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EFFECTS OF SIMULATED TRACTOR VIBRATION ON THE PSYCHO-PHYSIOLOGICAL AND MECHANICAL FUNCTIONS OF THE DRIVER: COMPARISON OF SOME EXCITATORY FREQUENCIES

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Erkki Wuolijoki

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ERKKI WUOLIJOKI

SELOSTE:

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HELSINKI 1981

CONTENTS

PREFACE

The aim of this study was to elucidate the effects of forest machine vibration on the working ability of the driver. Properties of the applied vibrations of different frequencies were evaluated from an ergonomic point of view.

The problem area of this study was derived from nineteen ergonomic test reports of different forest machine types, which I was allowed to perform at Work Efficiency Association (Työtehoseura ry) during 1973–1977.

This study done at Work Efficiency Association consists of laboratory experiments by using a vibration simulator at the Department of General Science, Helsinki University of Technology.

The assistance of the following persons made the study possible:

Jyrki Ronkainen, M.Sc. (Mech. Eng.)
– design of the simulator
– synthesis of excitatory vibrations

Tua Äikäs, M.Sc. (Phil.)
– Analysis of catecholamines

Professor Henrik Wallgren, Ph.D., Division of Physiology, Department of Zoology, University of Helsinki, encouraged me during various stages of my work.

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Mr Richard Burton, B.Sc., and Mrs Liisa Jones have revised the English language.

The investigation has been accepted to the publication series of both The Society of Forestry in Finland and Work Efficiency Association.

My wife Maria and our children Katariina and Sakari have made the success of this study possible by their sustained patience and encouragement.

I wish to express my sincere gratitude to all people and organizations mentioned above.

Espoo, Finland, July 1980

ERKKI WUOLIJOKI

CONCEPTS USED IN THE STUDY

In this study the term vibration means mechanical motion of a body to and from a position of equilibrium of all frequencies.

Vibration parameters used in this study:

Quantity:	Unit:
displacement	m, mm
velocity	m/s
acceleration	m/s²
frequency	cycle/s, Hz

Also root-mean-square values of three first parameters are used. In those cases the parameters are given with the letters RMS.

The term intensity is used for expressing the energy content of the vibration. Theoretically it could be measured in Watts (1 Watt = 1 kgm^2/s^3) but such measurements were not done in this study.

1 INTRODUCTION

1.1 The Research Problem

Man has been subject to many kinds of vibrations (walking, running, fighting) during his evolution. His ability to stand and absorb external forces and energy must have played a role in his survival.

Mechanical vibration affecting the machine driver's body may have positive and negative effects on the driving. In order to reduce the negative effects of vibration of machines, the designer of the machine must have information about the relative importance of different mechanical parameters of motion (e.g. displacement, velocity, frequency) having possible negative effects on machine driving.

The aim of the present investigation was to generate information on the effects of vibration on the forest machine driver and his driving ability. After getting knowledge of how driving ability generally responded to vibration, the degree of disturbance due to differences in mechanical vibration parameters was studied.

The experiments were designed to produce information on whether a special natural frequency of tractors within 1–4 Hz frequency area is less harmful for the drivers.

As the driver's body and seat form spring-mass systems with natural frequencies, the excitatory frequency of vibration may have a pronounced effect on the transmission of motion from machine to man. This effect may be especially pronounced in case of lateral motions, when the gravity of the earth does not fix the driver's body to the seat as tight as it does with vertical motions (figure 1).

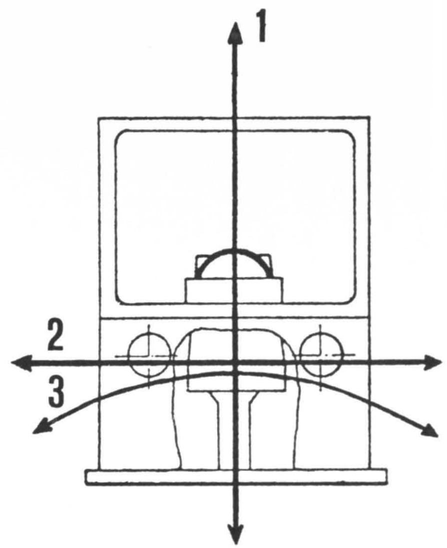

Figure 1. Definition of coordinate systems of cabin motions:
1 Vertical (z-axis) vibration
2 Lateral (y-axis) vibration
3 Rotational vibration in lateral direction

The characteristics of forest machine vibration can be modified by altering the displacement and/or the natural frequency of the cabin. Displacement and acceleration due to terrain roughness can often be decreased by the driver by choosing a good driving track or driving slower (ZYLBERSTEIN 1980, BÖRJESSON et al. 1980). Instead, the natural frequency of the machine cannot be altered by the driver as it has been already determined by the designer of the machine.

The natural frequencies of heavy tractors with air-filled tyres have been reported to be about 1 to 4 Hz with a bandwidth of about 10 to 40 %, in both lateral and vertical directions (CHRIST and DUPUIS 1963, BJERNINGEN 1966, SJÖFLOT and SUGGS 1972, KÄTTÖ and SALMINEN 1973, HAHLMAN 1977, and BÖRJESSON et al. 1980). As non-linearities in the frequency area of 2 to 20 Hz in body transmissions between excitatory frequencies are reported (ZAGORSKI et al. 1976, BASTEK et al. 1977), the possibility for reduction of vibration transmission by altering the natural frequency was present. The vibration characteristics of the already existing machines steered the study to a comparis on of effects of different frequencies of relatively narrow bandwidth (10 to 40 %) in the range of 1 to 4 Hz.

1.2 Methodology

Cabin vibration as an environmental factor may have psychological, physiological or mechanical effects on the driver. This loading, if intense enough, may result in fatigue* (psychological, physiological or mechanical). Fatique thus induced may in the long run secondarily lead to increased absence from work and even to direct clinical disorders (JOHANSSON 1974, ARONSSON 1976,).

The negative effects of vibration could theoretically be measured as "primary" effects (i.e. effects on the driver's fatigue or working ability) os as "secondary" effects (effects on the health, absenteeism and labour turnover.

Because effects of the varying parameters of vibration were studied, the required vibration would need to be adjustable according to the test situation. As parameters of vibration are not easily adjustable in field experiments, it was necessary to build a simulator in the laboratory. Correspondingly, the main emphasis was placed on the primary effects exerted by vibration on the driver.

* Fatigue: decreased working ability due to lack of recovery

2 SURVEY OF THE LITERATURE

2.1. Specifity of the Effects

Several hundred studies have been carried out on the effects of mechanical oscillations on the organism.

Among others, the following have published review articles on the effect of vibration on the mammalian body: CLEMEDSON (1962), DUPUIS (1969), HASAN (1970), SHOENBERGER (1972), COLLINS (1973), HUSBERG (1974), SOININEN (1975), WUOLIJOKI (1976), and HEIDE et al. (1978).

According to OBORNE (1977), in experiments with human material the effects of vibration have generally been evaluated by subjective rating scales or opinions, using movement of sinusoidal waveform in the frequency area from 0 to 100 Hz.

The purpose of many experiments involving human and animal material has been the elucidation of the effects of flying in which vertical acceleration is of importance (Hornick et al. 1966, KNAPP 1974, SHOENBERGER 1974, and GRIFFIN 1975).

The planning of a study on lateral rotational vibration with the aid of results of experiments made in vertical direction is difficult: firstly because of different directions of linear motions, and secondly because the centrifugal force of the rotational movement opposes the gravity of the earth.

The mechanisms of physiological effects of vibration reaching the whole body are poorly known, and there are differing explanations for various findings in the body. Most of the review articles do not propose any general mechanism of action for whole-body vibration.

HASAN (1970, p. 24) divided physiological reactions to low-frequency vibration (''from a few cps to about 100'') as follows:

1 Changes directly attributable to the differential vibratory movements, such as deformations of body tissues and structures
2 Changes of reflex action consequent to the excitation of various receptor organs and other neural elements by vibration
3 Functional alteration which represents generalized responses of the organism to vibration as a non-specific stressor

According to ASANOVA (1976, p. 128), whole-body vibration* produces a specific clinical picture. The most typical features are:

1 Disorders of the central nervous system (CNS) with diencephalic symptoms
2 Autonomic dysfunction with a neurasthenic background
3 Miscellaneous: total weakness, quick fatigability, disturbed sleep

VALČIĆ (1976, p. 84) describes the disorders resulting from ''the general effects of vibration'' (from 0 to about 25 Hz). According to him, the symptoms reveal an impairment of the central nervous system as well as of the vegetative system. ''The emotional area is noticeably altered and the psychoasthenic picture is very pronounced''.

WARBANOW and WASSILEWA (1977) divided the effects of vertical low-frequency vibration upon the driver into specific and non-specific alterations. The specific alterations of physiological function were linked to different frequencies (6 and 16 Hz) of vibration, while the non-specific alterations were linked to a general stress reaction with an increased activation of sympathetic nervous system.

A hypothetical ''unspecific influence'' of vibration on the central nervous activation is reported and discussed by BASTEK et al. (1977). They assumed (p. 174) that this was triggered by a reticulo-cortical mechanism similar to the one reported to occur due to high noise. Whether the reported decreased reaction times and increased number of errors in signal-detection test were due to too high or too low an activation level, is not discussed.

CUTCHEON (1974) classified the physiological effects of vibration into two major types. The first category included the changes produced directly by the applied acceleration as a function of the biomechanical properties of the body. The other category included the changes produced by compensatory or adaptive adjustments to the biomechanical alterations, and the changes produced indirectly by the effect of vibration exposure as an overall environmental stress.

* Apparently from 0 to about 100 Hz (note by the author of this publication)

ABRAMOVICH et al. (1973) classified the experimental effects of hand-arm vibration on the oxidative processes to direct local action (reduction) and to secondary general defensive reflex actions (intensification) aimed at maintaining the body homeostasis.

It is noteworthy that the alteration of intensity of vibration (in the meaning of a non-specific agent, SELYE 1950, p. 7–9) may have specific and non-specific effects.

In this study the specific effects can only be caused by alteration of vibration intensity, whereas the non-specific effects can as well be caused by other agents, like vibration contra no vibration

It seems fruitful to separate the non-specific effects from the specific ones. The non-specific effects may be similar to each other whether they are triggered by physical work, climate or fear (SINGLETON et al., 1971). This reduces the value of variables of non-specific effects as measurement tools in this study because the variation of physical vibration parameters is examined.

On the following pages, the effects of vibration are reviewed in order to build up a clinical picture on the effects of lateral motion in the frequency area of 1 to 4 Hz. According to page 9, chapter 1.2, the effects are divided into three groups as follows:

1 Effects on the psycho-physiological functions of the driver
2 Mechanical effects on the driving procedure
3 Mechanical effects on the driver's body

2.2 Effects on the Psycho-physiological Functions

Subjective rating

Vibration may be enjoyed e.g. in the case of rocking chairs and fun-fairs (LANCET 1977).

As the vibration of forest machines is supposed to be a factor of importance in the determination of driving speed owing to the discomfort it causes (APPELROTH 1975, p. 4, SIREN et al., 1979, p. 4), the subjectively perceived vibration can be considered as a variable having an effect on the driver's psycho-physiological functions.

The most widely used method for measuring effects of vibration on man has involved various subjective rating scales (MC CULLOUGH et al. 1974, p. 78). It has been assumed that the course of awareness of effects agrees to ''a considerable extent with the course of some reactions of the body'' to the vibration (LOUDA 1970, p. 62, DUPUIS et al. 1972, p. 238).

The norms dealing with negative effects of vibration (e.g. ISO 2631–1978, VDI 2057–1963) are also based on information provided by questioning methods (e.g. MIWA 1967 a, b, 1968 a, b, c, d, DIECKMANN 1958).

BASTEK et al. (1977) used three five-step dipolar rating scales simultaneously in a vertical vibration experiment. The scales evaluated comfort vs. discomfort, activating vs. fatiguing influence and influence on the fulfilment of the tasks (facilitating vs. impending). According to the results, the rating scales are valuable tools for evaluating the effects of different kinds of vibrations (sine vs. stochastic), but the effects of vibration on the performance and the physiological reactions ''do not always correspond to the statements in the way in which the situation is perceived'' (p. 1974).

In the study of JONES et al. (1974) with sinusoidal vibration exposures in vertical direction, the subjects (N = 66) were able to consistently estimate the relative intensity of two short-time stimuli following each other over an objective acceleration ratio in the frequency range from 5 to 80 Hz.

Because the vibration parameters in this study were bound to be adjustable according to test situation, a numerical rating system was chosen instead of a comparative estimation. The use of a pure semantic scale was ommitted, because various impressions (like unpleasant or irritating) may have different meanings to different subjects (JONES et al. 1974, MC CULLOUGH et al. 1974). FOTHERGILL et al. (1977) avoided this problem by using the subject's own adjustment of the excitation to a reference level with the same degree of discomfort.

If the subjective magnitude rating of vibration increases, the physiological functions of the body do not necessarily have to be more intense than before. On the other hand, it is possible that a person does not experience the vibration as disturbing even though it might be producing clinically demonstrable changes in certain tissues (DUPUIS 1971, p. 79).

Based on the papers referred to above, there are possibilities for measuring one component of the effects by subjective rating scales by using a numerical rating scale with corresponding semantic terms for reaching the necessary specifity.

Condition of the Central Nervous System

It has been assumed that the general effect of whole-body vibration on the central nervous system (CNS) is an alteration in the level of activation or arousal (HASAN 1970, p. 28). The characteristics of the motion, its continuity, intensity and regularity are of importance because an even or harmonic motion may even lower the activation level and act soporificly (GAEUMAN et al. 1962).

In a simulated vertical vibration study MALINSKAYA et al. (1975) noted "vestibulary-somatic, vestibulary-sensory, and vestibulary-vegetative" emergency reactions. Their experiment using 2, 4, and 8 Hz was done by measuring galvanic skin response, electronystagmography, EEG-protuberance and cerebral blood flow. Also a test on otholite function was used.

The findings of worsened attention performance during simulated vertical vibration experiments (BASTEK et al. 1977) as well as the increases in choice reaction time tests (SHOENBERGER 1970, COHEN et al. 1977) support the role of the altered activation level of the CNS in the picture of effects of whole-body vibration. HORNICK et al. (1966) reported a study using stochastic vertical vibration. The RMS-values of acceleration up to 2 m/s² at 1–12 Hz did not affect the reaction time. Instead, vigilance for sub-system monitoring was significantly impaired being independent on exposure time or intensity.

