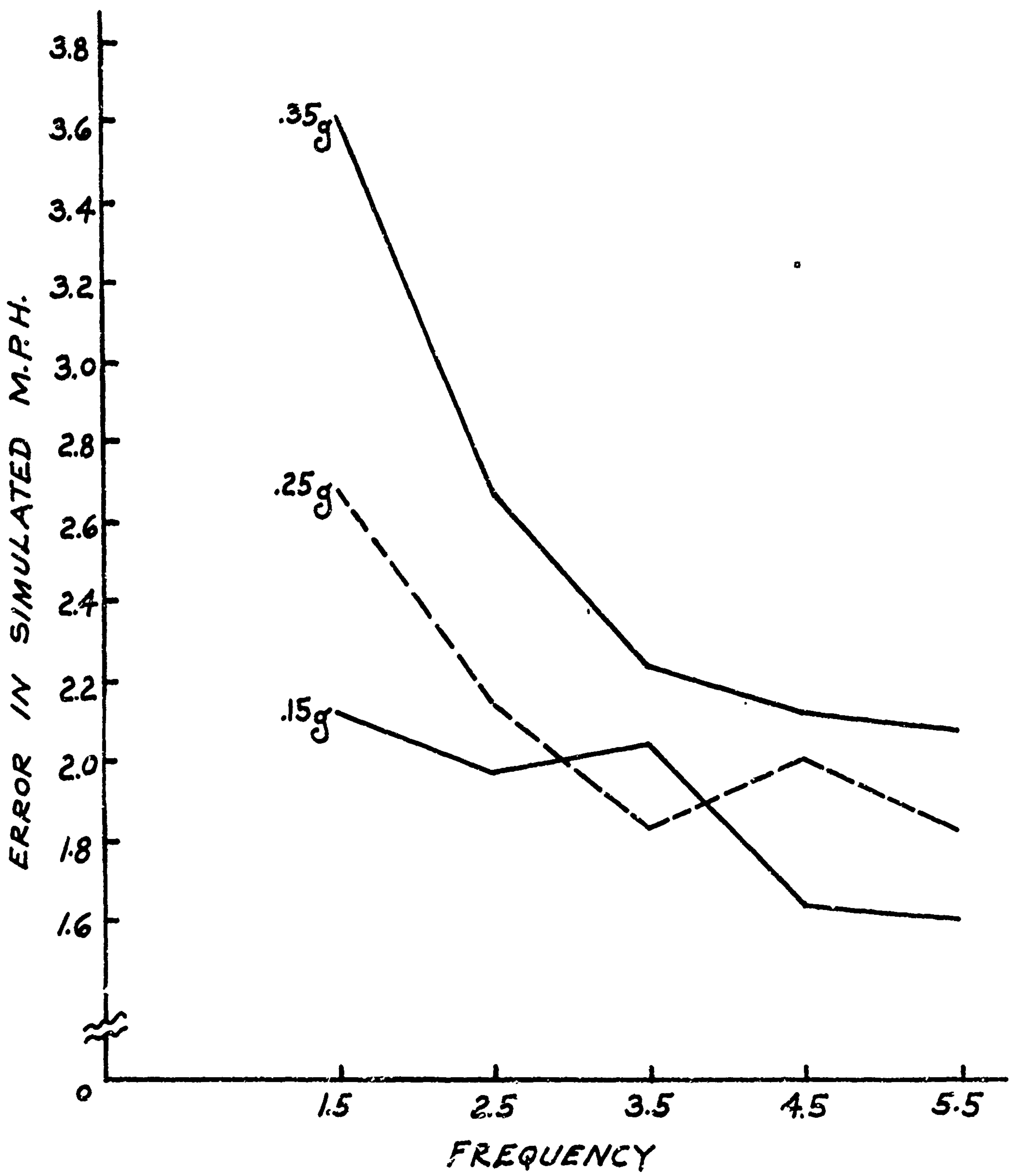

Fig. 6. Constancy of foot pressure as a function of frequency and intensity of transverse vibration.

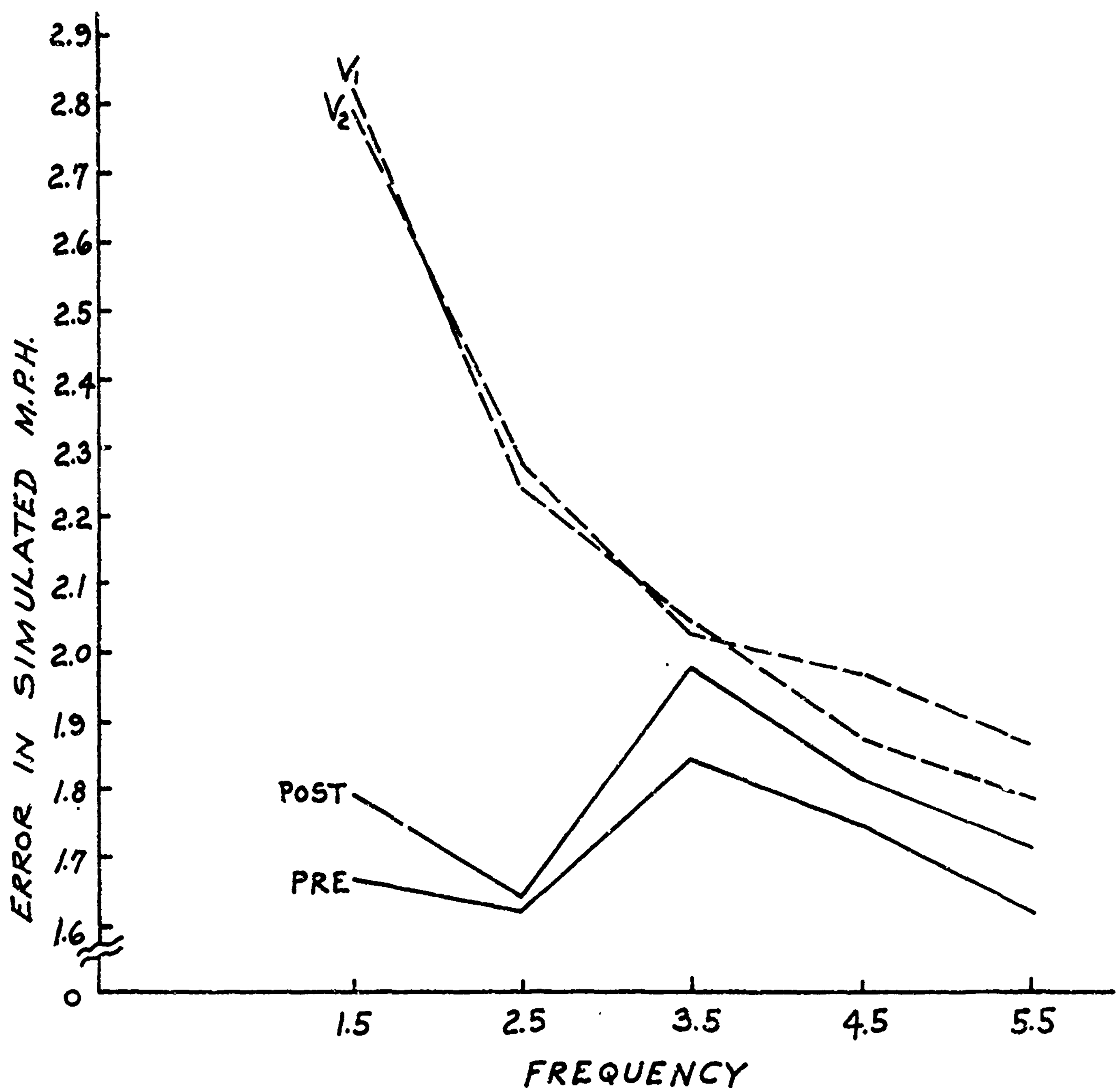

Fig. 7. Constancy of foot pressure as a function of frequency and time period for transverse vibration.

