METHODOLOGICAL INVESTIGATION OF VIBRATION EFFECTS ON PERFORMANCE OF THREE TASKS

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ABSTRACT

Twenty young Navy enlisted male volunteers were first rehearsed and then tested before, during, and after whole-body vibration. Fourteen were tested only at 8 Hz, and six were tested at 8 Hz/0.21 g rms, 16 Hz/0.43 g rms and 32 Hz/0.85 g rms, using three paper-and-pencil tasks involving visual, motor, and cognitive skills. The tasks were "Spoke", a speed of tapping test; "Aiming", a test of fine motor coordination; and "Coding", involving mental computation. Results showed an approximately equal decrement effect across conditions in the Spoke and Coding (but not Aiming) tests that conforms with the frequency function embodied in the current international standard (ISO 2631:1978) on human exposure to vibration; but that a modicum of previous vibration experience may be necessary before reliable data are obtained in this kind of testing. Implications for methodology and for the application of the current standard are briefly discussed.

INTRODUCTION

An experimental program is underway at the Naval Biodynamics Laboratory to measure whole-body vibration effects in man. These studies are aimed at establishing correlations between the psychophysiological response and the biodynamic (inertial) response of human volunteer subjects to various mechanical input forces of the kind to be experienced at the crew stations of naval ships and aircraft. As part of the program, a series of four small pilot experiments has been conducted using vertical sinusoidal whole-body vibration. The purpose of this preliminary study of motor and cognitive task performance in vibration was to provide a reliable methodological basis for the systematic testing of human performance during the vibration program as a whole. A subsidiary purpose was to obtain further experience pertaining to the validity of the current international standard (ISO 2631:1978) on human exposure to whole-body vibration (International Organization for Standardization, 1978).

METHOD

Subjects and Groups

The subjects were 20 Navy enlisted men (aged 18 to 21) who had volunteered for duty as biodynamic research subjects. They had been selected to be unusually free of skeletal, cardiopulmonary and other medical or psychological conditions which would preclude participation in potentially hazardous environmental research. The subjects were otherwise typical of the general enlisted population. All subjects were recruited, evaluated, and employed in accordance with SECNAV Instruction Series 3900.39 and BUMED Instruction Series 3900.6. These instructions are based upon informed voluntary consent and meet provisions of prevailing national and international guidelines regarding proper human experimentation. A more detailed description of the volunteers and their selection is given by Thomas, Majewski, Ewing, and Gilbert (1978).

Nineteen of the subjects were divided into three groups. The first and second (G1 and G2) consisted respectively of 7 and 6 subjects comprising the subject population available to the Laboratory at the beginning of this study. The second group (G2), still with this Laboratory, participated in the sequence of four vibration experiments (1, 2, 3, and 4) described below; while the first group (G1) participated only in experiment 1 before being reassigned upon completion of their tour at the Laboratory. The third group (G3) consisted of 6 new replacement subjects who have recently been run in experiment 4 (a replication of experiment 1). Data from the one subject not included in any group, also a recent replacement, run in experiment 4, was treated separately because the subject's eyesight was atypical of general enlisted and civilian populations. The data from the visually atypical subject (VAS), however, were used later for model generalization purposes.

In summary, the second group (G2) of 6 subjects, participated in all vibration experiments while all 20 subjects (G1 - G3 & the VAS) took part in the first vibration condition (experiment 1 or 4).

Vibration Conditions and Procedures

The four sinusoidal vibration conditions are summarized in Table 1. These conditions were selected with reference to ISO 2631:1978. At each frequency studied, the root mean square (rms) acceleration applied vertically to the seat was twice the value of the "Fatigue/Decreased Proficiency Boundary" defined in the standard for short-term, whole-body vertical vibration exposure. On the hypothesis that the standard is valid, each condition studied should have had an equal potential for degrading task performance. G2 subjects experienced these conditions sequentially, at approximately monthly intervals.

Table 1. Vibration Conditions

Experiment	Subject Groups	Frequency (Hz)	Acceleration (g_z rms)
1	G1 & G2	8	0.21
2	G2	16	0.43
3	G2	32	0.85
4	G2 & G3 + VAS	8	0.21

Experiment 4 replicated Experiment 1, in order to show whether repeated experimentation altered results obtained in identical conditions.

Prior to every vibration exposure, subjects were given 5 trials of each task in a training session on the day preceding their experimental run. On the experimental day, before boarding the vibration machine, subjects performed each task once, to "warm up". Once mounted on the vibration machine, one (data) trial of each task was adminstered before (B), during (D) and after (A) vibration. The duration of exposure to vibration was standardized at 8 minutes in all four experiments. The training session and the administration of vibration conditions in the same order for all subjects preserved individual differences of performance, thus vastly improving the sensitivity of the methodology to the effects of vibration.