In agreement with the review of HASAN (1970), CHERNIUK (1975) reported higher central nervous activity and pulse rate during wholebody vibration. The study, made with simulated intermittent excitation, came to a recommendation of pauses of 15 minutes between every 30 minutes of vibration. This recommendation was made to reduce the CNS-effects of whole-body vibration. This favors an experimental period not less than 30 minutes for monitoring the effects on the central nervous system.

In regard to the sensitivity of activation level of the central nervous system to different vibration intensities, HORNICK et al. (1961) did not find correlations between reaction time and frequency or intensity of lateral vibration of 1.5–5.5 Hz. Only the time period of vibration was a significant factor. This finding as well as the publication by HORNICK et al. (1966) supports the non-specific nature of vibration intensity as an agent disturbing the driver's attention performance.

Mental work has been reported to reflect on the flicker-fusion frequency (FFF), showing the cortical activation level of the person (SCHMIDTKE 1965). A positive relationship between the FFF, breathing volume and subjective load has been reported by DUPUIS (1969) in vertical vibration experiments. Also mental fatigue (psychische Ermüdung) has been reported to decrease the FFF (SCHMIDTKE 1951).

For reaching the best psychomotor skills the activation level of the cortex is required to be optimal. If the individual momentaneous activation level is too low, the vibration could increase it to the optimal level. Consequently, if the level was already high enough, an extra stimulant could promote a decrease in the performance (JOHANSSON 1976).

Whether the vibration-triggered change of cortical activity hampers the forest machine driver's ability cannot be evaluated on the basis of the papers reviewed. Measurement of both driving ability and activation level by flicker-fusion frequency test are thus indicated.

Vegetative Balance

High levels of sympathetic nervous activity and energy consumption are linked together in man. The human body reacts to high physical loading by activating the sympathetic nervous system. High activation of the sympathetic nervous system, however, is also possible without physical loading as a trigger mechanism. In such cases the reason for the activation can be psychological loading of the subject (BLIX et al. 1974). The reports of KOSTYUK (1976), ASANOVA (1976), GORNIK

(1976), VALČIČ (1976), and WARBANOW et al. (1977) support the assumption that a response to whole-body vibration is sympathetic activation. As also heart rate, blood pressure and pulmonary ventilation can all change rapidly after the start of exercise, it has been suggested that mechanoreceptors might be involved at the spinal level in these responses (CLOSKEY et al. 1972).

The sympathetic activation, as a result of stimulation of mechanoreceptors, would allow a sensitivity to the intensity variation of vibration. The finding of close quantitative relationship between stimulus intensity (electrical shocks), adrenaline release and subjective reactions (FRANKENHAEUSER et al. 1965) support the assumption that the sympathetic nervous system may be sensitive to alterations of intensities of excitatory stimuli. It is of interest, whether the increased adrenaline excretion is due to negative feelings (linked with emotional functions) or due to direct reflex pathways, because reactions of the former type can be considered as less specific to mechanical forces.

Reports on both differences of catecholamine secretions due to general stress situations in different personality traits (FRANKENHAEUSER and PATKAI 1965) and noise-induced influenses on the catecholamine release due to assumed direct reflex activation of the sympathetic nervous system (HAWEL et al. 1967) are available.

In the case of rotational 1–4 Hz vibration in lateral motion the sense organs may produce information to the cortex, which may be classified as unpleasant. Thus the sympathetic activation may be triggered by emotional factors as well as by lower reflex actions derived from the labyrinth, muscle spindles or other sense organs, as supposed by TYLER et al. (1949), HASAN (1970), and CUTCHEON (1974).

An increased reflex activity of the sympathetic fibers due to electrical excitation of myelinated somatic nerve afferents has been reported by several authors. SCHMIDT et al. (1970) suggest that the reflex pathway can be spinal or spino-bulbo-spinal. As there are several receptor types evoking the sympathetic reflexes (phasic and tonic mechanoreceptors (group II), cutaneous fibres, blood vessel nerve endings and thermoreceptors (group III), muscle spindle secondary endings (group II) (SCHMIDT et al. 1970), the sensitivity of sympathetic activation to various frequencies in the 1–4 Hz frequency area has not been clarified. The group I muscle afferents which come from spindle primary endings and tendon organs, have in the stuedies of SCHMIDT et al. (1970) and SATO et al. (1969) been shown not to evoke reflex sympathetic discharges.

Clinical and experimental findings of fall in the skin temperature, decrease in the finger pulsation amplitude (COERMANN et al. 1965, GORNICK 1976) and also increased heart rate (SJÖFLOT et al. 1972, COERMANN et al. 1965) support the proposed role of the sympathetic system as a defence mechanism of the body against vibration.

Vibration exposure over several years has been reported to lower the heart rate and beat force of resting professional crane drivers, as compared to controls (LYSINA et al. 1973). During the subjects' work the tone of middle-sized and small vessels increased leading to higher peripheral resistance on the precapillary side.

Reduced sympathetic tone during rest as a result of long-term vibration exposure is likewise reported by MATOTHENKO et al. (1971). According to them, diurnal excretion of catecholamines was reduced as a result of local medium-frequency vibration*. These findings gave reason to suppose that some kind of adaptation of the sympathetic nervous system may occur after long-term work involving vibration.

Simulated vibration experiments with animals have revealed more symptoms of non-specific stress agents (reviews: HASAN 1970, SOININEN 1975). Most of the studies have dealt with responses of the cardiovascular system to the sinusoidal vibrations in the frequency range from 2 to 100 Hz.

A central habituation of the labyrinth to vibration has also been reported by AANTAA et al. (1976 and 1977) in patients experiencing 1/2 to 10 years of vibration exposure while working on shipbuilding. The authors also report increased number of spontaneous nystagmus, lowered caloric excitability or both, but the original mechanism of these disorders remains unclear. The patients were exposed both to infrasound and to vibration of the building at 2.8 to 21.5 Hz.

* Apparently from about 10 to 50 Hz

As also infrasound has been reported to cause dysfunction of inner ear and balance control including nystagmus (WESTIN 1975, a review), these effects can be classified as non-specific. The stimulation of vestibular afferents has also been reported to activate the sympathetic nervous system (TANG et al. 1969).

The literature cited gives reasons for the measurement of sympathetic functions by appropriate, non-disturbing methods.

Energy Metabolism

The energy metabolism of the body may be increased by vibration at least for the following reasons:

- In order to keep his balance and body position the driver has to do muscular work while compensating for the displacement of the cabin
- Muscle contractions of reflex nature (or increased muscle tone) may appear because of increased receptor cell discharge in the various sense organs

Increased voluntary muscle work induced by vibration has been reported by ROSEGGER et al. (1960) , DUPUIS (1969), BJURVALD et al. (1973), CHERNIUK (1975), and by BASTEK et al. (1977).

Vibration (f=70–500 Hz) induced enhanced activity of muscle spindles as a possible reason for increased involuntary muscle contractions has been reported by TROTT (1975) and HOOD et al. (1966).

JACK and ROBERTS (1978) assume that the only significant excitatory action contributing to vibration reflexes is made by the I a afferents. Their works were made with decerebrate cats. MATTHEWS (1969, 1970) has supposed that also the group II muscle spindle afferents might have an activating effect on extensor motoneurons. This assumption supports the possibility of sympathetic reflex responses due to stretch of muscles although the 1 to 4 Hz excitatory frequency area is not yet studied. The monosynaptic reflexes to sudden stretshes are well-known.

GAEUMAN et al. (1962) have reported increased oxygen consumption in vertical 2–15 Hz vibration experiments. According to them the increase is dependent on the frequency of vibration (displacement being constant), and it results from an increase in metabolic activity due to voluntary and involuntary muscular guardening to dampen the vibration.

The respiratory muscles may be involuntarily activated by 0.5–3.0 Hz vibration as a result of labyrinthine stimulation thus causing increased energy metabolism as reported by ERNSTING et al. (1960), HORNICK et al. (1961), and GAEUMAN et al. (1962). According to DUFFNER et al. (1962), vibration induced hyperventilation can also be due to activation of stretch receptors of the lung.

Vibration has been reported to inhibit the monosynaptic reflexes at 30 Hz (DINDAR and VERRIER 1975) but no inhibition was found at 2 to 10 Hz in an earlier study by GUIGNARD and TRAVERS (1959).

Increased tone in or work done by muscles (breathing muscles and other muscles) may increase the heart rate. The increased heart rate has been observed in vibration simulation studies by DINES (1965), SJÖFLOT and SUGGS (1973), and MC CUTCHEON (1974).

There are findings indicating also that even high-intensity vibration (f > 10 Hz) may have no effect on tidal volume, breathing rate or heart rate (HORNICK and LEFRITZ 1966, DUPUIS 1969).

According to SJÖFLOT and SUGGS (1973, p. 467), heart rate (together with subjective judgement and tracking error) is "a good parameter for evaluating vibration conditions affecting man". According to the literature cited, energy metabolism may be increased due to alteration of vibration parameters.

2.3 Mechanical Effects on the Driving Procedure

Command of Controls

It is obvious that lateral movement of the thorax hampers manual adjustment of controls. It can be supposed that the nearer oscillatory excitement approaches the natural frequency* of the body, the more difficult is the manipulation of levers and switches.

* At the lateral natural frequency of the thorax the displacement response of the head to the lateral excitatory vibration is at its maximum.

In agreement with this, HARRIS and SHOENBERGER (1966) have reported excitatory vibration, at a frequency close to the natural frequency area of the body, to disturb the command of controls more than other frequencies.

The command of horizontally manipulated levers has likewise been observed to be disturbed by vertical sine-form vibrations of 2.0–2.5 Hz as reported by HANSSON and SUGGS (1973).

If the driver and seat are imagined to form a system consisting of masses, springs and dampers, one may conclude that the most negative effects of vibration on the command of controls appear at those frequencies that allow the motion to penetrate furthest into the system. Those very frequencies are the natural frequencies of the system.

In a study by HORNICK et al. (1961) compensatory tracking was hampered by horizontal vibration of sine-form type more at 1.5 and 2.5 Hz than at higher frequencies. Using frequencies of 1.5, 2.5, 3.5, 4.5, and 5.5 Hz, the transmission from seat to head was at its maximum at 1.5 Hz.

According to GOLDMAN and v. GIERKE (1960), the maximal transmission of lateral vibration occured at 1.5 Hz at the hip and 2.0 Hz at the head for a sitting subject.

Poorer control of manipulation may not necessarily result only from interference with manual skills. HUDDLESTON (1970), DUPUIS (1971) and COLLINS (1973) have pointed out that visual ability may be altered by vibration. In the material of SJÖFLOT (1971), rotational lateral vibration led to the largest increase in tracking error at 1.7 Hz, due to disturbances in eye function.

When the body is vibrated, the eyes automatically tend to fix themselves on a certain stationary point. So they are moving continuously at the rhythm of the vibration. This pursuit or fixation reflex starts to break down when either the velocity of target movement is too high or when the frequency of a direction changing movement is too high or when the frequency of a direction changing movement is too high (1–2 Hz, BENSON et a. 1978, a review).

The visual fixation ability has been reported to be about 50 % of normal at a vertical sinusoidal vibration of 2.0 Hz, and about 30 % at 3.0 Hz. At higher frequencies the eyes loose their ability to adjust to the vibration. At lower frequencies the fixation ability increases (GUIGNARD and IRWING 1962). This is in force at constant displacement levels.

According to the literature there are reasons for preferring frequencies in both lower and higher areas. At lower areas the fixation of the eyes is better, and at higher areas the transmission of displacement is smaller.

2.4 Mechanical Effects on the Driver's Body

Deformation of Various Tissues

Because of different natural frequencies of different organs, the frequency area of excitation may have an effect on the localization of vibrational damage of various tissues.

Table 1 presents a combination of the influences of vertical sinusoidal vibrations on various functions of the body, as reported by MAGID et al. (1960).

It appears that the frequencies irritating most body functions and organs only begin above 4 Hz (table 1).

Table 1. Effects of whole-body vertical vibration on some body functions (MAGID et al. 1960).

Symptom	Frequency of vibration (Hz)
General malaise	4– 9
Strange feeling in the head	13–20
Strange feeling in the mandible	6– 8
Speech disturbances	13–20
'Lump in the throat'	12–16
Chest pain	5– 7
Abdominal pain	4–10
Micturition urgency	11–18
Increase in muscle tone	13–20
Changes in respiratory movements	4– 8
Muscle cramps	4– 9

This observation thus suggests that natural frequencies of forest machines of less than 4 Hz are recommendable as regards vertical vibration.

It is unlikely that the data of table 1 can be extrapolated to lateral rotatory vibration because the dynamics of internal organs in lateral direction differs from the one in vertical direction.

In ROSEGGERS' study (1960) (N=312) made with agricultural tractors of the 1950's, there were more findings of decreased placement of the stomach and increased number of gastrointestinal symptoms than normal.

DUPUIS (1969) (N=2) has reported in an X-ray study increases in the surface area of the stomach up to 60–90 minutes after a meal, following vertical vibration by a simulator. In a control situation the surface area decreased immediately after eating. Subjective feelings of discomfort and the occurence of peptic ulcer in tractor drivers have also been reported by RENTSCH (1961, ref. HASAN 1970). The natural frequencies of the intestine and stomach depend on the mass of contents of the organ.

According to ROSEGGER et al. (1960), whole-body vibration may increase the number of pathological deformations of intercalated discs of the vertebral column in tractor drivers.

In a latter comparison by the same authors (1970) the pathological findings in the vertebral column were divided as in table 2.

According to a survey by CHRIST (1963), young male tractor drivers (N=211) drove their first five years professionally without any signs of increased number of back findings which could have been explained by tractor driving.

It has even been argued by VIDEMAN (1977) that the degenerative joint disease would not be caused by excessive movement of the tissues, but because of stationary or fixed posture. Videman points out that calculations of the width of the discs and waste products of cartilage in joint fluid show that joint cartilage would wear out in some months if no regeneration occured. According to the same author, immobilization is the most harmful factor in the fluctuation of joint liquid, although movement of a joint may even aid the penetration of nutrients into the cartilage cell (VIDEMAN 1979).

The health situation of forest tractor drivers is reported by KORHONENet al. (1980). The drivers (N=46) (as compared to lumberjacks (N=46) and referents(N=46)) out of all had the most back ailments, especially sciatic syndromes. The clinical investigation showed the drivers to have more tenderness in the lumbar spine under palpation and painful back muscles.

The authors point out that more attention should be given to the ergonomic design of the tractors, and that noise and vibration levels must be reduced.

2.5 The Synopsis

A synopsis regarding the effects of 1–4 Hz rotational vibration in a lateral direction was made on the basis of the literature reviewed. It was assumed that the reactions of the body to frequencies mentioned earlier do not differ much from the effects of 1–4 Hz vibration. This assumption was necessary because of lack of information about effects of frequencies normal in forest machines.