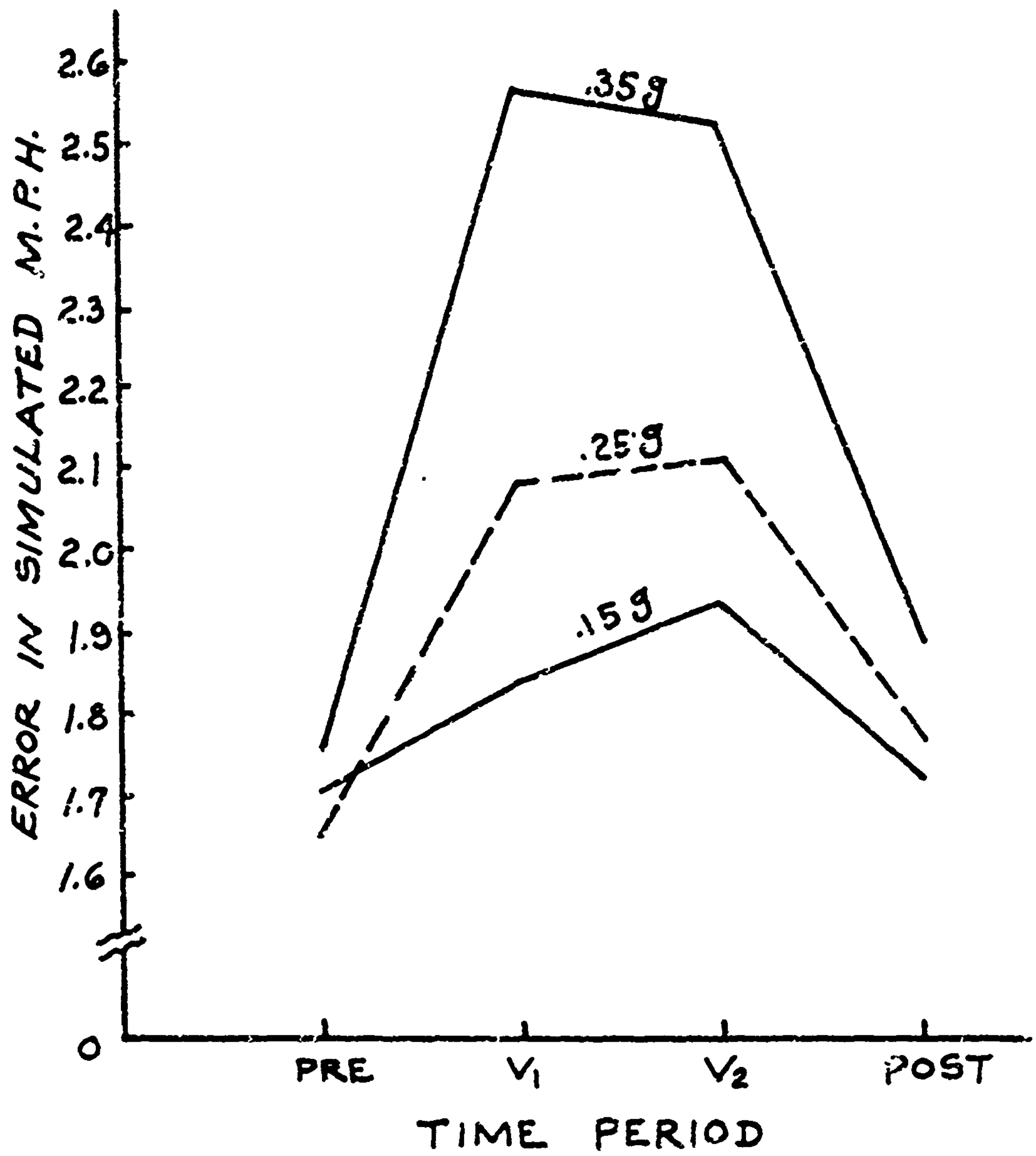

Fig. 8. Constancy of foot pressure as a function of intensity and time period for transverse vibration.

Table 4

Summary Analysis of Variance for Peripheral Vision
During Transverse Vibration

Source	SS	df	MS	F	
Between Subjects	38,035.629	19	2,001.875		
Within Subjects					
Frequency	69.122	4	17.281	2.84	.05
Intensity	2.755	2	1.378	0.23	N.S.
Time	260.285	3	86.762	14.24	.01
F x I	80.096	8	10.012	1.64	N.S.
F x T	196.674	12	16.390	2.69	.01
I x T	41.625	6	6.938	1.14	N.S.
F x I x T	77.528	24	3.230	0.53	N.S.
Residual	6,830.967	1121	6.094		
Total	45,599.68[illegible]	1199			

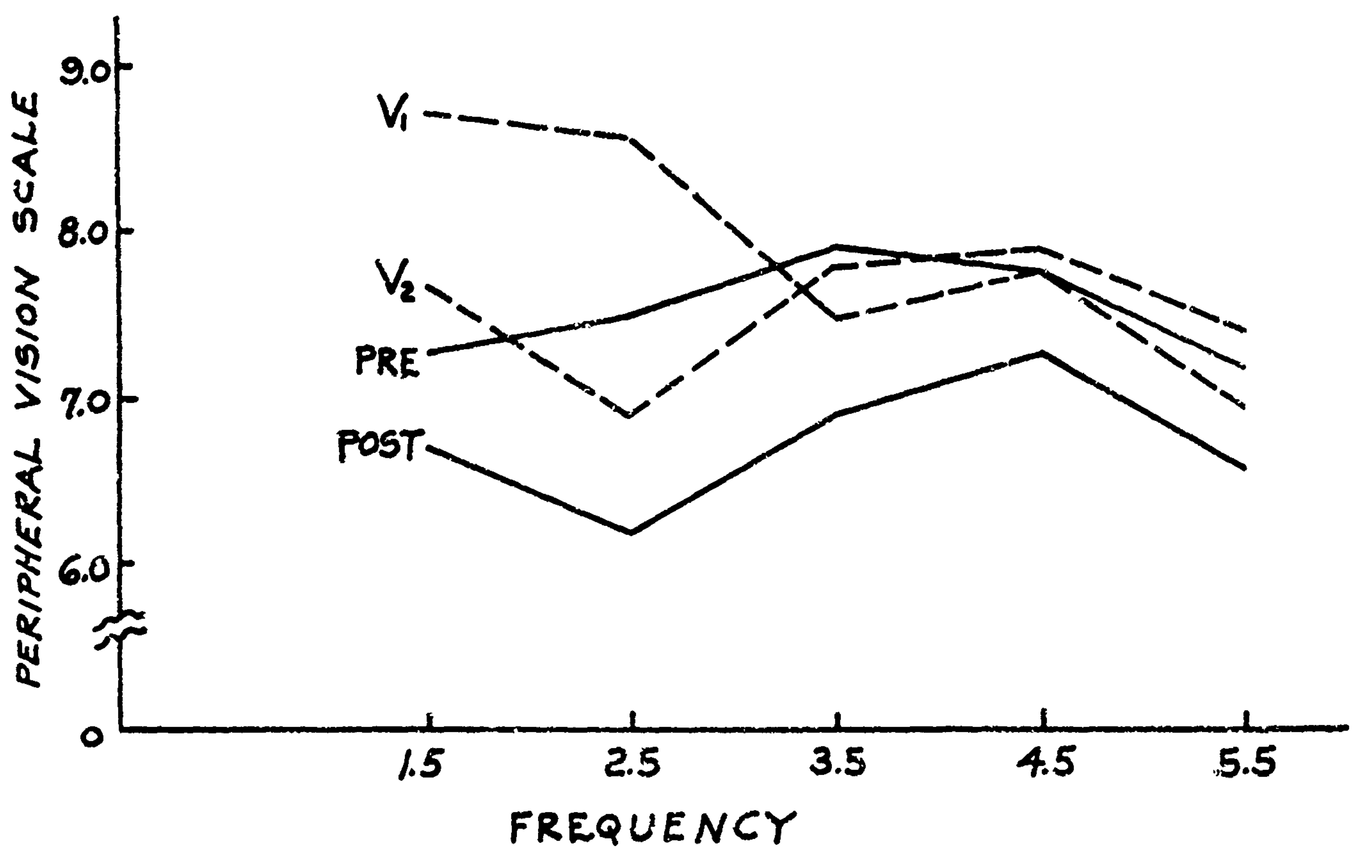

Fig. 9. Peripheral vision during transverse vibration. Values of the peripheral vision scale: 6.0 = 95°43'; 7.0 = 95° 12'; 8.0 = 94° 42'; 9.0 = 94° 10'.

Post-vibration peripheral vision is seen to be significantly superior to the pre-vibration control level.

Visual Acuity

Landolt "C" gaps were converted to values representing 1/visual angle. The analysis of variance indicates no significant differences between frequencies or intensities. There is no significant visual acuity decrement attributable to transverse vibration.

Body Equilibrium

A comparison of before- and after-vibration records indicates no differences for body sway in fore-aft or side-to-side planes. A _t_-test on the movement envelope areas verifies that there are no significant differences between before- and after-vibration periods.

Transmissibility

Peak acceleration of movement at the belt level is consistent in so far as all frequency-intensity combinations resulted in an amplification of intensity near 1.9 times. See Table 5.

Head accelerations result in a set of curves seen in Fig. 10. The transmissibility of the human body within the frequencies tested as measured at the head is 1.5 cps. Increasing input acceleration intensity from 0.15 to 0.35 g results in gradually lower amplification at the head. At 1.5 cps, for instance, a 0.15 g input elicits a peak to peak acceleration intensity 114% as great at the head; 0.25 g elicits an acceleration 63% as great; and 0.35 g elicits head acceleration 60% of the input. Actual head acceleration can be computed for any point on Fig. 10 by multiplying the indicated input intensity by the per cent transmissibility observed.

Table 5

Transmissibility at the Belt Level
(Transverse Vibration)

INTENSITY "g"	FREQUENCY 1.5	2.5	3.5	4.5	5.5
0.15	2.33	2.00	1.83	2.20	1.59
0.25	1.92	1.91	1.86	1.81	1.78
0.35	1.72	1.97	1.82	1.77	1.68