Apparatus

The subjects rode seated on the Laboratory's 28,000 lbf electrodynamic vibration machine, operating in its vertical mode (i.e., vibrating in the direction of gravity), and equipped with a rigid seat and foot-rest directly coupled to the armature of the machine. The hard seat was, for comfort, shaped in a fashion similar to that of a farm tractor seat; and incorporated the seat reference accelerometer used to monitor the vibration input to the subject in his Z-axis. Only gravity was used for restraint: there were no straps or back-rest. The machine is capable of shaking a seat and human subject without extraneous mechanical support or appreciable distortion of the vibration waveform in the conditions studied: rms acceleration at the seat was controllable to within ± 1%; vibration frequency was controllable to within ± 0.5%; and total harmonic distortion was negligible.

Subjects were provided with clip-boards for holding task materials and with fine-point marker pens to enter responses. Tasks were presented in a random order and timed by a test administrator who stood on the platform beside the vibration machine. Table 2 summarizes the three experimental tasks.

Table 2. Experimental Tasks

Task	Description	Reference
SPOKE	Tapping a marker pen inside 1 cm circles following hand movements of 12 cm for time to complete 32 taps (Score is time per correct response).	Bittner, Lundy & Kennedy (in the press)
AIMING	Tapping in adjacent 2 mm circles for 180 seconds (Score is number of taps correctly placed).	Fleishman & Ellison (1962)
CODING	Letter to digit coding for 120 seconds (Score is number correct).	Pepper, Kennedy, Bittner & Wiker (1980)

The tasks were chosen to test gross motor, fine motor, and mental performance in response to visual inputs: this selection was based upon previous work cited in the literature (Guignard, 1965, 1972) showing that vibration may degrade performance either by disruption at the point of contact between man and task or by the distraction of cognitive processing.

ANALYSIS AND RESULTS

Analysis was conducted in two phases. In the first phase, the data from all 20 subjects who served in experiments 1 and 4 (8 Hz, 0.21 g rms) were analyzed; and, in the second phase, the data for the 6 subjects who served in all four studies (1 to 4) were analyzed.

First Phase Analysis

The first phase analysis was directed at: (1) comparison of the 3 groups repeated over Before (B), During (D), and After (A) vibration exposures; (2) determination of the fine-structure models which best characterized task (Coding, Spoke and Aiming) response to vibration; and (3) estimation of the magnitude of individual mental (coding) effects uniquely due to vibration.

Comparison of Groups

Two-factor analyses of variance (ANOVA) with repeated measures over Before (B), During (D), and After (A) vibration conditions were conducted for Spoke, Aiming and Coding. Summaries of these analyses are given in Table 3 which reveals essentially equivalent results for all tasks. Non-significant effects are seen ($p > .3$) across all tasks, indicating no overall differences.

Table 3. Results of First Phase of Analysis

Source	df	MS	F	p
SPOKE TASK				
Between Subjects				
Group (G)	2	3.23	1.18	NS
Subs Within G	16	2.75	5.71*	10^{-4}
Within Subjects				
Repetitions (R)	2	5.94	12.33	.0002
B vs A	1	5.79	12.02	.002
D vs (B + A)/2	1	6.09	12.64	.002
R x G	4	0.36	0.74	NS
R x Subs Within G	32	0.48		
AIMING TASK				
Between Subjects				
Groups (G)	2	5238.1	0.59	NS
Subs Within G	16	8910.1	9.22*	10^{-6}
Within Subjects				
Repetitions (R)	2	32837.1	33.97	10^{-7}
B vs A	1	4949.8	5.12	.035
D vs (B + A)/2	1	60724.4	62.83	10^{-8}
R x G	4	980.0	1.01	NS
R x Subs Within G	32	966.6		
CODING TASK				
Between Subjects				
Groups (G)	2	209.4	1.27	NS
Subs Within G	16	164.1	5.51	10^{-4}
Within Subjects				
Repetitions (R)	2	1083.4	36.38	10^{-7}
B vs A	1	44.6	1.50	NS
D vs (B + A)/2	1	2122.1	71.27	10^{-8}
R x G	4	113.7	3.82	.02
R x Subs Within G	32	29.8		

* Conservatively tested against R x Subjects within G.