Table 2. Pathological back findings in different occupations. (ROSEGGER 1970).

Occupation	Percent of positive findings
Bank clerks	37
Bus drivers	44
Tractor drivers	71
Miners	73
Forestry workers	73
Locomotive firemen	80
Track drivers	80
Porters	98

The effects of vibration can be divided into psycho-physiological action on the driver and mechanical effects on the driving procedure.

The effects on psycho-physiological functions may be as follows:

- alteration of subjective feelings
- alteration of state of central nervous system
- alteration of vegetative balance
- alteration of rate of energy metabolism

The mechanical effects may be the following:

- alteration of command of controls

As this study concentrated on primary effects of vibration (see page 7), the possible secondary effects were not included in the synopsis.

It was assumed that the primary effects are experimentally dividable to those that are related to alteration of vibration parameters (specific effects, see page 00) and to those that do not clearly variate according to alteration of vibration intensity (the non-specific effects).

3 EXPERIMENTAL

3.1 The Vibration Simulation Device

The purpose of the apparatus was to simulate the lateral vibration conditions of the Lokomo 928 base machine which is used as a forwarder, a feller-skidder and as a processor.

In order to discover the required characteristics of the simulator movement, a forwarder and a processor were tested over terrain. The bandwidth of the rotational lateral vibration of the base machine was about 20 %, its first natural frequency being about 1.6 Hz. The field testing and building of the simulator is described in more detail by RONKAINEN and WUOLIJOKI (1978).

The apparatus was required to produce a rotational lateral vibration with about 10 to 40 % bandwidth in the frequency area from 0 to 5 Hz, in the required waveform.

The simulator was made up of a normal production Lokomo 928 cabin fastened to a base with beams and bearings. Movement was generated by an electrically controlled hydraulic cylinder of the universal testing unit at the Laboratory of Strength of Materials, Helsinki University of Technology (figure 2).

The mass of the cabin and base structure was about 950 kg, and thus its vibration needed rather large forces.

The testing unit for strength of materials is described in detail by PENNALA and JÄRVENPÄÄ (1974).

Rotatory movements were produced by two longitudinal axles mounted on steel beams.

On the basis of measurements from the base machine over terrain, the distance between the seat cushion and the central point of movement was chosen to be 1700 mm.

A pitching of 5° of one bearing produced a lateral displacement of 85 mm and a vertical displacement of 50 mm at the upper fixed point of the bearing to the cabin, as seen in figure 3.

The floor of the cabin was flat and no windows were mounted.

Depending on the nature of vibration the simulator was controlled either by a function generator producing a sinusoidal control signal or by an instrument tape recorder producing a stochastic control signal.

The seat was of Bremshey FA 408 type, and covered with a fairly rough textile material. The experimental room was air-conditioned. The temperature was held between 20–24°C. An overall picture of the laboratory arrangements is at the end of this publication (picture No. 1).

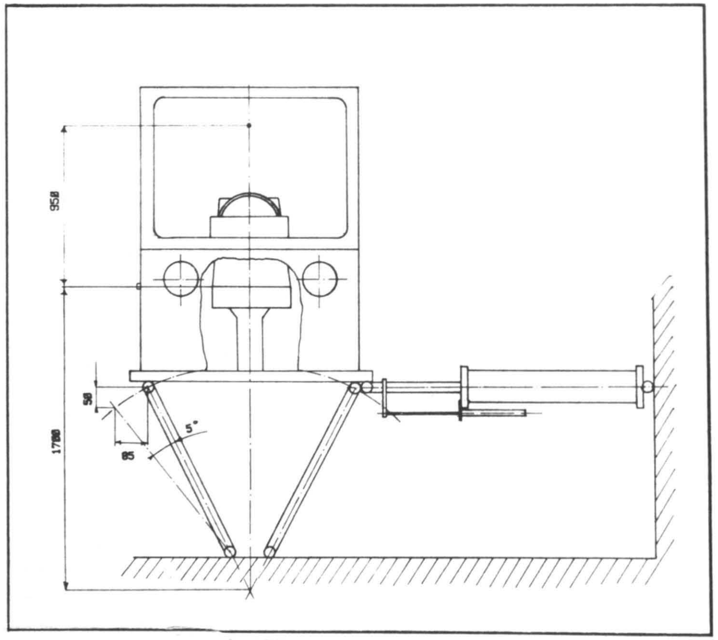

Figure 2.
The vibration simulation device.

Dynamic Properties of the Device

In order to obtain information about the dynamic properties of the apparatus, its natural frequencies were measured at different points of the cabin.

The simulator was controlled with a noise signal of 0 to about 10 Hz (figure 4).

The seat was loaded with test person (m ≈ 63 kg, l ≈ 1810 mm) sitting in a normal driving position with his hands on the steering wheel.

The acceleratory responses were measured with a Rockland FFT – 512 – S – II – 12 spectral analyzer in logarithmic y-scale, as a function of frequency with a bandwidth of 1/3 octave.

The accelerometers (General Radio Company 1560–P–54) were mounted in the piston of the hydropulsator beside the simulator at the height of the loaded seat cushion, and beside the loaded seat at the height of the reference point of the seat.

The control signal and respective responses are shown in the figures 3–6.

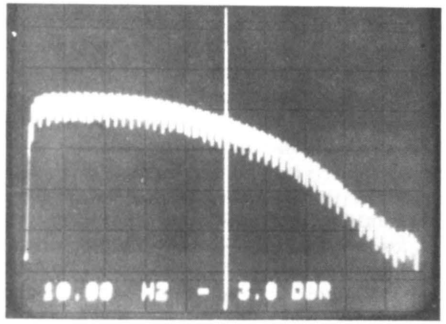

Figure 3. Control signal of 0 to 10 Hz.

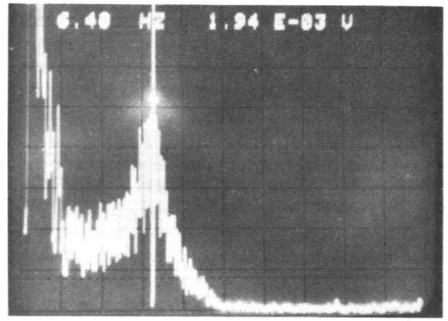

Figure 4. Response to the noise excitation. Recording from the piston of the hydropulsator.

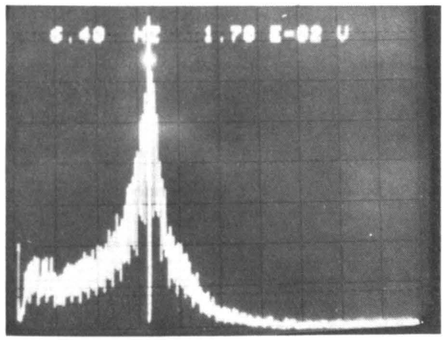

Figure 5. Response to the noise excitation. Recording from the side of the simulator at the height of the seat cushion.

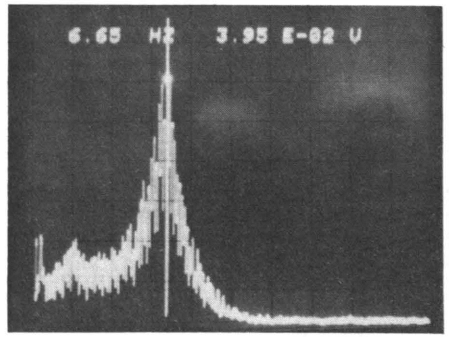

Figure 6. Response to the noise excitation. Recording from the loaded seat.

3.2 Experiment 1: Classification of Variables According to Sensitivity

3.2.1 Introduction

In order to separate variables of clear dependence on vibration intensity from those with lesser dependence and of a nonspecific nature, a pattern of promising variables was tested.

Because this experiment had to demonstrate the quantitative reactions of the variables to alterations of vibration intensity, displacement was chosen as the variable parameter of vibration, and frequency held constant. It was agreed that the decision excluded the possibility for examination of specifity of the variables to frequency.

In previous experiments the excitatory vibrations have largely been of sine-form. As forest machine vibration has a stochastic nature of acceleration but usually a narrow frequency area (see page 6) due to the natural frequencies of the machines, this series of experiments was carried out with vibrations having displacement of stochastic nature. For reference purposes, half of the test persons of this experiment received vibration having regular displacement alteration (sine-form). This comparison is reported in detail by ÄIKÄS (1979), and the results are pooled here including both vibration types.

3.2.2 Subjects

A total of 12 healthy male post-graduate students of Helsinki University of Technology volunteered as subjects.

None had professional tractor driving experience, though all had driven passenger cars regularly. The subjects, dressed in jeans during experiments, were informed in advance to avoid physical exercise, coffee, alcohol, and tobacco one day prior to the physiological measurements. No meal was allowed in the hour before testing.

Basic data on the subjects is given in table 3. The subjects were not paid for taking part in the experiments. They were informed that each subject was free to withdraw at any time or to stop the experiment whenever needed. During all of the vibration exposures, the subjects were free to use the most comfortable sitting posture.

The experiment was done with healthy volunteers because professional drivers might have developed an adaptation or habituation mechanism which could have masked the reactions to alterations of vibration intensity (AANTAA et al. 1976, MATOTHENKO et al. 1971).

According to LOUNENTO (1974), the usual age of members of the Union of Forest Machine Entrepreneurs is between 25 and 30 years.

3.2.3 Experimental Design

The aim of the experiment was to demonstrate whether or not the variable reacted to alterations in vibration intensity.

All subjects experienced four 1 h exposures at different intensities, either with sine-waveform or stochastic type vibrations. Every exposure took place at the same time of the day for each subject. The sequence of vibration intensity for individual subjects was randomized according to the Latin Square.

Since information as to whether the variables react to vibration as opposed to "rest" was not valuable (difficulties in definition of rest) no control situation without vibration was included.

It was assumed that the possible non-specific variables could respond also to a control situation without vibration because the experimental situation already included mental load.

Having arrived in the laboratory for experiments the subjects were instrumented for the measurement of heart rate, head displacement and blood pressure, and then seated in the cabin to read magazines for 10 minutes.

After this period the basic values for heart rate and blood pressure were measured in the cabin, and the subjects emptied their bladder in the lavatory.

Then the subjects were seated in the cabin again and given 330 ml of water to drink (+30°C) to ensure the urine sample after the session. After the vibration exposure the subjects emptied their bladder for analytical purposes. The record form for this experiment showing the times of different measurements is enclosed in appendix 1.

The Vibrations used

On the basis of previous experiments by the laboratory staff, vibration intensities were chosen such that the lightest vibration was almost unnoticeable during the treatment, whereas the most laborious vibration was uncomfortable.

4 Hz was chosen to be the mean frequency for testing the variables, both for sinusoidal and stochastic vibrations. The reason for this was that 4 Hz was as far both from the natural frequency of the simulator (about 6.5 Hz) and from the estimated natural frequencies of human thoraxes (2 Hz, HORNICK et al. 1961, GOLDMAN and v. GIERKE 1960).

The intensity of vibration (4 alternatives) was chosen so that the different intensities were used in different order for different subjects, for reducing the systematic effect of getting used to the experimental situation.

Single displacements of the cylinder piston were ± 0.5 mm, ± 2.0 mm, ± 3.5 mm and ± 6.0 mm for sinusoidal vibrations controlled by a function generator.

For stochastic vibration the simulator was controlled by a magnetic tape on which a 4 Hz control signal was synthesized in advance by modulating the amplitude of a pure harmonic signal with a noise signal. The RMS values of the stochastic displacement were measured from the piston and adjusted at 300 s averaging time to those of the sinusoidal vibrations. An infra-red light-emitting diode (ir-led) was mounted on top of the cabin about 2650 mm above the central point of movement and about 50 mm above the driver's head.

The movement of the diode was registered by an ir-camera and a light spot recorder.

The corresponding single displacements of the ir-led at sinusoidal vibration were about ± 1.5 mm, ± 5 mm, ± 8 mm, and about ± 13.5 mm. Samples of vibrations used, as recorded by the ir-equipment, are given in appendix 2.

Basic data on the vibrations used is also presented in table 4.

Table 3. Basic data on the subjects.

The subjective work capacity ($PWC_{subj.}$) was determined by asking the subjects to rate themselves by numbers from 4 (worst) to 10 (best).

Variable	Min.	Max.	Aver.
Age, years	27	36	30
Weight, kg	60	92	73
Height, cm	166	185	176
$PWC_{subj.}$	6	9	8

Table 4. Basic data on the vibrations used, as measured from the side of the seat using the equipment described in appendix 3.

No. of vibr.	Nature	Acceleration RMS peak m/s²	Acceleration RMS mean m/s²	Ratio peak/mean
1	sine	0.95	0.8	1.2
	stoch.	1.70	0.5–1.5	2.2
2	sine	3.4	2.7	1.3
	stoch.	4.5	1.0–2.5	1.6
3	sine	5.5	4.5	1.2
	stoch.	8.5	3.0–7.0	1.9
4	sine	9.5	7.3	1.3
	stohc.	12.0	5.0–10	1.6

Table 5. Data on vibrations used in previous experiments.

Author	Year	Frequency Hz	Acceleration m/s²	Direction
Hornick et al.	1961	1.5–5.5	1.5–3.4	y-axis
Woods	1967	2–8	1.0–2.9	"
Bjurvald	1973	1.7–5.5	1.7–5.8	"
Sjöflot et al.	1973	1–4	2.5–4.9	"
This study		1–4	0.8–7.3	"
Shoenberger et al.	1971	3.5–20	0.8–5.5	z-axis
Dupuis et al.	1972	0.5–30	0.1–10	"
Wilson	1974	2–10	0.4–8.9	"
Bastek et al.	1977	2–8	0.9–3.4	"

For reference purposes, data on excitatory vibrations of other studies is given in table 5. The RMS acceleration values of forest machines in terrain are about 0.5–4.0 m/s² (KÄTTÖ et al. 1973, SIREN et al. 1979).

3.2.4 Variables Used

According to the literature viewed, vibration may have

A effects on the psycho-physiological functions of the driver and
B mechanical effects on the driving procedure.

According to the aim of this investigation, the variables used should not only be sensitive to variation of displacement but also to variation of frequency. For this reason, nonspecific variables having a response to vibration viz. no vibration, but having no response to alteration in vibration parameters, were of lesser value.

Consequently, the variables showing the state of general stress of the organism were not expected to be specific to different excitatory frequencies or displacements.

Variables measured to assess the effects of vibration were as follows:

A

1 subjective rating of vibration
2 tracking ability
3 heart rate
4 blood pressure
5 urinary excretion of catecholamines
6 finger skin temperature
7 flicker-fusion frequency

B

1 manipulating ability
2 head displacement

At the presentation of results some tests of statistical significance were used. This was not done for an extrapolation of the results to a hypothetical basic population. Instead, the tests were used only for the description of the results and the data collected.