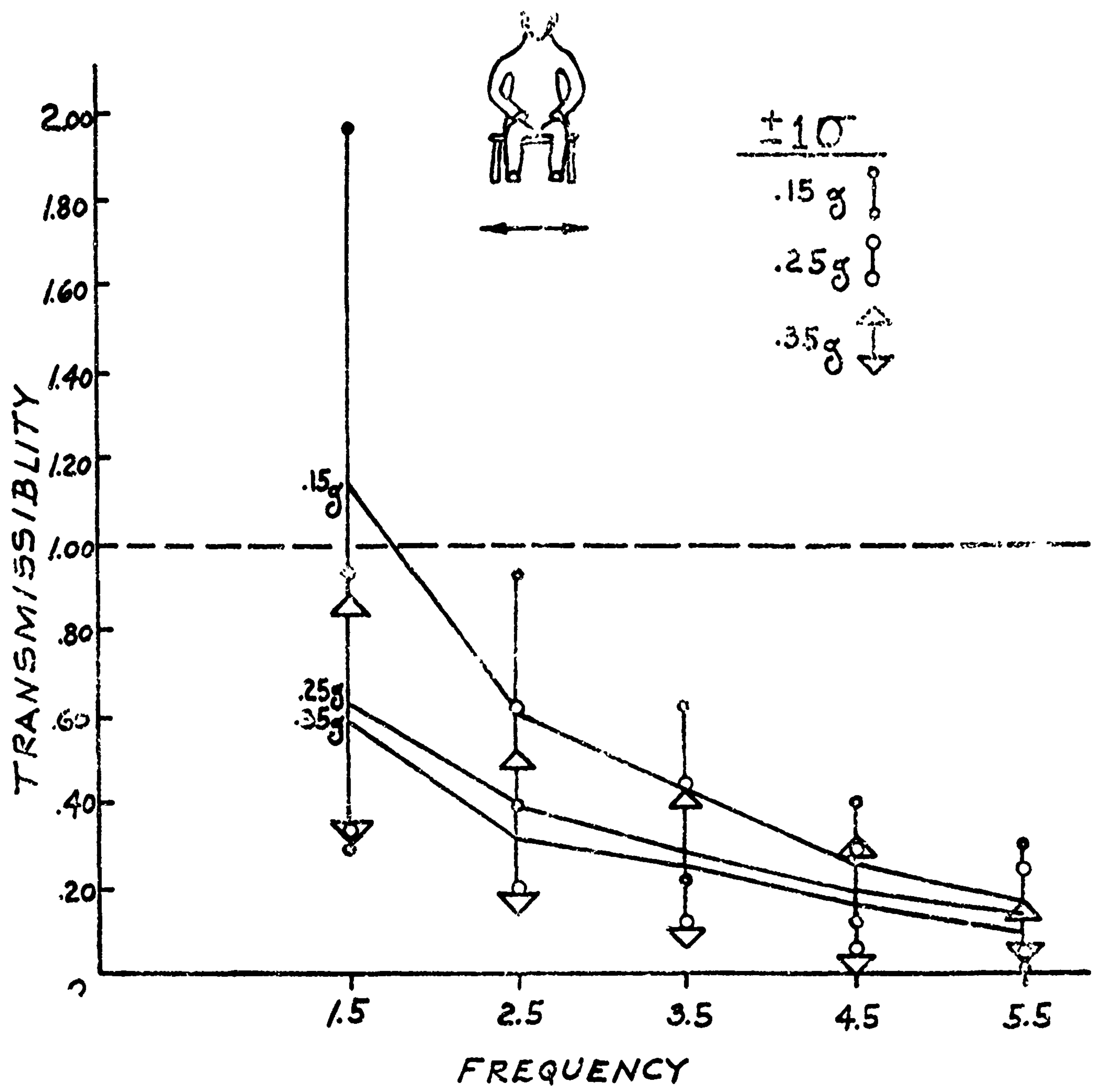

Fig. 10. Transmissibility at the head during transverse vibration. Values represent the ratio of head acceleration intensity to the table acceleration intensity. Standard deviations appear for each mean.

Oxygen Consumption

The oxygen consumption is expressed in the terms "calories per square meter of surface area per hour", or: CAL/M^2/HR. As is seen in Fig. 11, for frequencies of 3.5 cps and above, no change from a control level occurs. However, 1.5 and 2.5 cps elicit greater oxygen consumption with intensities of 0.25 g and 0.35 g.

Breathing Rate

No systematic change is seen in Fig. 12 as a function of vibration conditions. There is, however, a general lowering of breathing frequency during transverse vibration.

Total Ventilation

The total amount of gas moved by inspiration and expiration is shown in Fig. 13. For frequencies above 3.5 cps no significant difference from a control measure is indicated. For 1.5 and 2.5 cps, the liters per minute of air moved is generally related to increases in intensity with 1.5 cps eliciting the greatest increase in total ventilation. At 1.5 cps the average number of liters per minute ranges from 7.82 for 0.15 g to 11.06 L/min for 0.35 g. At 2.5 cps the range for 0.15 to 0.35 g is from 7.07 to 9.67 L/min.

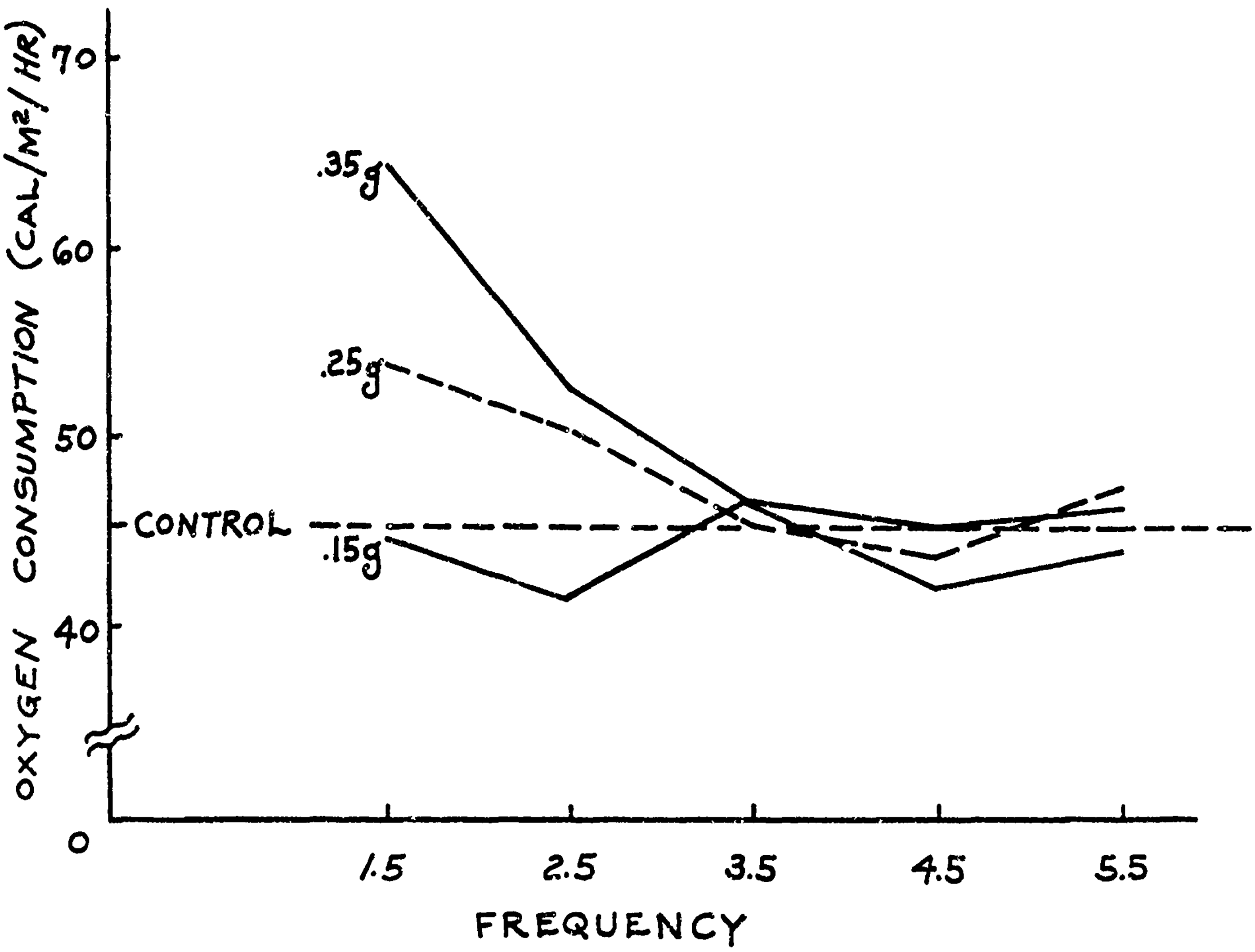

Fig. 11. Oxygen consumption during transverse vibration.