Individual differences, as assessed by very highly significant ($p < 10^{-4}$) subjects-within-group effects, are seen to be a large source of variation for all tasks. The orthogonal (B vs A) Repetition contrasts revealed significant ($p < .035$) overall improvements in performance for Spoke and Aiming, but overall improvement for Coding was not significant ($p > .22$). However, the vibration-baseline (D - (B + A/2)) contrasts were very highly significant ($p < .001$) across all tasks in all cases. The Groups by Repetitions (R x G) interaction was not significant ($p > .4$) for Spoke and Aiming. However, the Coding R x G interaction was significant ($p < .02$): Table 4 illustrates this interaction.

The Groups can be seen to be equivalent in the Before and During conditions; but for the After condition, Group 3 shows an incomplete recovery falling below the improving performances of Groups 1 and 2.

Table 4. Coding: Groups by Repetitions Interaction

	REPETITION		
Group	Before	During	After
1	72.4	58.1	78.0
2	73.2	60.0	77.8
3	68.3	59.8	64.2

Pertinently, the Coding Baseline-Vibration (D vs (B + A)/2) Repetition contrast is significant ($F(1, 4) = 18.66$; $p < 0.05$) when tested against R x G, indicating main effects generalization across groups. Hence, the ANOVA overall revealed substantial vibration versus baseline effects which generalize across groups for all tasks.

Fine Structure Response to Stress

Three linear-form models of subject response to stress were fitted to data for the 19 subjects in Groups 1 to 3 for Spoke, Aiming, and Coding. Letting the i-th subject's baseline be $X_{0i} = (B_i + A_i)/2$, and his stress performance be $X_{1i} = D_i$, and e_i = random error, these models were: (I) $X_{1i} = a+X_{0i}+e_i$, (II) $X_{1i} = bX_{0i}+e_i$, and (III) $X_{1i} = a+bX_{0i}+e_i$, where a and b are empirical constants.

These models have been described earlier and applied to preliminary data (Bittner, 1981). Subsequent to fitting models, vibration performance of the visually atypical subject (VAS) was predicted from his baseline for each model.

Analysis of data from each test using 19 subjects provided no evidence for rejection of the simplest model (I) in favor of a more complicated model (II or III) ($p > .07$). Comparison of the models based on the VAS, indicated Model I was best for the Aiming Test, Model II was best for Code Substitution, and Model III was best for the Spoke Test. In summary, the simple additive model (I) appears to be adequate for description of effects of vibration, at least at 8 Hz, although more complex models may be more appropriate for generalization to some unusual subjects like our VAS.

Assessment of unique Vibration Effects on Coding

Multiple correlation analysis was performed to assess the nature of vibration effects on Coding. Employing Coding during vibration as the criterion, predictors were: Coding Before; Spoke Before and After; and Aiming Before and After. The substantial R = 0.86 ($F(5,13) = 7.15$; $p < .003$) indicated that only a relatively small proportion of the change in coding scores during vibration could be attributed to a mental (not manual) effect of vibration.

Second Phase of Analysis

Code Substitution

Means and standard deviations for each condition are shown in Table 5.

Table 5. Means (and Standard Deviations) for Code Substitution

	Before	During	After
8 Hz(1)	73(12)	60(14)	78(11)
16 Hz	72(11)	75(7)	76(11)
32 Hz	80(11)	79(26)	75(8)
8 Hz(4)	84(10)	70(10)	80(7)

The question of primary interest was whether the effect of vibration (D- (B + A)/2)) changed from one frequency to another No such change was detected ($F(1,15) = 1.87$, $p > .1$). Hence, the ISO limits provided acceleration contours which produced indistinguishable performances at each frequency. Averaging across frequencies, there was a dip in performance attributable to vibration ($F(1,5) = 7.27$, $p = .04$), and that effect accounts for 99.8% of the variance of B, D, and A. Averaging across B, D, and A, the (linear) increase in performance due to repeated exposure to the tasks at each frequency narrowly missed statistical significance ($F(1,5) = 4.95$, $p = .08$). All non-linear trends were nonsignificant ($p > .5$). The change of performance from B to A within each of the four frequency conditions shows a bigger practice effect during earlier conditions (8 Hz(1), 16 Hz) than during later conditions (32 Hz, 8 Hz (4)) ($F(1,5) = 34.4$, $p < .02$). These were the only salient effects of vibration and repeated measurements on code substitution performance.