Description of Measurements

A Effects on the Psycho-physiological Functions of the Driver

1 Subjective Rating of Vibration

A numerical scale from 6 to 20 was mounted in the cabin in the visual field of the driver. The scale and explanations are presented in table 6.

Before the experiments the subjects were allowed to try different intensities of vibration used in the four exposures for calibrating their individual rating ability.

When asked, the subject told his opinion about the vibration magnitude by saying the rating number.

The rating scale (table 6) was modified from the one presented by BORG (1975).

2 Tracking Ability

The equipment for the tracking test consisted of a double-pen xy-recorder of Bryans A3 type which was placed in the visual field of the driver at a distance of about 2500 mm.

Table 6. Rating scale of the subjective magnitude of vibration.

Rating number	Semantic evaluation
6	unnoticeable
7	light
8	
9	fairly light
10	
11	neither light nor laborious
12	
13	fairly laborious
14	
15	laborious
16	
17	very laborious
18	
19	extremely laborious
20	unbearable

A red laterally moving flat metal circle of about 100 mm in diameter was mounted in place of the lower recorder pen. Its motion was controlled by a periodical signal obtained by multiplying two harmonic signals with each other. The maximum double-amplitude of the motion of the circle was 300 mm, the duration of the cycle being 12 seconds.

A red metal pointer of about 100 mm long was mounted in place of the upper recorder pen. The pointer was controlled by rotating the steering wheel in the cabin. One half cycle of the steering wheel corresponded to a double-amplitude of the moving circle.

The driver's task was to keep the pointer in the middle of the moving circle. The relative positions of the circle and pointer were registered by a 3-channel recorder of type 4 3020–3, with a paper speed of 0.1 mm s^{-1}. Every loss of attention performance lasting longer than about 1 s caused a peak on the error signal recording paper.

The scores from the tracking test were calculated by ignoring the ten longest peaks from the last 50 mm of the recorder track and measuring the width of the record track still remaining. This method allowed the attention performance monitoring of the last 8.3 minutes before the end of the vibration exposure.

As both too low and too high an activation level of cortical functions worsen he performance in an attention test, the tracking apparatus cold only show alterations in attention performance but not whether they result from lowering or heightening of activation levels.

3 Heart Rate

The biotelemetric equipment (Medinic 1 C 45) consisted of three electrodes fastened to the skin of the chest, and of a radio transmitter weighing about 130 g placed in the chest pocket of the subjects. The signal was received and monitored during the experiment and recorded on tape by a Stellavox SP-7 instrument recorder. The heart rate calculations were made on the basis of ten beats. The biotelemetric apparatus has been described in more detail by WUOLIJOKI (1974). Also its sensitivity to alterations of heart rate was tested beforehand during an earlier study (WUOLIJOKI 1977).

4 Blood Pressure

Systolic and diastolic blood pressures were measured using a VEDA sphygmomanometer mounted on the right lateral pillar of the cabin roof. The cuff was kept round the upper right arm during the whole vibration experiment.

5 Urinary Excretion of Catecholamines

The concentrations of urinary adrenaline and noradrenaline were measured fluorometrically by the method of v. EULER and LISHAJKO (1961). The spectrophotometer used was a Perkin–Elmer MPS-3.

As the equipment used permitted the adjustment of wavelenght, the method for calculating concentrations was the one presented by VENDSALU (1960).

After the vibration exposure the subject emptied his bladder into a graded jug as completely as possible, measured his urine volume and poured a sample of about 100 ml into a plastic bottle.

The pH of the sample was adjusted to about 3 with 1 N HCl after the collection. Then the samples were stored at –20°C until analyzed within the following week, as double samples.

The accuracy of the method was tested by analyzing seven double-samples with known concentrations of both adrenaline and noradrenaline (totally 28 samples). The mean percentage values of analyzed results from the original concentrations were for noradrenaline 100.9 ± 4.2 (s.e.) ± 11.1 (s.d.) %, and for adrenaline 110.6 ± 5.7 (s.e.) ± 14.9 (s.d.) %.

The calculation of excretion rate of free catecholamines was made on the basis of total urine volume excreted during the exposure. The analysis is described in detail by ÄIKÄS (1979).

6 Finger Skin Temperature

Skin temperature was measured with a Wallac thermoanemometer (type GGA 23–S) from the dorsal side of the right middlefinger (middle phalange) using a surface temperature probe Ni 101 X with an accuracy of ± 0.5°C and a 1/2 value time constant of 1 second. About 30 seconds were allowed for the measurement to settle before reading.

7 Flicker-Fusion Frequency

A stroboscope of BBE-Neheim-Hüsten type was fixed in the visual field of the driver. The frequency of the light flashes (Ø 100 mm) was adjusted from about 10 Hz upwards, until the subject was unable to detect any dark period between the flashes. Then the flash rate was reduced from about 100 Hz until separate flashes were again detected. The average of the two frequencies thus measured was the recorded value.

B Mechanical Effects on the Driving Procedure

1 Manipulating Ability

A wooden perforated plate (18 holes on the upper side) of 140 mm x 140 mm was used as the base for nine wooden pegs 37 mm long and 15 mm in diameter.

The subjects were asked to move the pegs from their holes on the right side, where they were in the beginning, to the left side which was empty, and then back to the original holes by using two fingers only.

The time used for the task served as the test result. During the test the subjects were not required to steer the tracking apparatus. Whereas the tracking test measured the attention performance of the driver, this test measured his motor skills.

2 Head Displacement

An optoelectronic ir-camera and ir-light-emmitting diodes of "Selspot" type were used for monitoring head and cabin displacement during vibration. The system was developed by the Selective Electronic Company Ltd. The ir-led was fastened with plaster onto the forehead of the subject. The signal was recorded with a light spot recorder of H 115 type.

Head displacement was measured in millimeters as a double amplitude using five different peaks in three different points on the recordings lasting 30 seconds. In the case of stochastic vibrations, the calculations were made at the points where the excitation displacement was at its maximum.

3.2.5 Results

One subject was excluded due to coryza (common cold) and replaced by a new one. The two subgroups (N=6+6) being exposed to either stochastic or sinusoidal vibration were comparable in respect to age, heart rate at rest, and blood pressure at rest. Additional basic data on the subjects is given in the appendix 4.

A Effects on the Psycho-physiological Functions

1 Subjective Rating

Subjective rating number varied from 9 ± 2 (9=fairly light) at vibration No 1 to 17 ± 2 (18=very laborious) at vibration No 4 (figure 7).

According to one-way analysis of variance the rating number was significantly enlarged by increased vibration displacement ($p < 0.001$).

Two-way analysis of variance showed that the quality of vibration (alternatives: sine/stoch.) had no significant effect on the rating.

Significant correlation between both subjective rating number and head amplitude and manipulating ability was found ($p < 0.001$), (correlation matrix).

The subjective rating number was sensitive to variation of vibration displacement.

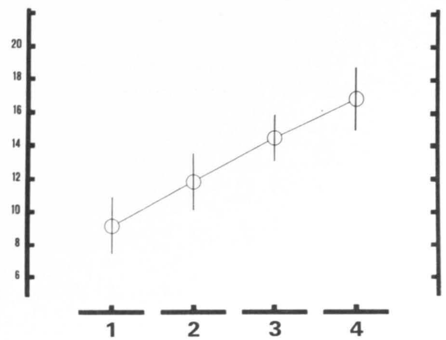

Figure 7. Relationship between subjective rating and displacement of vibration.
Ordinate: Subjective rating number.
Abscissa: Number of vibration in accordance with the numbers in table 4 (p. 00).
The figure as all the following figures 8–11 includes both vibration of sineform and of stochastic nature. Vertical lines show standard deviations, circles show mean values (48 observations).

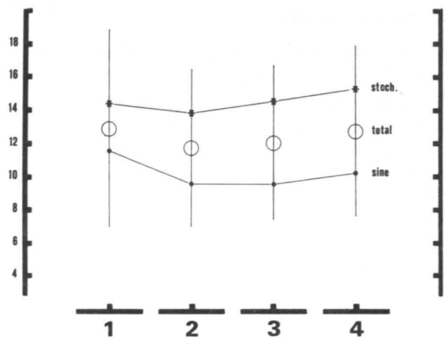

Figure 8. Relationship between tracking ability scores and displacement of vibration.
Ordinate: Scores in mm expressing the width of the steering track.
Abscissa: Number of vibration in accordance with the numbers in table 4. Mean values for sinusoidal and stochastic vibrations are separated. Standard deviations are calculated from the total mean values (48 observations).

2 Tracking Ability

Tracking ability scores varied from 12 ± 5 at vibration No. 2 to 13 ± 6 at vibration No. 1. Relationship between tracking ability and intensity of vibration is presented in figure 8.

One-way analysis of variance showed that alteration of displacement did not have any significant effect on the tracking ability.

According to two-way analysis of variance there was a significant difference in tracking ability between sinusoidal and stochastic vibrations ($p < 0.001$).

Statistically significant correlations between tracking ability scores and the other variables were not present.

Although there may be a difference between responses to sinusoidal and stochastic vibrations, no differences can be seen between responses to various intensities of vibration. This observation supports the insensitive nature of tracking ability to intensity of vibration.

3 Heart Rate

Heart rate varied from 69 ± 10 beats min^{-1} at vibration No. 1 to 72 ± 11 beats min^{-1} at vibration No. 3, the overall mean value being 71 ± 9 beats min^{-1}. The overall mean value after reading magazine for 10 min before the experiment was 68 ± 6 beats min^{1}. No statistically significant effect of quality or quantity of vibration on the heart rate was present.

4 Blood Pressure

Systolic blood pressure varied from 123 ± 11 mmHg at vibration No. 1 to 128 ± 8 mmHg at vibration No. 3, the overall mean value being 126 ± 10 mmHg. After 10 min reading before the experiment the value was 126 ± 10 mmHg.

Diastolic blood pressure varied from 75 ± 7 mmHg at vibration No. 3 to 79 ± 10 mmHg at vibration No. 2, the overall mean value being 77 ± 9 mmHg. After 10 min reading before the experiment the value was 74 ± 9 mmHg.

No statistically significant effect of quality or quantity of vibration on the blood pressure was found, but the diastolic blood pressure correlated negatively with subjective physical work capacity ($p < 0.001$) (correlation matrix). The heart rate and blood pressure did not show any sensitivity to variation of vibration intensity.

5 Catecholamines

Adrenaline excretion rate in the urine during the 1 h vibration exposure varied from 10 ± 7 ng min[1] at vibration No. 3 to 12 ± 5 ng min^{-1} at vibration No. 2, the overall mean value being 11 ± 7 ng min^{-1}.

Neither the quantity nor quality of vibration had any significant effect on adrenaline excretion rate.

Noradrenaline excretion rate during the 1 h exposure varied from 36 ± 11 ng min^{-1} at vibration No. 3 to 40 ± 12 ng min^{-1} at vibration No. 4, the overall mean value being 38 ± 10 ng min^{-1}.

Differences in noradrenaline excretion rate were not statistically significant between any of the frequences on vibration types, but there was a tendency for increased excretion at the most intense vibration No. 4. The mean values and standard deviations of catecholamine excretion at different intensities at both vibrations of sine-form and of stochastic nature are presented in table 7.

For reduction of inter-individual variation in the result, the excretion values were also calculated by using every subject as his own control in respect to different vibration intensities. The lowest individual values of experiments were used as baselines for percentual increases of excretion.

The adrenaline excretion varied from 134 ± 67 % of baseline at the vibration No. 3 to 194 ± 123 % at the vibration No. 2, total mean value being 158 ± 86 %. The noradrenaline excretion varied from 119 ± 27 % at the vibration No. 3 to 146 ± 38 % at the vibration No. 4, total mean value being 130 ± 31 %.

Percentual noradrenaline excretion as a function of displacement alteration is presented in figure 9.

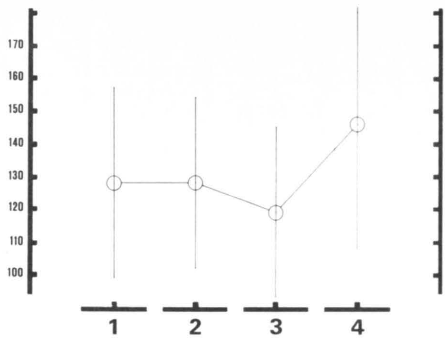

Figure 9. Relationship between noradrenaline excretion and displacement of vibration.
Ordinate: Percentual increase of NA-excretion.
Abscissa: Number of vibration agreeing with the numbers in Table 4. Mean values and standard deviations include both sine and stochastic vibrations (48 observations).

Table 7. Catecholamine excretion rate at different vibration exposures. Number of vibration is in accordance with the number in table 4, page 19.

Adrenaline excretion rate, ng min^{-1} ± s.d.			
No. of vibr.	Sine	Stoch.	Aver.
1	10 ± 7	11 ± 9	11 ± 8
2	10 ± 5	14 ± 5	12 ± 5
3	10 ± 7	10 ± 6	10 ± 7
4	9 ± 6	12 ± 13	11±10

Noradrenaline excretion rate, ng min^{-1} ± s.d.			
No. of vibr.	Sine	Stoch.	Aver.
1	38 ± 15	39 ± 5	39 ± 10
2	32 ± 6	41 ± 7	37 ± 7
3	37 ± 14	35 ± 8	36 ± 11
4	36 ± 9	44 ± 16	40 ± 13

The most intense vibration No. 4 had an effect on the noradrenaline excretion (figure 9). As the catecholamine excretion is largely accepted as a component of general or non-specific stress, the observed sensitivity to variation of vibration intensity may be due to activation of general defence mechanisms of the body against high-level irritation, the displacement variation being only a secondary factor.

6 Skin Temperature and Flicker-Fusion Frequency

The skin temperature varied after 10 min reading from 22.5 to 34.0°C (mean 30.3°C) and during vibration exposures from 22.0 to 33.0°C (mean 29.6°C). No significant correlation between the skin temperature and vibration intensity was present.

The flicker-fusion frequency varied after 10 min reading from 38 to 48 Hz (mean 43 Hz) and during vibration exposures from 37 to 48 Hz (mean 43 Hz). No significant correlation between the FFF and vibration intensity was found. The FFF was measured only during sinusoidal vibration experiments.

Neither the skin temperature nor the FFF showed any dependence on any of the variables measured.

B Mechanical Effects on the Driving Procedure

1 Manipulating Ability

The time used to move the pegs varied from 16 ± 1 s at vibration No. 1 to 53 ± 13 s at vibration No. 4, with a mean value of 31 ± 16 s (fig. 10). The value before the vibration exposures after reading varied from 12 to 17 s, with a mean value of 15 s.