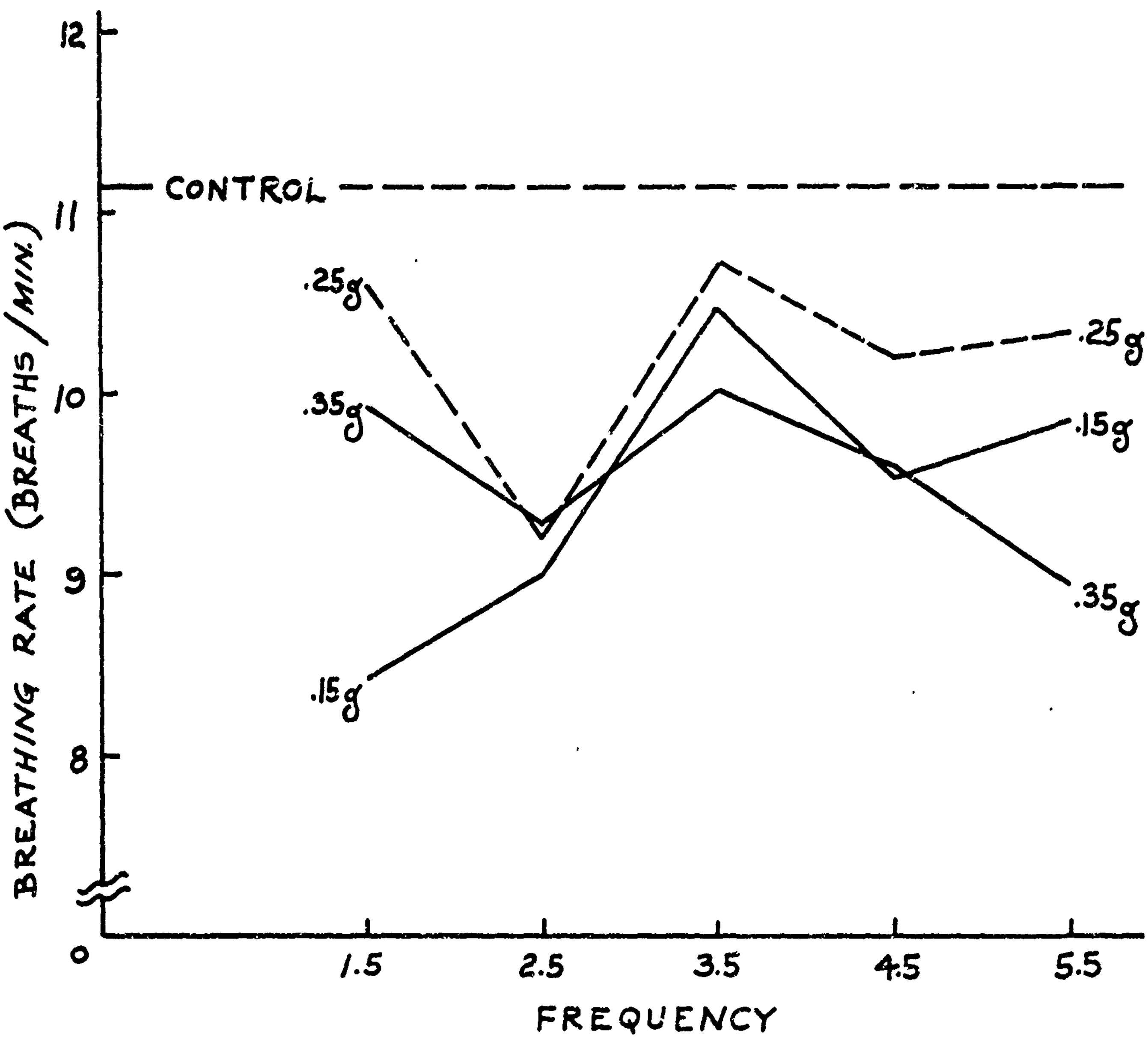

Fig. 12. Breathing frequency during transverse vibration.

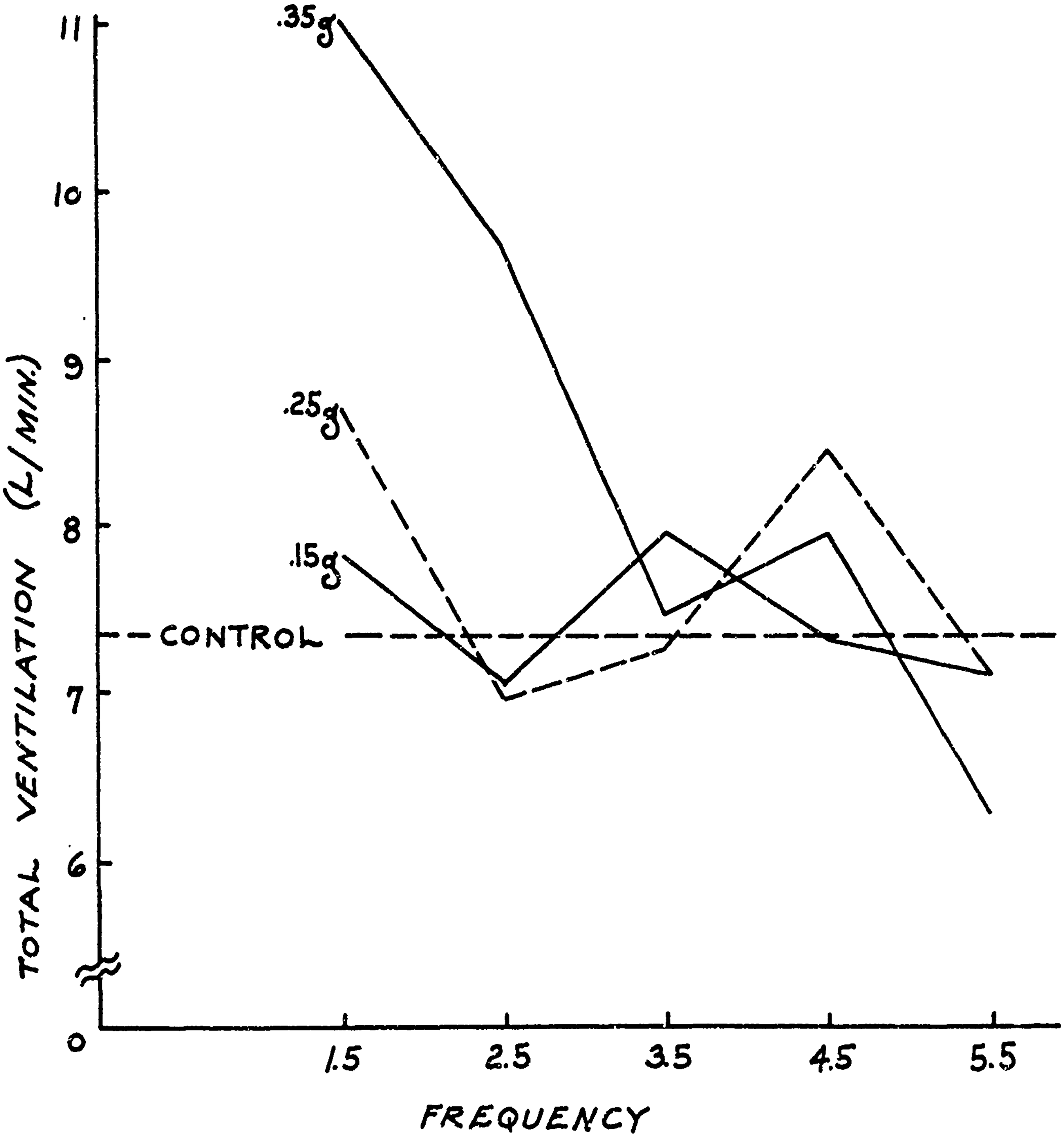

Fig. 13. Total ventilation during transverse vibration.

Results

(Longitudinal Vibration)

Compensatory Tracking

The summary analysis of variance for tracking ability during longitudinal vibration appears in Table 6. Intensity and time period variables show significant effects. Fig. 14 shows the tracking error as a function of intensity and time. In general, higher intensities produce greater error during vibration, with recovery of tracking ability not being complete following exposure. The frequency-intensity interaction is explained by the error being greatest at 0.30 g intensity across the frequency spectrum except at 3.5 cps where 0.25 g intensity results in slightly greater error than 0.30 g. At 4.5 and 5.5 cps, there is essentially no difference in error between the intensity levels.

Choice Reaction Time

The analysis of variance reveals no significant main effects or interactions for choice reaction time during longitudinal vibration.

Foot Pressure Constancy

The analysis of variance (Table 7) for foot pressure constancy reveals significant main effects and interactions. Fig. 15, 16, and 17 show that 3.5 cps produces greatest error; as intensity increases, error increases; recovery following exposure is virtually complete.

Peripheral Vision

The analysis for peripheral vision reveals no significant interactions or main effects during longitudinal vibration.

Table 6

Summary Analysis of Variance for Compensatory Tracking
During Longitudinal Vibration

Source	SS	df	MS	F
Between Subjects	0.816	19	0.043	
Within Subjects				
Frequency	0.003	4	0.001	N.S.
Intensity	0.010	2	0.005	.01
Time	0.036	3	0.012	.01
F x I	0.016	8	0.002	.01
F x T	0.003	12	--	N.S.
I x T	0.002	6	--	N.S.
F x I x T	0.003	24	--	N.S.
Residual	0.634	1121	0.001	
Total	1.523	1199		