Spoke Test

Means and standard deviations are shown in Table 6. As with code substitution, the

Table 6. Means (and Standard Deviation) for the Spoke Test

	Before	During	After
8 Hz(1)	10.1 (1.3)	10.3 (.8)	9.5 (1.1)
16 Hz	8.7 (1.0)	9.0 (1.1)	8.9 (1.0)
32 Hz	8.3 (.8)	8.8 (1.0)	8.3 (1.2)
8 Hz(4)	8.2 (.9)	8.9 (1.2)	7.9 (1.2)

effect of vibration, (D- (B + A)/2)) did not change appreciably from one vibration condition to the next ($F(3,15) = 1.46$, $p > .25$). Hence the ISO standard seems to be validated for this gross manual task, as it was for the mental task of Code Substitution. Averaging across frequencies, there was a dip in performance during vibration (D) compared with baselines (B and A), $F(1, 5) = 22.25$, $p = .005$). Averaging across B, D, and A, there was a practice effect from one frequency to the next that was 86% linear ($F(1,5) = 15.74$, $p = .01$), with no significant nonlinearity.

Aiming

Means and standard deviations are presented in Table 7.

Table 7. Means (and Standard Deviations) for the Aiming Test

	Before	During	After
8 Hz(1)	415 (28)	379 (44)	438 (30)
16 Hz	453 (43)	456 (21)	469 (41)
32 Hz	482 (36)	472 (28)	466 (59)
8 Hz(4)	495 (59)	438 (15)	523 (60)

The results for this task are quite different from the results for the other two. Most notably, there is a difference in the size of the effect of vibration from one frequency to another ($F(3,15) = 11.96$, $p < .01$). The effect was larger by an order of magnitude at 8 Hz, than it was at 16 or 32 Hz. The ISO limits did not provide for homogeneous performance across frequencies in the case of Aiming. Averaged across frequencies, there was no statistically significant main effect of vibration ($F(1,5) = 4.23$ $p = .1$). There was, however, a plethora of practice effects, within frequencies ($F(1,5) = 7.01$, $p = .05$), and a linear effect across frequencies ($F(1,5) = 17.32$, $p = .01$) which explained 88% of the overall variance of performance from one frequency to the next.

DISCUSSION

Individual Differences

Large individual differences were a consistent feature of both analysis phases. These differences were highlighted in the first phase where ANOVAs for all tasks, fine-structure models and assessment of vibration effects on coding relied on their presence. The consistency of individual differences was a goal which motivated the selection of tasks, training, and use of the same order of treatments for all subjects. The efficacy of the present procedures appears to be supported. However, there is some basis for caution when testing naive subjects indicated by the first phase analysis of Coding.

In this analysis, the group least exposed to vibration (G3) was seen to differ from more experienced groups only in the After-condition. This finding suggests that there should be familiarization of subjects to vibration prior to collection of performance data in future studies of this kind. However, the results, taken together, support the repeated measures procedures and experimental design employed in this investigation.

Practice Effects

A consistent feature seen in this investigation was both between- and within-condition evidence of learning. Assessment of vibration effects independent of learning, however, appears facilitated by the use of the Vibration vs Baseline, D -(B + A)/2, contrast. Only for subjects inexperienced in vibration was there any indication that this contrast might be unsuitable. The analysis of fine-structure responses to stress also provides some indication that alternative (e.g., co-variance) methods would be of value when atypical subjects are included. However for "typical" subjects, the additive model has utility. Altogether, the D - (B + A)/2 contrast is supported for future investigations.

Standards

The efficacy of applying current vibration standards to performances was questioned in this study. While Spoke and Coding performance were found equivalent across vibration conditions, Aiming was found to be differentially affected at 8 Hz vs 16 and 32 Hz. Indeed, the vibration decrement is an order of magnitude greater at the lowest frequency, indicating mechanical interference. The differential interference of frequency on performance during vibration deserves further investigation.

The results showed that performance of the Code Substitution and Spoke tasks (although not for Aiming) was significantly degraded in a way consistent with the human response frequency function for task performance embodied in the international standard, ISO/2631:1978, "Fatigue/Decreased Proficiency Boundary". In other words, the data appear to support the frequency-weighting given in the standard to provide an "iso- decrement" guideline, at least for the relatively high acceleration levels and short durations used in our experiment. In a previous experiment, Guignard, Landrum and Reardon (1976) had found no significant change in performance scores on a variety of tests during human exposure to the corresponding vibration levels standardized by ISO/2631:1978 for long-term exposures up to 8 hours, and had concluded that, for such exposures at least, the standard might be unduly conservative. This may well be an indication that the guidelines in the standard for long-duration exposures beyond a few minutes duration are indeed based uncertainly on extrapolation from very meager data and will require revision in the light of future experimentation.

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