There was a significant correlation between the manipulating ability time and the subjective rating of vibration, as as reported on page 00.

According to one-way analysis of variance, the manipulating time was significantly lengthened by the increase of vibration intensity ($p < 0.001$).

Two-way analysis of variance showed that the quality of vibration had no significant effect on the time used.

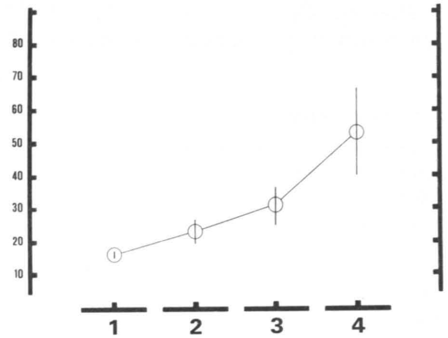

Figure 10. Relationship between manipulating time and displacement of vibration.
Ordinate: Time taken to move pegs in seconds.
Abscissa: Number of vibration in accordance with the numbers in table 4. (48 observations).

2 Head Displacement

Head displacement varied from 3.0 ± 0.9 mm on paper at vibration No. 1 to 6.8 ± 2.7 mm at vibration No. 4, with the mean value of 4.7 ± 2.4 mm (fig. 11).

According to one-way analysis of variance, the alteration of cabin displacement affected the head displacement ($p < 0,001$).

According to two-way analysis of variance, the sine-form vibration effected head displacement less than vibration of stochastic nature ($p < 0.05$).

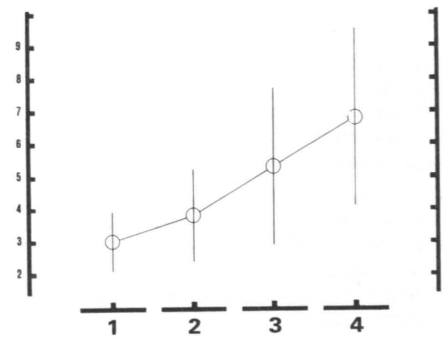

Figure 11. Relationship between head displacement and displacement of vibration.
Ordinate: Head displacement in millimeters on recorder paper.
Abscissa: Number of vibrations in accordance with the numbers in table 4 (48 observations).

The table of variables used and the correlation matrix are presented in appendices 5 and 6.

3.2.6 Conclusions

The results did not entirely agree with the synopsis of the literature review (p. 14). The effects of increased vibration displacement on heart rate, blood pressure and adrenaline excretion rate were small, if any.

The psycho-physiologically oriented variables "subjective rating", "tracking ability" and "noradrenaline excretion" responded to increased vibration displacement.

The mechanically oriented variables "manipulating ability" and "head displacement" were highly sensitive to the increase of displacement.

The variables used were dividable into those that responded clearly to enlargement of vibration intensity, and to those that needed more intense excitation or were not so sensitive.

According to these observations, the variables were divided as follows:

a) Variables of good sensitivity:
   - subjective rating
   - manipulating ability
   - head amplitude

b) Variables of low sensitivity:
   - tracking ability
   - catecholamine excretion
   - heart rate
   - blood pressure

Measurements of skin temperature and the FFF were rejected from the test battery because of lack of response to increased vibration intensity.

It was decided to extend the series of experiments further in two ways:

a) by a trial design for the variables of good sensitivity, collecting a large matrix of observations for detailed analysis of differences between various vibration parameters (experiment 2)
b) by a trial design for the variables of worse sensitivity collecting a more intensive matrix of observations for identifying psycho-physiological differences between the control and vibration situations (experiment 3)

As the aim of experiment 1 was to test the behaviour of different variables against the synopsis of literature, the aim of experiment 2 was to examine the effects of different frequencies of vibration by using the variables already tested.

3.3 Experiment 2: Vibration Parameters

3.3.1 Introduction

As the aim of this experiment was to compare the effects of different frequencies with each other, some kind of constant physical factor was necessary between vibration tests at different frequencies.

As different norms focus on different parameters (USSR: velocity, ref. VALČIČ 1976) (ISO, 1978: acceleration), it was decided to use so many different vibrations that the various needs for constant acceleration, velocity and displacement were all satisfied.

In this experiment only subjective rating and manipulating ability (variables with good sensitivity) were used.

For examining differences between professional drivers and students as test persons, a group of members of the Union of Forest Machine Entrepreneurs volunteered for the trial.

3.3.2 Subjects

A total of 11 healthy male agricultural students volunteered as subject group 1, and 11 male professional forwarder or professional drivers as subject group 2. All the subjects were dressed in jeans. Basic data on the subjects is presented in table 8.

3.3.3 Experimental Design

All subjects experienced fourteen different vibrations of stochastic nature twice during exposures of about 1 h duration.

Before the experimental vibration exposures the subjects were allowed to try the vibrations of different intensities at different frequencies, and to learn the manipulating ability test. The basic data was collected from the subjects beforehand.

Table 8. Basic data on the subjects.

Variable	Students			Professionals		
	Min.	Max.	Aver	Min.	Max.	Aver.
Age, year	23	30	27	25	37	31
Weight, kg	60	92	71	63	112	79
Height, cm	166	185	178	160	187	176
PWC subj.*)	6	9	7.7	5	9	6.8
Driving exp., year	–	–	–	3	15	8.2

*) 4=worst possible
10=best possible

The Vibrations Used

The RMS-value of velocity was chosen as the main constant parameter of vibration. There were three different values of RMS-velocities used, viz. 15 mm/s, 25 mm/s and 45 mm/s.

Because there were different levels of RMS-velocity at different frequencies, the RMS-acceleration was nearly constant at some levels of vibration. At constant RMS-acceleration of about 300 mm/s² throughout the whole 1–4 Hz range, the RMS-velocities were as follows (figure 12):

1 Hz : 45 mm/s
2 " : 25 "
3 " : 15 "
4 " : 12,5 "

At constant RMS-displacement of about 2.4 mm the corresponding RMS-velocities were as follows:

1 Hz : 15 mm/s
2 " : 30 "
3 " : 45 "

The vibration intensity corresponding to the 4 Hz value at constant RMS-displacement was technically impossible to produce.

When calculating the results, only those vibrations were picked up from the vibration battery which gave either constant RMS-velocity, RMS-acceleration, or RMS-displacement at different frequencies.

The constant value used for RMS-acceleration was about 300 mm/s² and for RMS-displacement about 2.4 mm. For constant RMS-velocity all values 15, 25, and 45 mm/s were used for the calculation of results.

The vibrations used are presented in figure 12. Because the vibrations were of stochastic nature, they cannot be taken as exact points on the diagram. Calculations between the different parameters were made according to the method of harmonic analysis.

The spectrum analysis of frequencies of different control signals and their corresponding vibrations at the 25 mm/s velocity level are presented in appendix 7. The corresponding vibrations as recorded by the opto-electronic system are given in appendix 8.

Calculations of percentual bandwidths were made by using the 3 dB attenuation of the signal from the average values.

The vibration intensities in this experiment were higher than in experiment 1, the RMS-accelerations of 4 Hz vibrations being about 3 to 11 m/s². The exposure time for each vibration was only about two minutes.

The intensities at constant RMS-acceleration (3 m/s²) were comparable with those of original forest machines driven on a forest terrain, the RMS-accelerations in terrain being about 0.5 to 4 m/s² (see page 20).

3.3.4 Results

A Constant RMS-Velocity

1 Subjective Rating

The mean subjective rating number of both students and professional drivers varied from 13 ± 2 at 1 Hz vibration to 15 ± 2 at 2 Hz vibration (13=fairly laborious) (fig. 13).

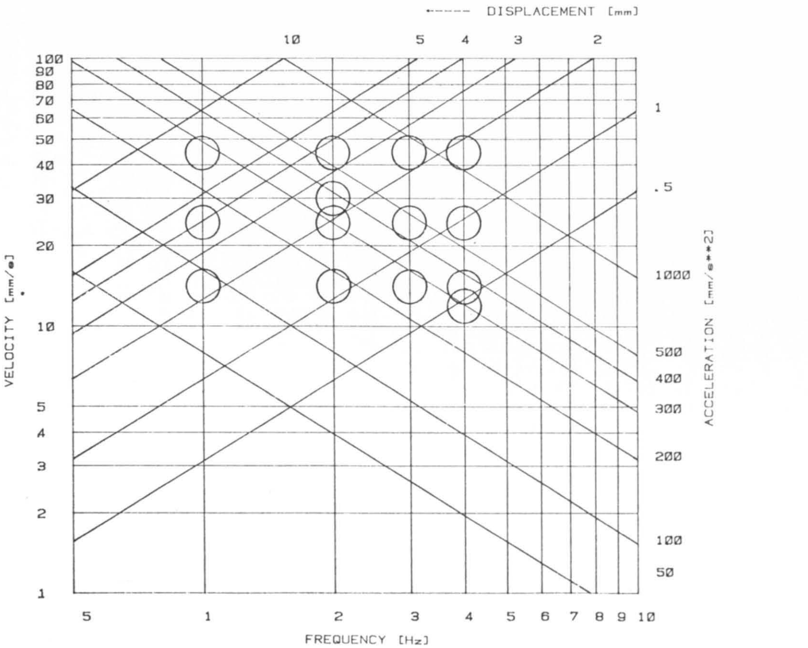

Figure 12. The vibration alternatives used in experiment 2.
Ordinate: Velocity, mm/s
Abscissa: Frequency, Hz. Ascending curves: displacement, mm. Descending curves: acceleration, mm/s.

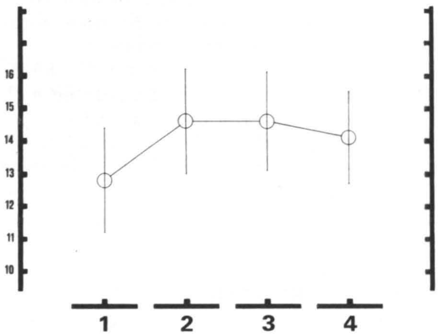

Figure 13. Relationship between subjective rating and frequency of vibration.
Constant RMS-velocity.
Ordinate: Rating number, (15=laborious).
Abscissa: Frequency, Hz. Means and standard deviations. (528 observations).

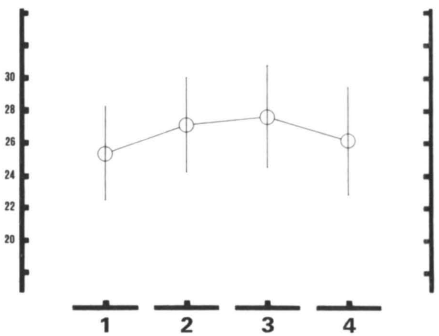

Figure 14. Relationship between manipulating time and frequency of vibration.
Constant RMS-velocity.
Ordinate: Time taken to move pegs, s.
Abscissa: Frequency of vibration, Hz.
Means and standard deviations (528 observations).

Differences in subjective rating numbers were statistically insignificant between 2, 3, and 4 Hz, but the 1 Hz vibration was rated with smaller numbers than all the others ($p < 0.01$), Student's t-test). The mean rating number of all frequencies of professional drivers was 13 ± 2, the one of the students being 15 ± 1.

2 Manipulating Ability

The time taken to move the pegs including both subject groups varied from 25 ± 3 s at 1 Hz vibration to 28 ± 3 s at 3 Hz vibration level (fig. 14).

Differences in manipulating times were statistically insignificant between all of the frequencies and both subject groups (Student's t-test). The mean manipulating time including all frequencies of professional drivers was 26 ± 4 s, the one of the students being 27 ± 3 s.

B Constant RMS-Acceleration

1 Subjective Rating

The subjective rating number varied from 11 ± 2 (11= neither light nor laborious) at 4 Hz vibration to 15 ± 2 (15=laborious) at 1 Hz vibration level (fig. 15).

According to one-way analysis of variance, the increase of excitation frequency decreased the values of subjective rating numbers at constant RMS-acceleration ($p < 0.001$).

2 Manipulating Ability

The time taken to move the pegs varied from 23 ± 3 s at 4 Hz vibration to 27 ± 4 s at 1 Hz vibration level (fig. 16).

According to one-way analysis of variance, the increase of excitation frequency decreased the manipulating times at constant RMS-acceleration ($p < 0.001$).

C Constant RMS-Displacement

1 Subjective Rating

The subjective rating number varied from 11 ± 2 (11=neither light nor laborious) at 1 Hz vibration to 17 ± 2 (17=very laborious) at 3 Hz vibration level (fig. 17).

According to one-way analysis of variance the increase of excitation frequency increased the values of subjective rating at constant RMS-displacement ($p < 0.001$).

2 Manipulating Ability

The time taken to move the pegs varied from 24 ± 3 s at 1 Hz vibration to 32 ± 5 s at the 3 Hz vibration level (fig. 18).

According to one-way analysis of variance, the increase of excitation frequency increased the manipulating time at constant RMS-displacement ($p < 0.001$).

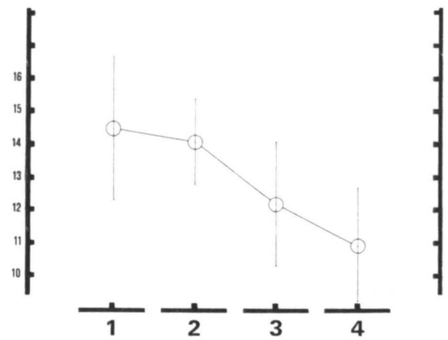

Figure 15. Relationship between subjective rating and frequency of vibration. Constant RMS-acceleration. Ordinate and abscissa as in figure 13 (176 observations).

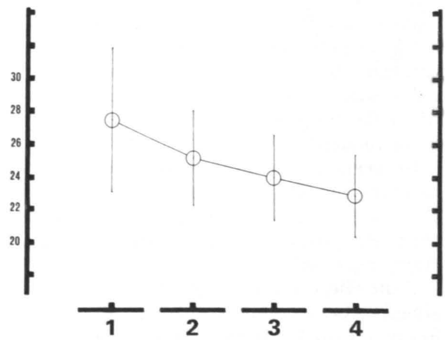

Figure 16. Relationship between manipulating time and frequency of vibration. Constant RMS-acceleration. Ordinate and abscissa as in figure 14 (176 observations).