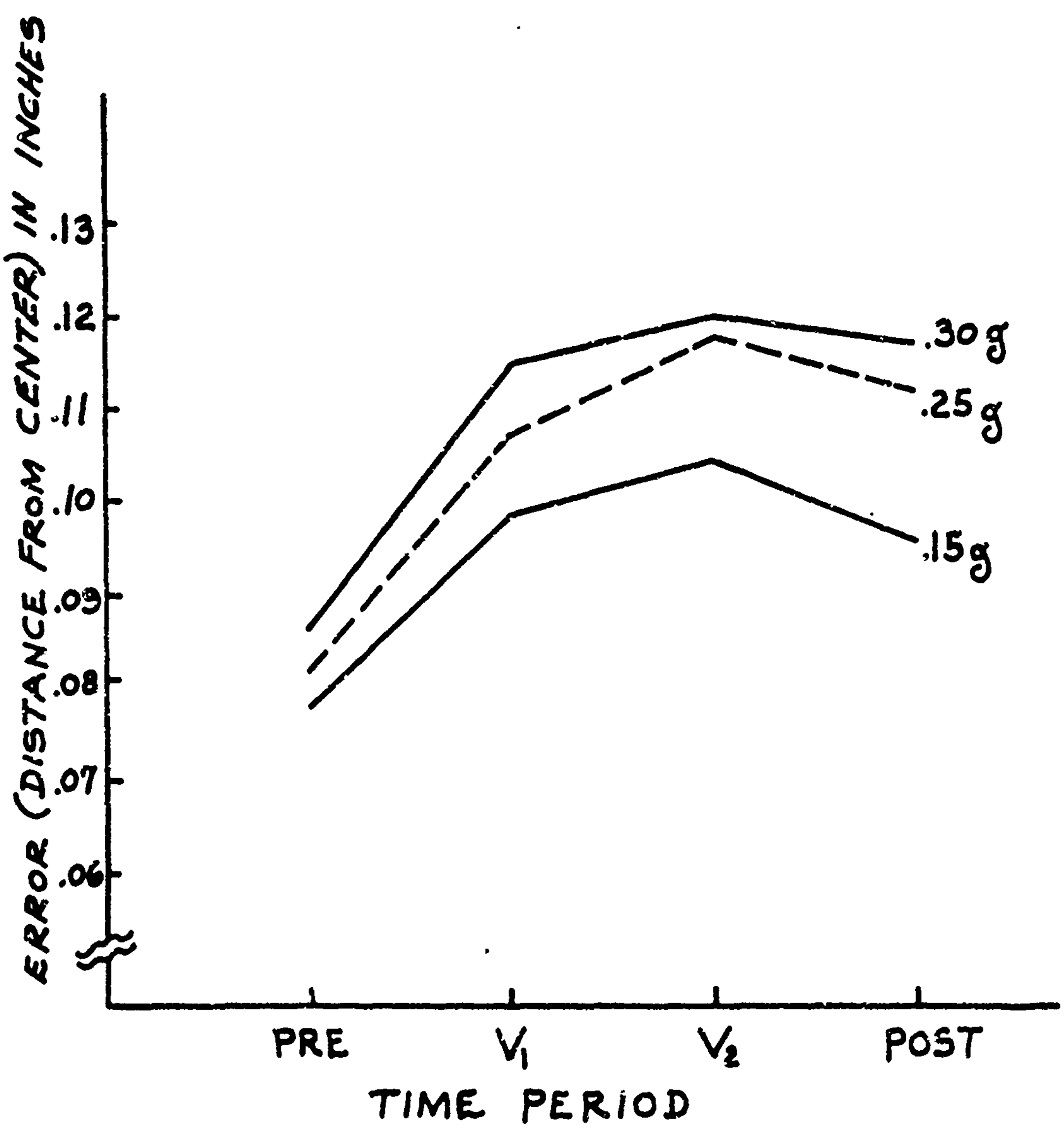

Fig. 14. Compensatory tracking as a function of intensity and time period for longitudinal vibration.

Table 7

Summary Analysis of Variance for Foot Pressure Constancy
During Longitudinal Vibration

Source	SS	df	MS	F
Between Subjects	245.75	19	12.93	
Within Subjects				
Frequency	18.25	4	4.56	.01
Intensity	18.14	2	9.07	.01
Time	57.53	3	19.18	.01
F x I	16.04	8	2.01	.01
F x T	7.59	12	0.63	.05
I x T	10.09	6	1.68	.01
F x I x T	4.98	24	0.21	N.S.
Residual	397.48	1121	0.35	
Total	775.85	1199		

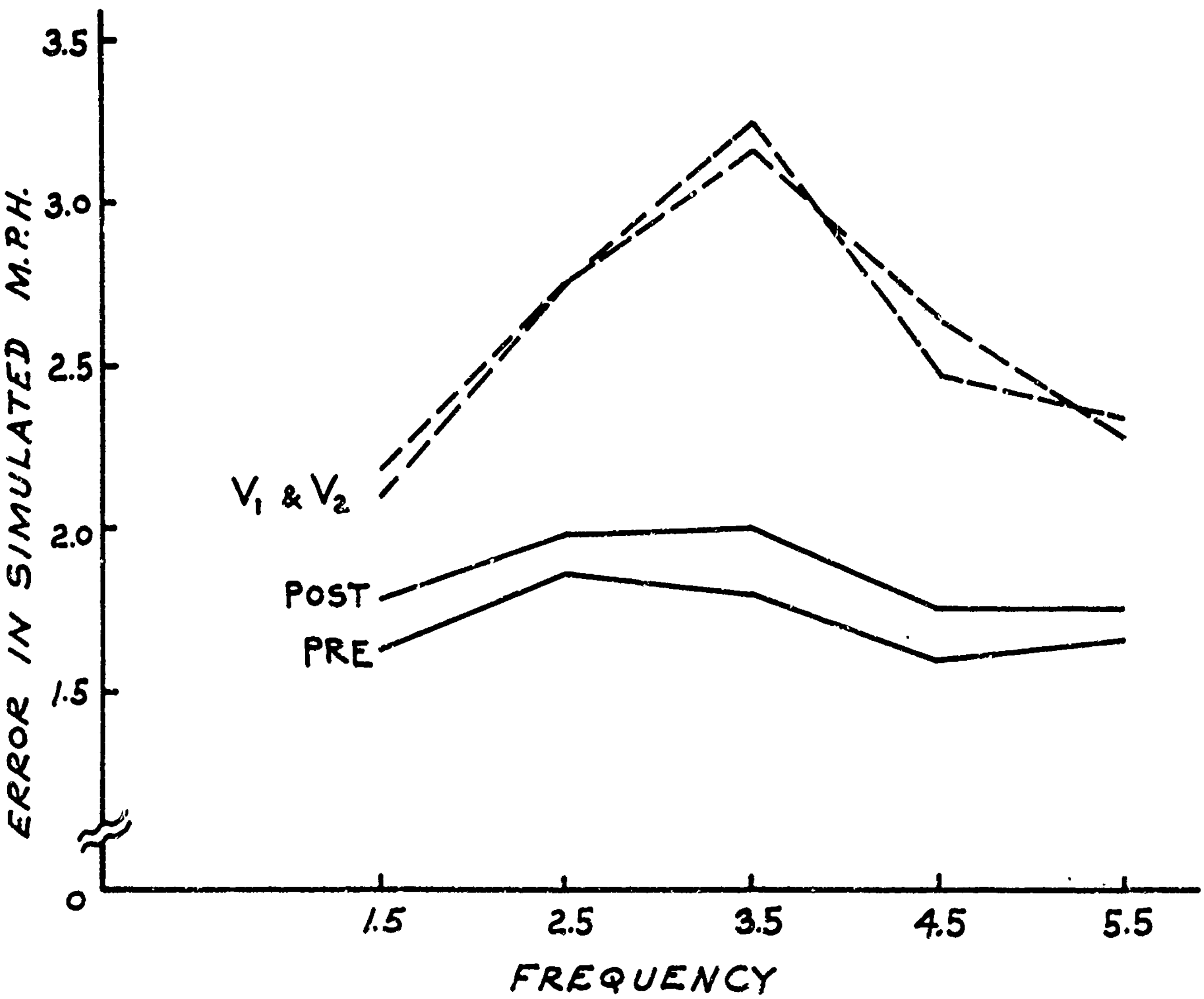

Fig. 15. Constancy of foot pressure as a function of frequency and time period for longitudinal vibration.

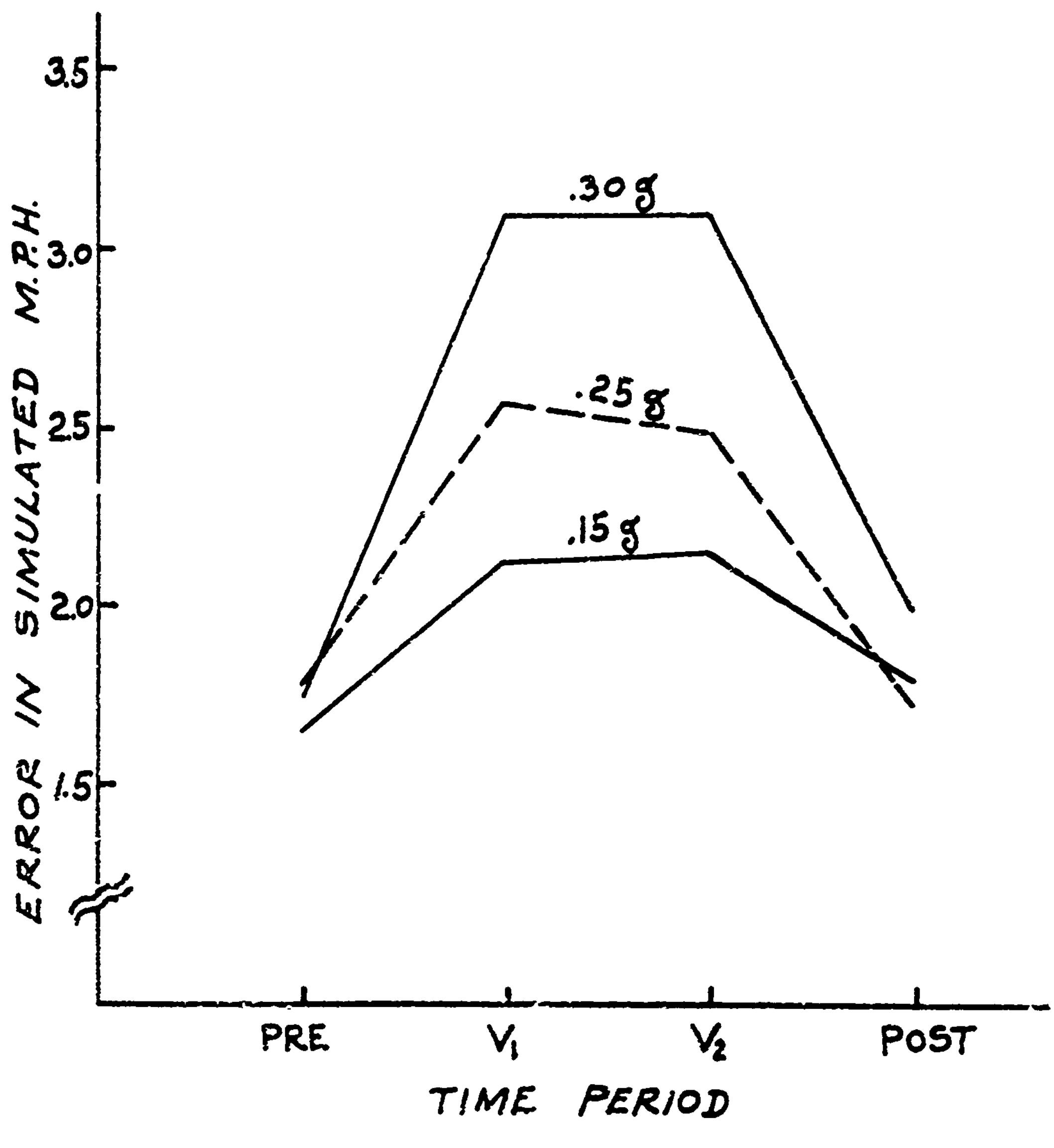

Fig. 16. Constancy of foot pressure as a function of intensity and time period for longitudinal vibration.