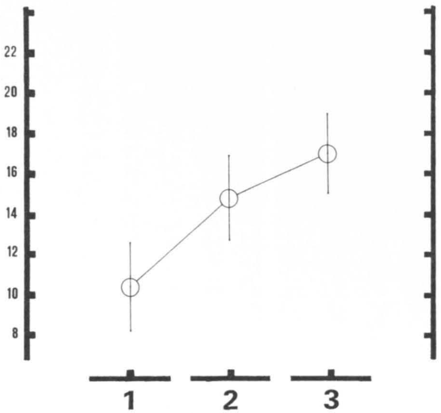

Figure 17. Relationship between subjective rating and frequency of vibration.
Constant RMS-displacement.
Ordinate and abscissa as in figure 15. (132 observations).

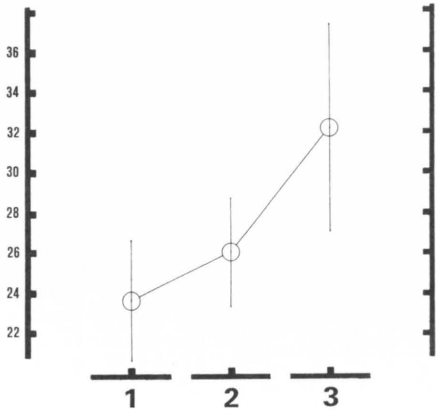

Figure 18. Relationship between manipulating time and frequency of vibration.
Constant RMS-displacement.
Ordinate and abscissa as in figure 16 (132 observations).

3.3.5 Conclusions and Discussion

The professional drivers rated the vibrations with smaller numbers than the students, but the manipulating ability times between the two subject groups did not differ from each other statistically significantly.

By keeping the velocity (RMS-value) constant the subjective rating number of 2, 3, and 4 Hz remained equal, the 1 Hz vibration being rated with smaller numbers than the higher frequencies. The manipulating ability times did not differ statistically significantly from each other at various frequencies.

By keeping the acceleration (RMS-value) constant, the effects of vibration on both variables was reduced statistically significantly when the frequency was increased (displacement reduced).

By keeping the displacement (RMS-value) constant, the effects of vibration on both variables was statistically significantly increased when the frequency was increased (acceleration increased).

If the effect of the vibration of the tractor is aimed to be reduced by changing the natural frequency of the machine, the designer must reduce the velocity of vibration as well.

Correspondingly, if the effects of vibrations of unknown frequencies (within 1 to 4 Hz) are to be compared with each other by the aid of acceleration levels, also the velocities must be measured or calculated.

By discussing the displacement or acceleration of the tractor alone, one may do misjudgements, because the effects of vibration change by alteration of the excitatory frequency.

The evaluation methods of this experiment gave only mechanical and subjective information about the effects of vibration on the human body and driving.

As the subjective rating of vibration does not necessarily indicate physiological reactions of the body, no conclusions were made on the physiological effects of 1 Hz vibration as compared with higher frequency areas.

Instead, the 1 Hz vibration is examined with other variables in the following experiments.

The subjective magnitude rating was in agreement with ISO 2631 standard (1978) which evaluates the vibrations in terms of "reduced comfort boundary", fatigue-decreased proficiency boundary", and "exposure limit for health and safety". The GDR standard TGL 22312 which stresses the 4–8 Hz frequency area as most harmful was not supported by the subjective magnitude rating of this trial.

The natural frequency area of a machine plays a significant role as a factor affecting the manipulating ability and subjective rating of vibration of the driver.

3.4 Experiment 3: Psycho-physiological Responses

3.4.1 Introduction

This experiment is designed to clarify the psycho-physiological responses of the body to different values of vibration parameters. According to the experiences of experiment 1, only rather coarse differences in vibrations were expected to be distinguishable by these variables.

The examined vibrations were thus chosen to be 0 Hz, as a control, and two vibration exposures, viz. 1 and 4 Hz. The reason for the comparison of 1 Hz with 4 Hz (not 2 or 3 Hz) was that the 4 Hz vibration might resonate with the inner organs as reviewed by MAGID et al. (1960), see page 13, and thus differ in the effects from the 1 Hz vibration, which does not exite the inner organs to resonance. Also the finding of experiment 2 that the 1 Hz vibration was rated with smaller numbers than the 4 Hz vibration, supported the assumed resonance theory.

3.4.2 Subjects

A total of 6 male subjects from the research staff of Work Efficiency Association volunteered as test persons. They all had experienced in advance the simulator vibration in a test situation, and all knew the leader of the experiments personally. None of them had professional experience of tractor vibration. This was necessary because experienced people would be expected to have adapted to the vibration frequencies they are used to in their regular work. Basic data on the subjects is given in table 9.

3.4.3 Experimental Design

All subjects experienced three 45 min exposures at the same time of the day during the same week, one at 0 Hz (control), one at 1 Hz and one at 4 Hz stochastic vibration. All subjects experienced the control situation first and then randomly either 1 Hz or 4 Hz vibration exposures.

The design of the test procedure was the same as that presented for experiment 1.

The Vibrations Used

As the constant RMS-velocity had proved in the previous experiment No. 2 to put the variables measured to a comparable level at different frequencies, the RMS-velocity was kept at 40 mm/s (constant) both for 1 Hz and 4 Hz vibration. Correspondingly, the RMS-acceleration at 1 Hz was about 2.5 m/s^2 and at 4 Hz about 10 m/s^2 (figure 12).

Although there are differences in field analyses of acceleration levels of forest machines (largely due to different integrating and recording times of measurements), (KÄTTÖ et. al. 1973, HANSSON et al. 1974), it is obvious that the RMS-velocity of this experiment was higher than is usual in forestry work lasting one day. Even higher values can be registered in terrain, when the recording times are short, for example when driving over a big stone.

Variables Used

In order to find out the possible differences in activation level of the sympathetic nervous system or rate of energy metabolism excretion of catecholamines and heard rate were measured.

The following variables were used:
1 urinary excretion of catecholamines
2 heart rate
3 blood pressure

Table 9. Basic data on the subjects.

Variables	Min.	Max.	Aver.
Age, year	23	30	27
Weight, kg	57	88	67
Height, cm	172	185	180
$PWC_{subj.}$	7	9	7.8

4 tracking ability
5 manipulating ability
6 subjective rating of vibration
7 urine temperature

Measurement techniques were the same as in experiment 1. As subjective rating and manipulating ability test with tested sensitivity did not disturb the situation they were included in the test pattern, as was also the measurement of urine temperature.

The motivation of the subject for the tracking test was enhanced by making the situation competitive and offering prizes for the three best records.

Because the body receives mechanical energy from the excitatory vibration, the body temperature may rise due to friction between the organs or because of increased energy metabolism due to muscular work. For clarifying this phenomenon, the temperature of the urine filtered through the kidneys while the 45 min exposure was measured. After the exposure, the subject emptied his bladder into a thermos flask in which a mercury thermometer (accuracy ± 0.1°C, 1/2 value time constant about 5 s) was placed. The thermometer was read by the subject 50 s after the sample had been collected.

The record form of the experiment with the times of different measurements is presented in appendix 9.

3.4.4 Results

1 Catecholamines

The average value of adrenaline excretion varied from 8 ± 5 ngmin^{-1} at 4 Hz vibration to 22 ± 19 ngmin^{-1} at the control situation, the overall mean value being 15 ± 10 ng min^{-1}. No alterations were found in the adrenaline excretion which could have been explained by the different test vibrations including the control situation.

The average value of noradrenaline excretion varied from 28 ± 9 ngmin^{-1} at 1 Hz vibration to 39 ± 11 ngmin^{-1} at the control situation the overall mean value being 31 ± 8 ngmin^{-1} No statistically significant differences in catecholamine excretion were found, but the excretion of noradrenaline excretion during control situation tended to be higher than during both vibration situations.

2 Heart Rate

The average heart rate varied from 76 ± 13 beats min^{-1} at the control situation to 77 ± 7 beats min^{-1} at 1 Hz vibration, the overall mean value being 77 ± 9 beats min^{-1}.

No alterations were found in the heart rate which could have been explained by the different test vibrations including the control situation.

The mean values of urinary catecholamine excretion and the heart rate are also given in table 10.

3 Blood Pressure

Systolic blood pressure varied from 133 ± 10 mmHg at the 4 Hz vibration to 135 ± 8 mmHg at the 1 Hz vibration, with an overall mean value of 134 ± 10 mmHg.

Diastolic blood pressure varied from 79 ± 10 mmHg at 4 Hz vibration to 83 ± 10 mm Hg. at 1 Hz vibration, the overall mean value being 81 ± 10 mmHg. No alterations were found in blood pressures which could have been explained by the different test vibrations including the control situation.

4 Tracking Ability

The tracking scores varied from 12 ± 6 at 4 Hz vibration to 15 ± 5 at 1 Hz vibration, with an overall value of 13 ± 5.

No alterations were found in the tracking ability scores which could have been explained by the different test vibrations or control situation.

Table 10. Excretion rate of urinary catecholamines (NA = noradrenaline, A = adrenaline) and the heart rate (HR) at different vibrations. Number of vibrations: 0 = control, no vibration, 1 = 1 Hz vibration, 4=4 Hz vibration.

No of vibr.	NA ng min^{-1} ± s.d.	A ng min^{-1} ± s.d.	HR min^{-1} ± s.d.
0	39 ± 11	22 ± 19	76 ± 13
1	28 ± 9	15 ± 6	77 ± 7
4	27 ± 5	8 ± 5	77 ± 9

5 Manipulating Ability

The manipulating time varied from 21 ± 3 s at the control situation to 26 ± 4 s at 4 Hz vibration, the overall mean time being 24 ± 4 seconds (fig. 19).

The manipulating time at the control situation was statistically significantly shorter ($p < 0.05$) than at the vibration situations, but no statistical difference was found between 1 Hz and 4 Hz vibrations (Student's t-test).

6 Subjective Rating

The subjective rating number varied from 6 ± 0 at the control to 14 ± 2 at 4 Hz vibration, the overall mean value being 11 ± 4 (fig. 20).

The subjective rating number at the control situation was statistically significantly lower ($p < 0.001$) than during vibration, but no statistical difference was found between 1 Hz and 4 Hz vibrations (Student's t-test).

7 Urine Temperature

Urine temperature varied from 35.9 ± 3.0°C at 4 Hz vibration to 36.2 ± 3.0°C at 1 Hz vibration, the overall mean value being 36.0 ± 4.2°C.

No alterations were found in the urine temperature which could have been explained by the different test vibrations including the control situation.

3.4.5 Conclusions and Discussion

The aim of this experiment was to compare the effects of different frequencies and control situation on the psycho-physiologial functions of the driver.

No statistically significant differences were found in excretion rate of catecholamines between the different vibrations including control.

The heart rate and blood pressure values, as well as urine temperature remained at the same level during the different vibrations and the control situation.

These observations led to the conclusion that the sympathetic nervous system was not activated due to rather intensive vibrations. The results of experiment No 1 also support this conclusion.

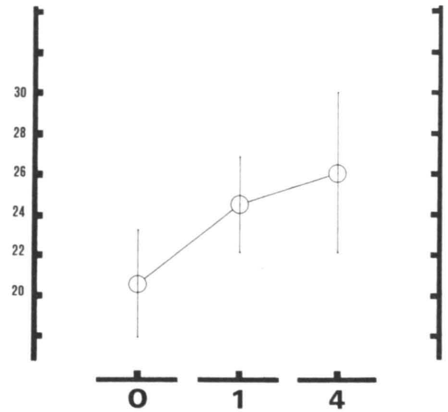

Figure 19. Relationship between manipulating time and test situation.
Ordinate: Time taken by the task, s
Abscissa: Test situation (18 observations).

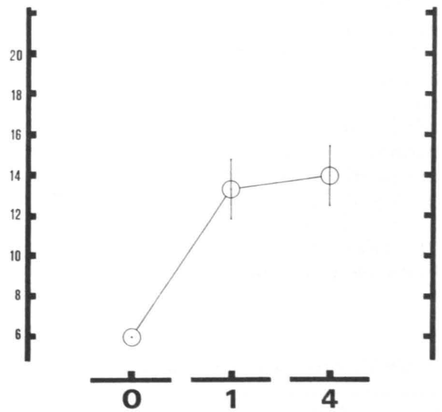

Figure 20. Relationship between subjective rating and test situation.
Ordinate: Subjective rating number (13 = fairly laborious)
Abscissa: Test situation (18 observations).

When the subjective rating of vibration varied from "fairly light" to "very laborious" (fig. 7, p. 23), the heart rate and blood pressure remained at the same level, the heart rate values resembling more those typical to rest than the ones typical to physical exercise and sympathetic activation (WUOLIJOKI 1977).

The subjective rating of vibration as well as the manipulating ability test agreed with the results of experiment 2 (constant RMS-velocity), the 1 Hz vibration tending to have smaller effects on the variables than the 4 Hz vibration (pp. 27–29).

At aerobic muscular work (a bicycle exercise test) the heart rate is linearly connected with the subjective magnitude rating of work load (BORG 1975). This correlation did not exist in these experiments when the work load consisted of whole-body vibration.

3.5 Experiment 4: Biomechanics of Vibration

3.5.1 Introduction

In this experiment, reasons for the smaller effect of 1 Hz vibration as compared with 4 Hz vibration was surveyed on the basis of dynamic properties of the body.

The natural frequency area of the upper human body, the thorax, was examined.

The infra-red light-emitting diodes (ir-leds), placed on the forehead of the subjects, showed the location of the head relative to the cabin and simulator base. The natural frequency of the test persons was measured by sweeping the sinusoidal frequency of the cabin slowly from about 0.2 to 2 Hz while keeping the amplitude constant. The cabin vibration was controlled with a sine-wave generator.

3.5.2 Subjects

Seven healthy male students and three professional drivers volunteered as subjects (table 11).

One infra-red led was fastened onto the middle of the forehead of the subjects with plaster, and another one onto a lateral bar mounted over the driver's head. The sweeping procedure took about 120 seconds. The movements of both ir-leds were registered during the whole procedure by a lightspot recorder. The definition of natural frequency was taken as a phase lag being 90 degrees between the head and the cabin.

3.5.3 Results

An example of how the natural frequency was determined is presented in figure 21.

When the rising excitation frequency approached the natural frequency of the thorax, the subject began to lag behind the excitation and the phase lag reached first 90° and then very soon 180°. After this the thorax stopped following the excitation as one-mass system, and different body parts (e.g. neck-head) tended to act as different systems. A phase lag of 180° is presented in figure 22.

Calculation of natural frequency according to a 90° phase lag showed the natural frequency to be 0.9 ± 0.1 (s.e.) Hz. Calculation according to 180 ° phase lag showed the head to move in the opposite direction to the cabin at 1.1 ± 0.1 (s.e.) Hz. Calculation of phase lag at 1 Hz resulted in 138 ± 41° (s.e.) allowing smaller displacement of the head, than what is at resonance area. This is seen in the last two cycles in figure 21.

3.5.4 Conclusions and Discussion

Although the subjects had different body dimensions, the natural frequency of the thorax laid in rather a narrow frequency band, i.e. from about 0.8 to 1.0 Hz.

Table 11. Basic data on the subjects.

Variable	Min.	Max.	Aver.
Age, year	23	35	28
Weight, kg	60	112	74
Height, cm	160	187	177

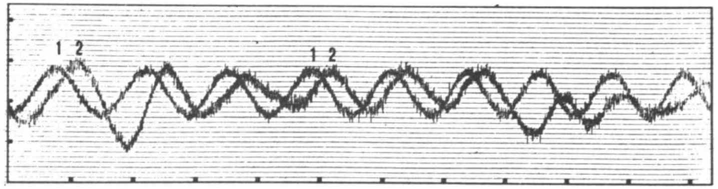

Figure 21. Head and cabin displacement as a function of time.
Ordinate: Displacement, scale 10 mm
Abscissa: Time, paper speed 25 mm/s scale 1 s. 1: cabin displacement. 2: head displacement. At the first marked cycle the amplitude ratio is at its maximum: at the second marked cycle the phase lag is about 90° indicating naturel frequency.

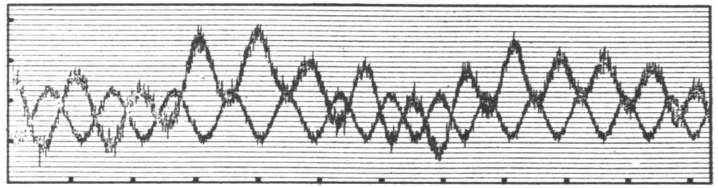

Figure 22. Head and cabin displacement as a function of time. Ordinate and abscissa as in fig. 21. The phase lag is about 180 degrees.

In experiment 1, the subjective rating of vibration correlated statistically significantly with the head displacement.

In experiments 2 and 3 the 1 Hz vibration was rated smaller than the higher frequency areas, and it affected the manipulating ability less than higher frequencies at constant RMS-velocity. This may have been the result of the body movement at 1 Hz as a one-mass system, but without the maximal amplitude ratiotypical to resonance.

In earlier comparisons of some low-frequency linear transversal vibrations, the biggest transmissibilities have been reported to be about 1 to 2 Hz (DIECKMANN 1958, SJÖFLOT et al. 1973, HORNICK et a. 1961, and WOODS 1967). The natural frequency measurement of this trial gives more accuracy to the previous meansurements.

4 GENERAL DISCUSSION

Subjective rating

The test persons' subjective rating of vibration magnitude agreed well with the physical parameters of vibration when the rating was done by the aid of a numerical rating scale.

The rating correlated with the vibration displacement (experiment 1, p. 23) in a positive linearity, by constant 4 Hz frequency (velocity increased).

By constant RMS-displacement (exp. 2, p. 29), the subjective rating correlated positively with the increase of frequency from 1 to 3 Hz (RMS-velocity increased).

Having constant RMS-velocity (exp. 2, p. 27), the alteration of frequency did not affect the rating by 2, 3, and 4 Hz, whereas the 1 Hz vibration was rated with smaller numbers than the higher frequencies. Experiment 3, p. 33, did not show statistically significant differences in subjective rating numbers between 1 and 4 Hz, by constant RMS-velocity.

Having constant RMS-acceleration (exp. 2, p. 29) the subjective rating number correlated negatively with frequency (velocity decreased).

These observations led to the conclusion that the driver's subjective rating of vibration is not sensitive to alterations of the displacement or acceleration alone, but the rating is most sensitive to the energy content of vibration per time unit. Because the velocity of vibration can be derived with one derivation both from the displacement and the acceleration, the velocity expresses the energy content of vibration better than the other parameters mentioned. This is offered as the explanation of the subjective ratings' dependence on the RMS-velocities.

The energy content of vibration can be expressed in Watts (1 kgm^2/s^3), which is also a way to express the rate of energy consumption of an organism.

The improvement of tractor vibration by reduction of only displacement or acceleration may not necessarily result in reduction of energy content and subjectively percieved magnitude of vibration. This is important in the design of boggie axles for tractors.

The professional drivers rated the vibrations with smaller numbers than the students. This led to the conclusion that amateur test persons may be more sensitive to vibrations than the professional drivers. The high sensitivity of subjective rating to variation of vibration parameters is in agreement with previous results of SHOENBERGER (1978) and HANSSON et al. (1979).

Attention Performance

The attention performance was evaluated by the aid of tracking ability test. Also a flicker-fusion test was used for the evaluation of activity of cortical functions.

The magnification of vibration displacement (exp. 1, p. 23) did not have a statistically significant effect on the tracking ability. This negative finding was supported by the results of experiment 3 (p. 32): the tracking ability scores remained unchanged during different excitatory frequencies or the control situation. The volunteers' motivation to the test was high, because two of the six drivers were prized.

Also the critical flicker-fusion frequency was independent of the magnification of vibration displacement (exp. 1, p. 22).

All the assessments of the attention performance were done with amateur drivers. The variation of vibration parameters as well as the vibration as compared with control situation were not shown to have an effect on the test persons' attention performance.

BASTEK et al. (1977) have assessed the attention performance by the aid of signal response time-tests in a vertical vibration experiment. In their study, vibration caused a delay in the mean response time, but no frequencyrelated diffrences were reported, although 2.4 and 8 Hz excitations were examined.

Vegetative Balance and Energy Metabolism

The balance of vegetative nervous system was evaluated by heart beat frequency and urinary catecholamine level.

Experiment 1 (p. 23) did not show any statistically significant effect of alteration of displacement of 4 Hz vibration on the heart rate or adrenaline or noradrenaline excretion rate. However, the noradrenaline excretion tended to increase during the largest vibration displacement.

Experiment 3 (p. 32) did not reveal alterations in the heart rate or catecholamine excretions which could have been triggered by alterations in vibration parameters.

There were two explanations for a possible sympathetic activation due to mechanical forces (p. 11):

1 The sympathetic activation could result from a direct reflex mechanism from the labyrinth or mechanoreceptors to the sympathetic trunk.
2 The sympathetic activation could result from negative feelings linked to emotional functions.

These results did not support the possibility for nervous pathway allowing a direct sympathetic activation by a mechanical 1–4 Hz stimulus, even if the stimulus is graded as "very laborious". Moreover, the volunteered test persons did apparently not have negative feelings against the vibrations, the emotional factors being thus uninvolved.

As the heart rate remained near the values of a resting person, a masking effect of test situation over the effect of vibration was not assumed.

The published assumptions of sympathetic activation of HASAN (1970), ASANOVA (1976), GORNICK (1976), VALČIĆ (1976), BASTEK et. al. (1977), and WARBANOW et al. (1977) were not supported by this study.

There were also two assumptions on the mechanism of a possible increase of energy metabolism due to increased vibration intensity:

1 For keeping his balance the driver has to do extra muscular work when vibrated.
2 Muscle contractions or increased muscle tone may appear due to reflex functions of the vibrated body.

In case of these functions more Watts (1 Watt = 1 kgm^2/s^3) would have been lost and physiological functions typical to increased energy consumption would have appeared. This was not the case (exp. 1 and 3) as the heart rate, blood pressure, and catecholamine excretion rate remained unchanged.

BASTEK et al. (1977) has reported increased electrical activity of dorsal extensors in vertical vibration in strictly controlled body posture.

In the present stydy the electrical activity of some muscle groups may also have been increased, but the metabolic effects of this has been so small, that it has not affected the physiological variables mentioned.

As the energy content of vibration (unit: 1 Watt) correlated with subjective magnitude of vibration, one could have assumed that the subjective magnitude of vibration could have correlated with the energy consumption of the body (unit: 1 Watt). This assumption was shown to be wrong, because the increase of vibration energy did not increase the energy consumption of the body. The subjective magnitude rating of vibration was independent of the psycho-physiological functions measured.

The subjective rating of vibration does not necessarily correspond to physiological cost of the vibration, but to the energy content of the vibration.

Instead, the manipulating ability was highly sensitive to energy content of vibration showing no unlinearities in frequency responses within 1 to 4 Hz.

Mechanical Effects on the Driver's Body

Displacement of the cabin caused immediate displacement of the body.

In experiment 1 (p. 25) the head displacement showed high sensitivity to the vibration. When this variable was used for examination of resonance areas (exp. 4, p. 34), the natural frequency of the driver's thorax was found to be in the frequency area of 0.9 ± 0.1 (s.e.) Hz. This area is lower than what is usual in natural frequency areas of tractors. Thus the possible unlinearities in responses to various frequencies due to thorax resonance are not expected. Instead, a 180° phase lag may occur at excitatory frequencies higher than 0.9 Hz.

It is obvious that the vibration magnitude estimation is dependent on the dynamic state of the head and thorax.

The body movement as an one mass-system

seems desirable in terms of subjective comfort. The high amplitude ratio typical to resonance areas is avoidable with excitatory frequencies slightly higher than 0.9 Hz, allowing a phase lag of 180 degrees.

Summarizing Remarks

The healthy body seems to be rather resistant towards this kind of vibration. This may arise from the fact that man has been walking or running since the beginning of his development.

The subjective magnitude rating of vibration did not correlate with variables of physiological fatigue. The norms which are based on subjective ratings of vibration can equally not precisely indicate the drivers physiological fatigue, decreased proficiency or exposure limits.

The variables assessed in this study, indicate only momentary responses of the body to vibration. It is not possible to use them for estimation of negative effects of work extending over years.

5. SUMMARY

Horizontal (y–axis) random whole body vibrations of 1, 2, 3 and 4 Hertz were compared with each other in order to find out the importance of various mechanical parameters of vibration as factors having ergonomic effects on the driver.

The assessed variables of the driver were psycho-physiological (sympathetic tone, attention performance) and mechanical (manipulating ability). Also the subjective magnitude rating of vibration was used.

Healthy male volunteers, both professional drivers and students, were exposed totally to 692 different vibrations in four different experiments, total number of subjects being 34.

Increase of vibration displacement affected clearly the subjects' manipulating ability. The subjective magnitude rating of vibration correlated with the energy content of vibration (physical unit: 1 Watt), but no correlation was found between subjective rating and heart rate, blood pressure or urinary catecholamine excretion, although the variables mentioned do correlate with energy consumption of the body (physical unit: 1 Watt).

The independence of subjective magnitude rating of vibration on physiological energy consumption opposes assumptions published.

The subjective magnitude rating of vibration was in close connection with the root-mean-square value of velocity of vibration. Thus, frequency alteration of tractor vibration, effecting on the velocity, can be a possibility for reduction of vibrational effects as a tool for industrial hygiene.

The professional drivers rated the vibration with smaller numbers than amateur drivers, the 1 Hz vibration being rated with smaller numbers than the other frequencies, by both subject groups. In order to find out a reason for this an analysis of natural frequencies of the subjects' thoraxes was performed.

A phase lag of 90 degrees indicating resonance was present at about 0.9 Hz. A phase lag of 180 degrees was recorded at about 1.1 Hz, the 1 Hz vibration producing a phase lag of about 138 degrees allowing a relatively small movement of the head and upper thorax at the 1 Hz excitation. It was assumed that movement of the body as one mass-system plays a role in subjective magnitude rating of vibration.

In terms of subjective comfort, the 1 Hz vibration is preferred for natural frequencies of the machines, but the subjects' fatigue is not in close relation to the subjective magnitude rating of horizontal vibration.

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SELOSTE

TRAKTORIN SIMULOIDUN TÄRINÄN VAIKUTUKSET KULJETTAJAN PSYKOFYSIOLOGISIIN JA MEKAANISIIN TOIMINTOIHIN: ERÄIDEN HERÄTETAAJUUKSIEN VERTAILU

Horisontaalisia koko kehoon kohdistuvia yhden, kahden, kolmen ja neljän hertsin taajuisia satunnaistärinöitä verrattiin toisiinsa laboratorio-oloissa. Tutkimuksessa selvitettiin tärinän mekaanisten muuttujien keskinäistä tärkeyttä kuljettajan toimintoihin vaikuttavina tekijöinä.

Mitatut kuljettajien toiminnot olivat psykofysiologisia (sympaattisen hermoston tasapaino, keskittymiskyky) ja mekaanisia (hallintalaitteiden käyttö). Myös subjektiivista tärinän voimakkuuden arviointia käytettiin.

Terveet, ammattikuljettajista ja opiskelijoista kootut koehenkilöt (n = 34) altistettiin kaikkiaan 692 eri tärinälle neljässä osatutkimuksessa.

Tärinän siirtymän suurentaminen vaikutti huonontavasti hallintalaitteiden käyttöön. Tärinän voimakkuuden subjektiivinen arviointi korreloi tärinän energiasisällön kanssa, mutta ei korreloinut kehon energiankulutusta ilmaisevien muuttujien kanssa.

Ammattikuljettajat arvioivat tärinän pienemmäksi kuin opiskelijat.

Tärinän subjektiivinen arvio oli kytkeytynyt lähinnä tärinän nopeuteen. Täten traktorin tärinän ominaistaajuuden muuttamista voidaan käyttää apuna työhygienisissä toimenpiteissä ja ergonomisessa koneen suunnittelussa.

Yhden hertsin tärinä arvioitiin muita pienemmäksi. Tämän selvittämiseksi analysoitiin koehenkilöiden ylävartaloiden poikittaisheiluntojen ominaistaajuus.

Resonanssia osoittava 90 asteen vaihesiirto mitattiin noin 0,9 hertsin herätetaajuudella. 180 asteen vaihesiirto mitattiin noin 1,1 hertsin taajuudella. Tällöin koehenkilöiden pää liikkui vastakkaiseen suuntaan kuin heräte. Yhden hertsin heräte aiheutti noin 130–140 asteen vaihesiirron ja mahdollisti vain vähäisen pään ja ylävartalon liikkeen sekä kehon värähtelyn yksimassajärjestelmänä. Tästä pääteltiin, että pään ja ylävartalon liikkeillä yksimassajärjestelmänä on merkitystä tärinän voimakkuuden subjektiivisessa arvioinnissa.

Kuljettajan mukavuuden kannalta yhden hertsin tärinää voidaan pitää muita tärinöitä parempana, mutta kuljettajan fyysinen kuormittuminen tai keskittymiskyky eivät riippuneet poikittaistärinän subjektiivisesta arvioinnista tai kokemisesta.

Tämän tutkimuksen tuloksia voidaan käyttää hyödyksi koneen suunnittelussa. On kuitenkin huomattava, että vuosia jatkuvan työn kuormittavuutta ei voida arvioida simuloiduilla kokeilla.