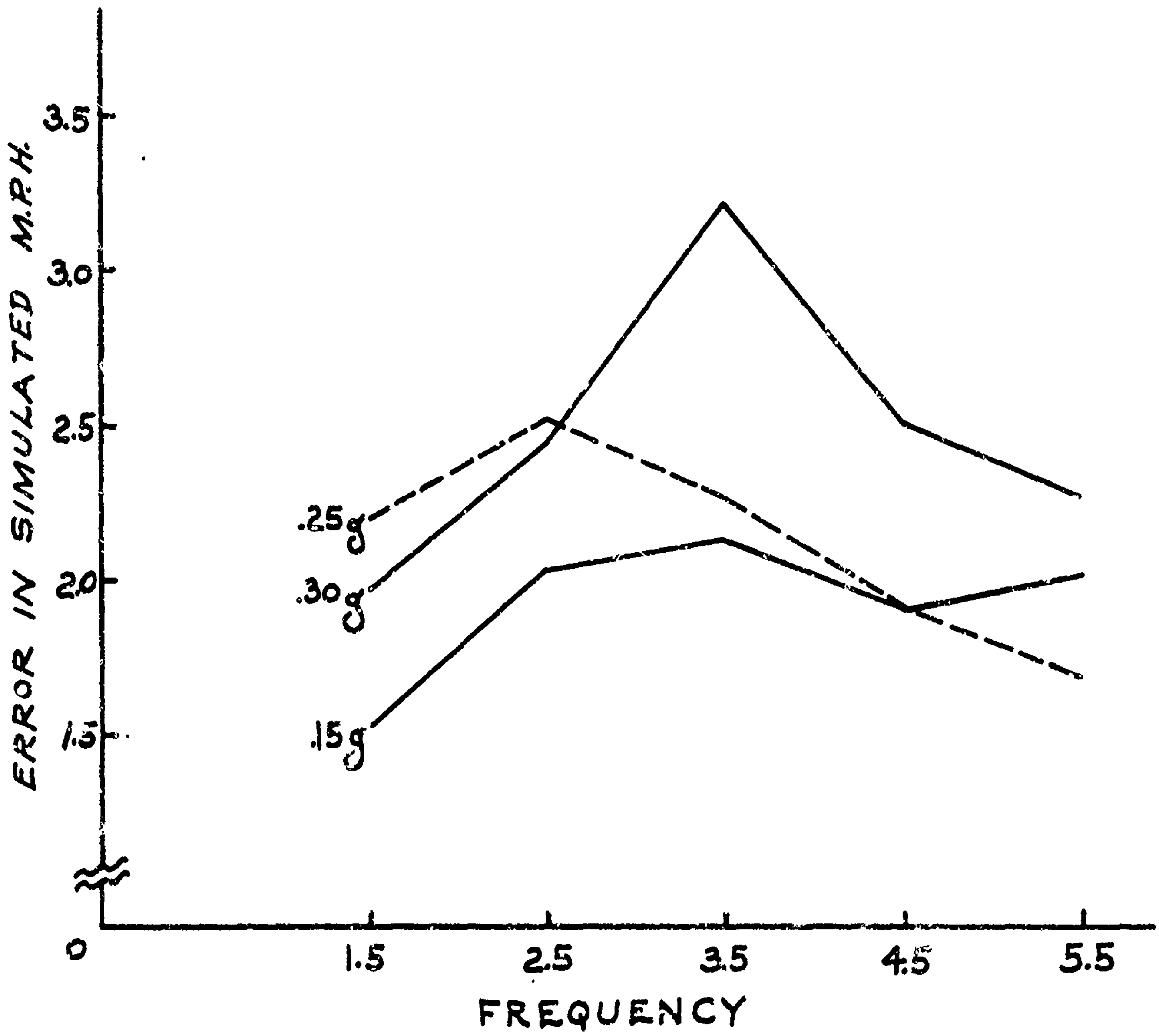

Fig. 17. Foot pressure constancy as a function of frequency and intensity during longitudinal vibration.

Visual Acuity

Analysis for visual acuity during longitudinal vibration indicates no significant effects.

Body Equilibrium

A comparison of body movement records indicate no differences for body sway in fore-aft or side-to-side planes. A _t_-test on the movement envelope areas verifies that there are no significant differences between pre- and post-vibration periods.

Transmissibility

The ratio of movement intensity of the body levels to the table motion is presented in Fig. 18. For each frequency the levels of intensity (0.15, 0.25, and 0.30 g) were combined because of a homogeneous group of means. Essentially, 5.5 cps elicits the greatest ratio of head to table, chest to table, and belt to table movements with a secondary peaking for the belt at 3.5 cps.

Oxygen Consumption

As is seen in Fig. 19, higher levels of longitudinal vibration (0.25 and 0.30 g) result in greater oxygen consumption than a control (no vibration) state. There is no relationship between vibration frequency and oxygen consumption.

Breathing Rate

There is no systematic relationship between vibration frequency or intensity and breathing rate. There is, however, a general lowering in breathing rate (as compared to a control level) during longitudinal vibration (See Fig. 20).

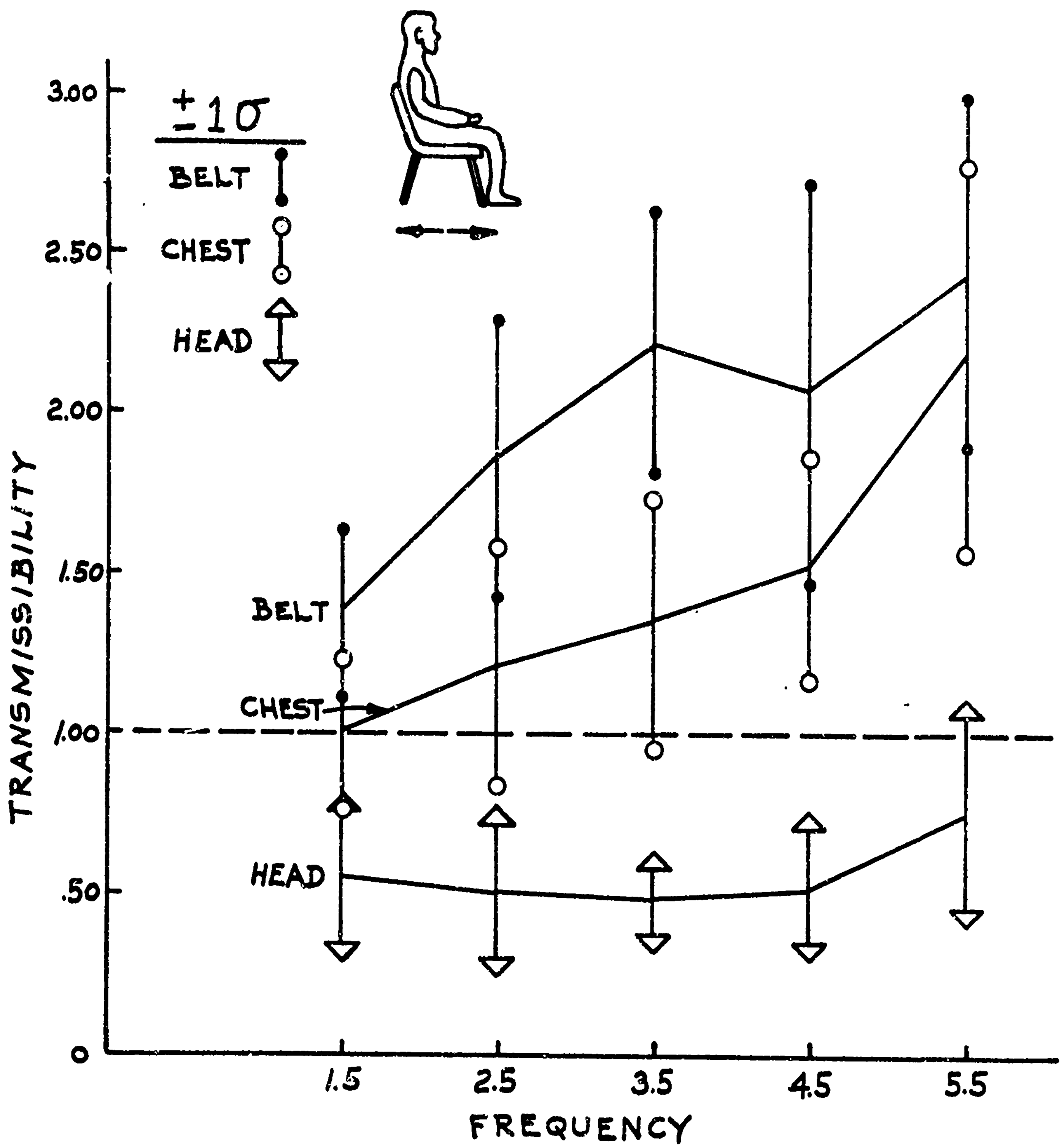

Fig. 18. Transmissibility at belt, head, and chest levels during longitudinal vibration. Values represent the ratio of the body acceleration intensity to table acceleration intensity. Standard deviations are presented for each mean.