APPENDICES

Appendix 1: Record form of experiment 1

Exposure No .... date .... subj. ....
Airt: temp. .... press .... hum. ....
PWC_{subj} (4–10) .... hours slept last night ....
age .... weight .... height .... expt.leader ....
displacement .... frequency ....
potentiometer scale .... cab acceleration ....
seat acceleration ....

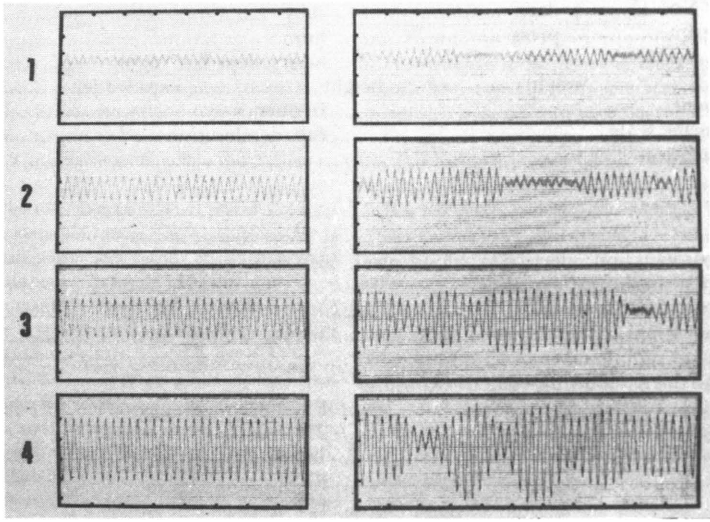
Time:
(min)
–20 instrumentation: electrodes, blood press. (BP) cuff,
subj. sitting in cab. reading
–10 heart rate (HR) ..../................/................ BP ..../................
–08 finger temp. (FT)................................. manip. ability (MA)..............................
–05 WC, no sample taken, no running, FFF ....
–01 water drink (330 ml), start of exposure
+10 HR ..../ ..../ ..../ BP ..../ .... FT ....
+20 HR ..../..................../..................../ BP ..../ ....
subj.rating (SR)...................................... ir-led ....
+30 HR ..../ ..../ .... BP ..../ ....
FT............/.................MA .... FFF.......... ....
+40 HR ..../ ..../ ..../ BP ..../ ....
SR.. ir-led
+50 HR ..../ ..../ ..../ BP ..../ ....
+60 HR ....
SR.. ir-led
+61 WC, sample of urine..............................ml

adrenaline...
nonadrenaline...

Appendix 2: Vibrations of experiment 1

The numbers of the vibrations related to the numbers in table 4. On the left side are sine-form vibrations and on the right side the respective vibrations of stochastic nature. Recording was done with a light spot recorder. Paper speed was 25 mm/s.

Ordinate: Displacement. Scale 10 mm.
Abscissa: Time. Scale 1 s.



Appendix 3: Equipment for the measurement of acceleration

The equipment was as follows:

- accelerometer Brüel & Kjaer 4332
- integrator B & K ZR 0020
- narrow-band filter B & K WH 6517
- impulse precision sound level meter B & K 3204
- calibrator B & K 4291

The peak values of table 4 were measured with the main switch of the B & K 2204 in the "peak" position, with a bandwidth of 16 %, and with a 30 s averaging time.

The equipment used for frequency analyses:

- accelerometer, General Radio Company 1560-P54
- pre-amplifier, Philips TAA-320
- vibration meter, Wärtsilä WIB-6-72

Appendix 4: Basic data on the subjects of experiment 1

Initials	length cm	weight kg	age years	heart rate at rest r/min	blood press. at rest mmHg	subj. working capacity	type of vibration
J.R.	175	60	26	57	132 69	9	sine
I.J.	175	75	36	63	130 80	7	–"–
M.H.	177	71	33	55	132 67	8	–"–
B-O.L.	177	67	33	65	126 64	8	–"–
E.W.	181	64	29	65	124 80	7	–"–
M.S.	171	65	27	65	111 68	9	–"–
$\bar{x}$	176	67	31	62	124 71	8	
J.K.	185	92	31	62	129 81	6	stoch.
E.W.	181	64	29	70	134 88	7	–"–
K.H.	172	69	27	62	122 72	8	–"–
H.V.	180	82	25	65	124 74	8	–"–
V.T.	166	81	29	60	110 66	7	–"–
J.M.	172	82	36	60	141 78	8	–"–
$\bar{x}$	176	78	30	63	127 77	7	

Appendix 5: Table of variables of experiment 1

1 Number of session
2 Number of test person
3 Age of test person, years
4 Subjective work capacity, (scale: 4–10)
5 Heart rate before session – heart rate at rest, beats/min
6 Individual ordinal number of session
7 Displacement of vibration, mm
8 Waveform (sine/stoch.) (scale: 1–2)
9 Subjective rating of vibration (scale: 6–20)
10 Manipulating ability, s
11 Head double-amplitude, mm on paper
12 Heart rate during exposure, beats/min
13 Systolic blood pressure, mmHg
14 Diastolic blood pressure, mmHg
15 Adrenaline excretion, % of baseline
16 Noradrenaline excretion, % of baseline
17 Tracking ability, scores

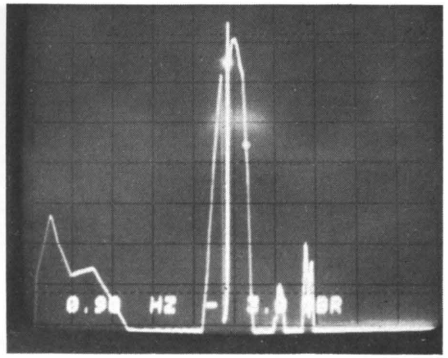
Appendix 6: Correlation matrix of experiment 1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1000																
2	997	1000															
3	-10	-10	1000														
4	-198	-199	-320	1000													
5	-156	-151	-320	8	1000												
6	9	0	0	0	2	1000											
7	80	0	0	0	-50	124	1000										
8	866	869	-163	-392	-79	0	0	1000									
9	40	-31	15	-166	-19	-72	863	25	1000								
10	86	17	-34	-140	111	15	885	34	808	1000							
11	233	185	-311	44	138	23	605	242	637	548	1000						
12	-113	-121	-179	-335	383	-112	81	121	201	197	161	1000					
13	182	171	317	-125	-1	-73	137	41	-71	135	5	123	1000				
14	120	118	319	-659	-65	101	41	234	12	156	-53	371	458	1000			
15	204	206	-176	1	207	54	-6	99	-35	32	-148	-259	23	-76	1000		
16	191	177	-92	96	161	-175	207	98	125	191	91	-308	81	-209	265	1000	
17	445	448	-405	-114	134	-221	1	434	166	146	210	-130	-337	-263	260	257	1000

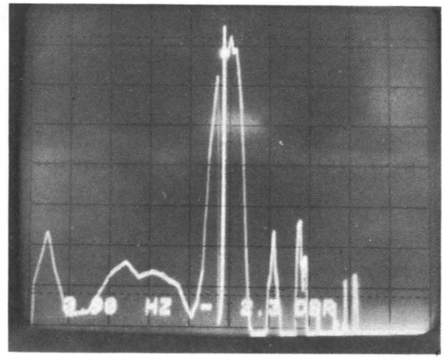
Appendix 7: Vibrations of experiment 2

Spectrum Analyses

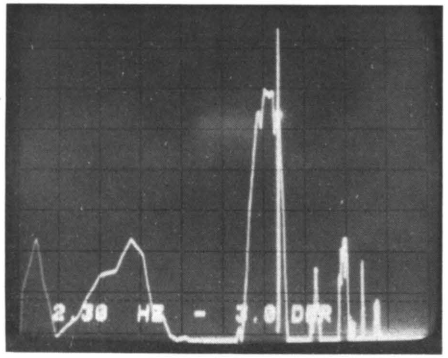
Measurement are made by the same equipment as for the dynamic properties of the simulator (p. 00) from the loaded seat, in the acceleration mode.



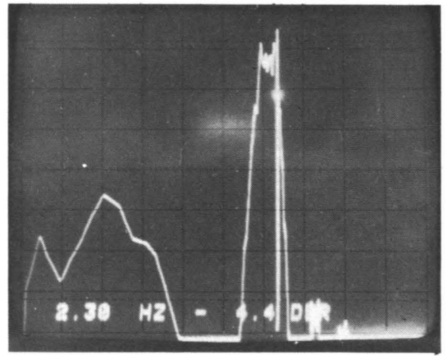
Control signal of the 1 Hz vibration (from tape)



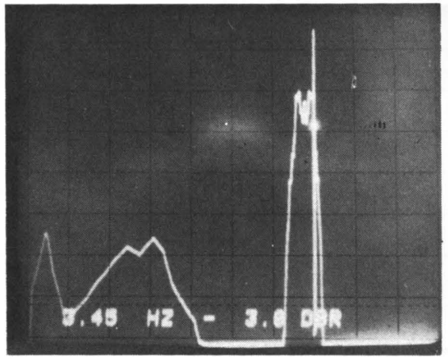
Simulator response to the 1 Hz excitation



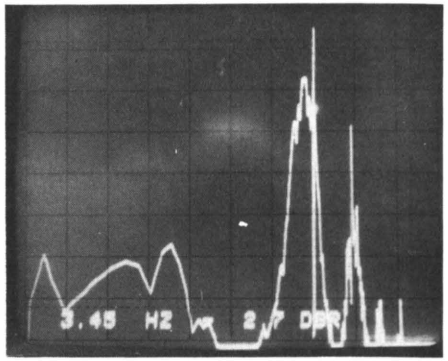
Control signal of the 2 Hz vibration



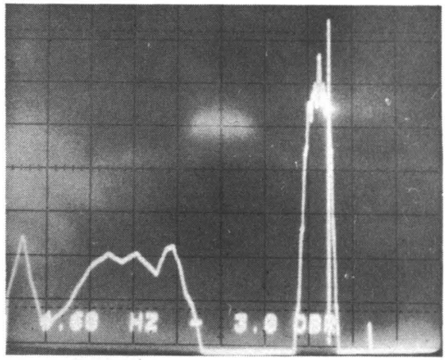
Simulator response to the 2 Hz excitation



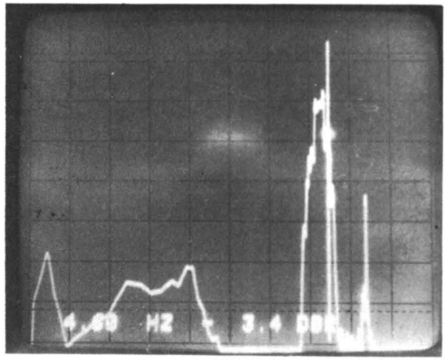
Control signal of the 3 Hz vibration



Simulator response to the 3 Hz excitation



Control signal of the 4 Hz vibration

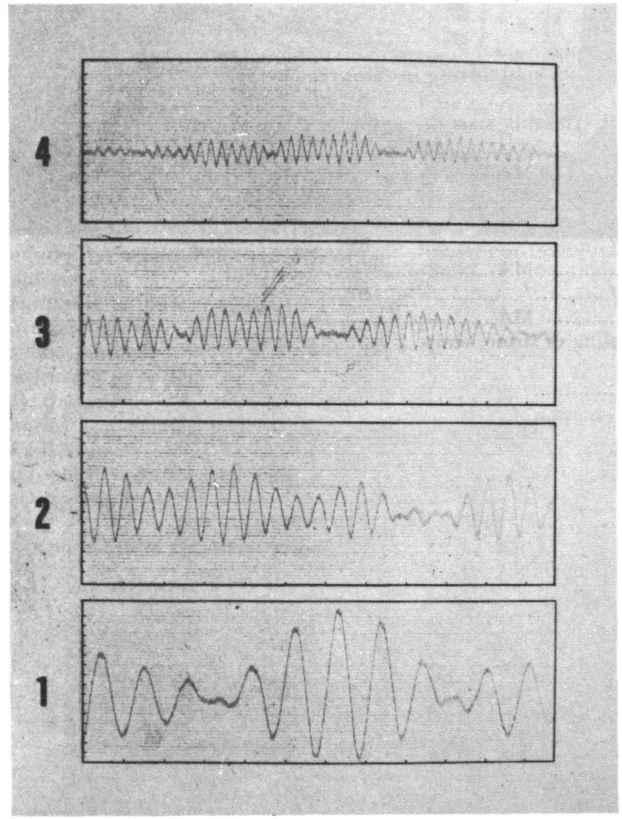


Simulator response to the 4 Hz excitation

Appendix 8: Vibrations of experiment 2

Displacement Analyses
Recording of displacement as a function of time

Number of vibration agrees with the frequency of vibration.
Paper speed 25 mm/s.
Ordinate: Displacement, scale 10 mm
Abscissa: Time, scale 1 s



Appendix 9: Record form of experiment 3

Exposure No .... date .... subj. ....
Airt: temp. .... press .... hum. ....
PWC_{subj}..................... adress ....
age .... weight................. time...
Frequency................... potentiometer scale velocity...
displacement... acceleration..
indic. number of exposure...................................... leader..

Time:
(min)
−20 WC, urine temp. .... no sample taken
−15 instrumentation, subj. sitting in cab., reading
−05 HR ..../ ..../ ..../ BP........./ ....
−01 water drink (200 ml), start of exposure
+10 HR ..../ ..../ ..../ BP........./ ....
SR..................... MA..................................
+20 HR ..../ ..../ ..../ BP........./ ....
SR..................... MA..................................
+30 HR ..../ ..../ ..../ BP........./ ....
SR..................... MA..................................
+40 HR ..../ ..../ ..../ BP........./ ....
SR..................... MA..................................
+46 WC, sampling of urine, temp. .... ml

adrenaline ....
noradrenaline ....

Picture 1. Overall picture of the laboratory set-up.
1 Simulator cabin
2 Control desk of the hydropulsator
3 Instrument tape recorder
4 Function generator
5 Biotelemetric equipment
6 Pulse counters
7 Infra-red light-emitting diode
8 Infra-red camera
9 Light-spot recorder for the former
10 Tracking-recorder

(Photo: Rauma-Repola Oy, Mauri Kivistö).

WUOLIJOKI, ERKKI O.D.C. 302 + 304

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Healthy male volunteers, both professional drivers and students, were exposed totally to 692 different vibrations in four different experiments, total number of subjects being 34.
The subjective magnitude rating of vibration correlated with energy content of vibration, but no correlation was found between subjective rating and heart rate, blood pressure or urinary catecholamine excretion, although the last variables mentioned indicate the energy consumption of the body.
Frequency alteration of tractor vibration can be a possibility for reduction of vibrational effects as a tool for industrial hygiene.

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