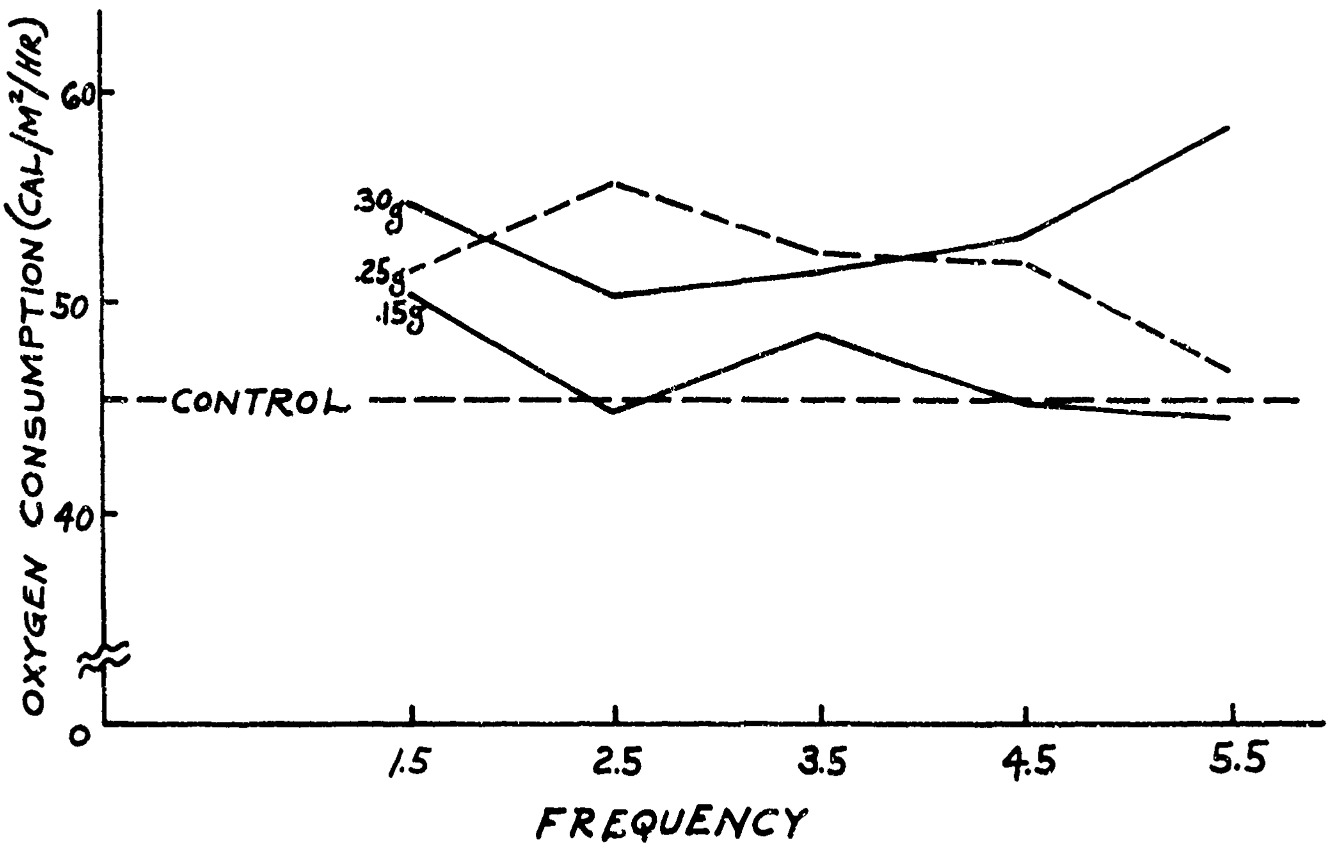

Fig. 19. Oxygen consumption during longitudinal vibration.

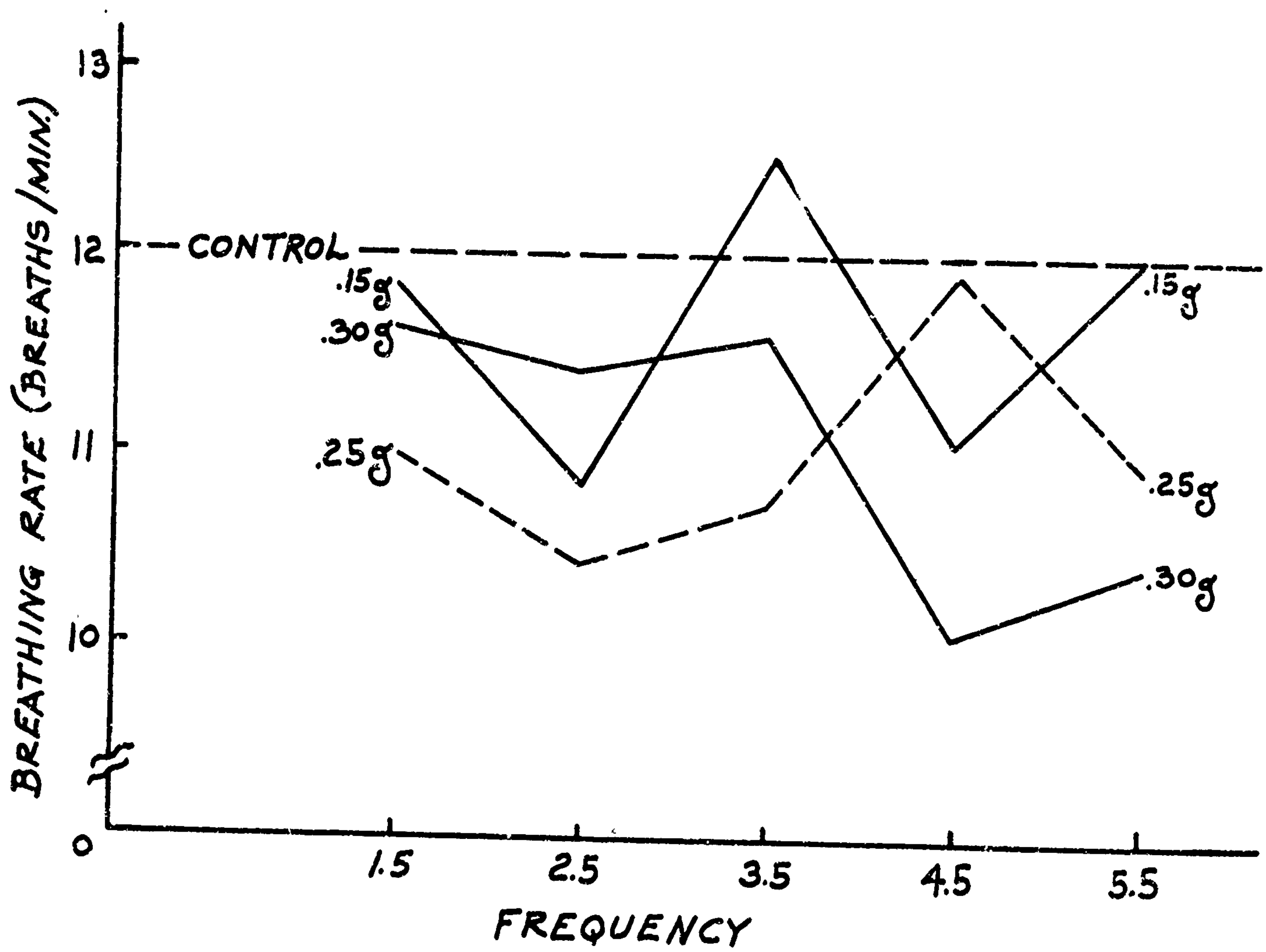

Fig. 20. Breathing frequency during longitudinal vibration.

Total Ventilation

The total amount of air moved increases during longitudinal vibration as compared to a control level. In addition, Fig. 21 reveals that as the intensity increases within a frequency, the amount of air moved also increases.

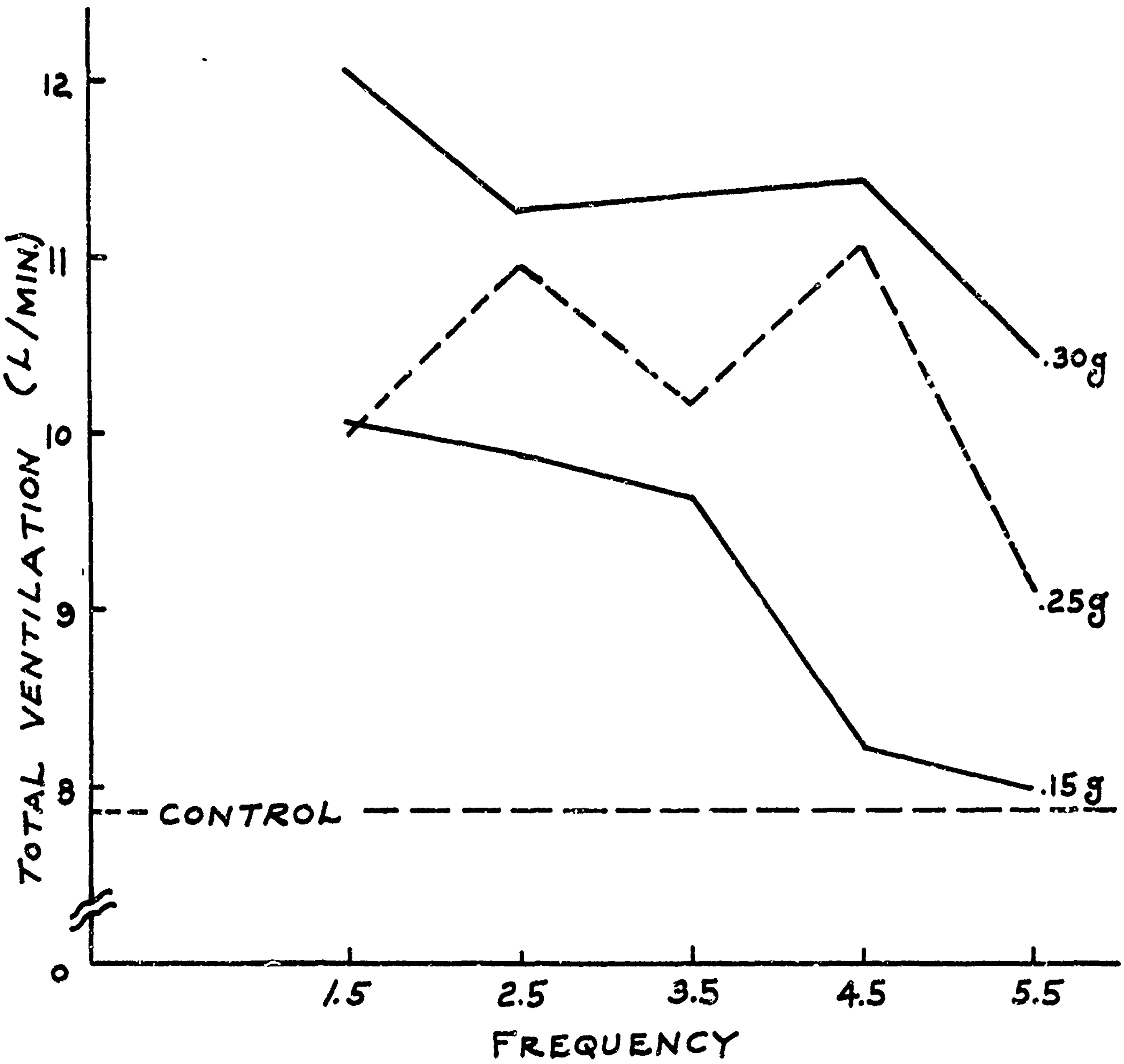

Fig. 21. Total ventilation during longitudinal vibration.

Discussion

The results did verify portions of the hypotheses stated in the introduction; other aspects were not borne out.

Regarding compensatory tracking ability, 1.5 cps produces greatest tracking error in the transverse direction, while no frequency was significantly most detrimental in the longitudinal direction. In both cases, there is significant tracking error as a result of the vibration itself, with error increasing as a function of vibration intensity. In both directions of vibration, there was a trend in error with time, with error being greatest during the last 15-minutes of vibration. In transverse and longitudinal vibration, this ability is not recovered completely during 15-minutes following vibration exposure. Such results are in partial agreement and conflict with those of Fraser (1960). Essentially, he found no difference in error between longitudinal and control conditions, but did find significant tracking error during transverse vibration. Fraser also found a significant intensity variable, but it was due to a low intensity level eliciting superior tracking performance to a control state, whereas this experiment revealed increases in intensity to yield increasing tracking error.

The fact that compensatory tracking ability does not show complete recovery has importance. It is conceivable that operators of some vehicles may have to perform a tracking task (on missile courses, for instance) after the vehicle has been in motion. It is seen here that one cannot assume that tracking ability recovers completely following vibration exposure. For some time during the 15-minutes after exposure, tracking ability is impaired.

The increase in tracking error through time is also an important consideration that will have to be handled in advanced vehicles which may be under power for great lengths of time and which require tracking on the part of operators.

Since tracking error is least for low intensity levels of vibration, the design engineer of crew compartments has a prime responsibility of developing vehicle suspensions and seating equipment which attenuates the inherent transverse and longitudinal vibration as much as possible.

Choice reaction time with either transverse or longitudinal motion shows no relationship to frequency or intensity of motion. No difference from a pre-vibration control level was noted during vibration. However, reaction time significantly increases (subjects slow down) following exposure to transverse vibration. This is consistent with simple reaction time experiments (Schmitz *et al.*, 1960; Hornick, 1961a) in which no vibration condition itself elicited a reaction time effect. Schmitz *et al.* (1960) also found a rise in reaction time following vertical vibration.

Here again is an ability which may be required of personnel in vehicles after being in motion. If situations are such that hasty decisions are required of vehicle occupants after a vertical or transverse vibration experience, it can be expected that they will respond slower than normal, and even slower than during such vibration.

A possibility for the rise in reaction time following exposure to vibration in vertical and transverse directions is that of a drop in subjects' motivation. It is possible that subjects relax during the post-vibration period and therefore react more slowly. However, if this were the case, it could be expected that other performance measures should show the same rise in error during the post-vibration session, which is not the case. Another reason for dismissing the drop in motivation possibility is that choice reaction time following longitudinal vibration does not reveal such a slowing down.

Foot pressure constancy is believed to be predominantly a bio-mechanical function. That is, human subjects cannot fully control the effective angle of the foot applying pressure to an accelerator pedal during transverse and longitudinal vibration. Foot pressure constancy was most severely affected at 1.5 and 2.5 cps during transverse, and at 3.5 cps during longitudinal vibration. Error increases with intensity. There is no trend of error over time, and recovery is virtually complete following exposure.

It is true, of course, that results as these may be due in part to the 42.3 pound-inches necessary for perfect foot pressure constancy. Different results might evolve from a situation in which greater or less pressure is required.

Peripheral vision is only impaired during transverse vibration, and only during the first 15-minutes of exposure, and at 1.5 and 2.5 cps. It is seen (Fig. 9) that the post-vibration period results in better peripheral vision than before or during vibration. However, it should be pointed out that while these variables (frequency and time period) do have statistical significance, there can hardly be much practical importance to the narrowing of the visual field from 95° 12' to 94° 42'.

The possible superiority of the post-vibration (transverse) peric for peripheral vision can most readily be accounted for in ter-s of either practice or inadvertant glancing to the sides on the part of the subject. This superiority is not seen with longitudinal vibration.

Visual acuity is not affected by horizontal vibration. As is indicated elsewhere (Hornick, 1961c), this is not surprising since studies indicate visual acuity to be affected by frequencies above 10 cps (Mozell and White, 1958; Guignard and Irving, 1960).

Body sway is not affected by horizontal vibration as measured in these experiments. A possibility that this phenomenon is affected by such vibration still exists, however, since due to the experimental procedure, the post-vibration measure was taken 15 minutes after the vibration sessions. This was necessary because it was essential to take other performance measures during the 15 minutes immediately following vibration exposure. It is possible that if body equilibrium is affected, it recovers during this time interval.

Transm ibility measures, particularly head movement, indicate body disturbanc to occur near or below 1.5 cps in the transverse direction. Belt, chest, and head movements indicate a disturbing frequency of 5.5 cps or above, with a secondary peaking of belt movement at 3.5 cps for longitudinal vibration. This is cons'stent with Dieckman's statements (1958) that resonant frequencies for transverse vibration are at 1.5 - 2 cps. For the longitudinal transmissibility phenomena, it is to be remembered that the maximum 5.5 cps disturbance comes about with the human seated on a chair with a rigid back support while wearing a lap-type seat belt.

Respiratory measures of oxygen consumption, breathing rate, and total ventilation indicate that probably a state of hyperventilation occurs during horizontal vibration. In general, during such vibration, breathing rate diminishes while oxygen consumption and total air moved increases. In addition, oxygen consumption increases most at 1.5 and 2.5 cps in the transverse direction with highest intensities of motion. Total ventilation during transverse vibration also is related to intensity increases. During longitudinal vibration, again, the oxygen consumption and total ventilation increases with the vibration intensity.

In general, for transverse vibration, greatest performance decrements occur at 1.5 to 2.5 cps; error increases as intensity increases; the resonant frequency of the body occurs near 1.5 cps; and probable hyperventilation takes place at 1.5 and 2.5 cps.

In general, for longitudinal vibration, greatest performance decrements occur at 2.5 to 3.5 cps; error increases as intensity increases; the largest mechanical response of the body occurs at 5.5 cps in the frequency range explored; and hyperventilation apparently takes place across this frequency range (1.5 to 5.5 cps).

Summary

Experiments were conducted to determine the effects of transverse and longitudinal vibration upon man's performance, body response, and physiological responses.

The experiment upon transverse vibration consisted of vibration frequencies of 1.5, 2.5, 3.5, 4.5, and 5.5 cps, intensities of 0.15, 0.25, and 0.35 g, while measures were taken before, during, and following vibration. Performance measures were of compensatory tracking ability, choice reaction time, foot pressure constancy, peripheral vision, visual acuity, and body equilibrium. Mechanical transmissibility records were taken at head and belt levels. Respiratory measures were of oxygen consumption, breathing rate, and total ventilation.

The experiment upon longitudinal vibration consisted of the same five frequencies with intensity levels of 0.15, 0.25, and 0.30 g. The same psychomotor performance and respiratory measures were taken. An additional transmissibility measure was obtained at the chest level.

Results were presented indicating specific frequency-intensity conditions as eliciting performance decrements; trends during exposure were noted; relationships of error to intensity pointed out; resonant frequencies of the human body determined; with physiological measures indicating hyperventilation during transverse and longitudinal vibration.

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