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In terms of human communication and the ease of carrying out everyday tasks, hearing is one of the most important of man's senses. This is why hearing and the way in which it functions have for decades been the subject of intensive study.

Numerous fairly comprehensive studies are available on the effects caused on hearing by separate physical phenomena occurring in the environment and varying in intensity, duration or form (spectrum), such as noise. However, few investigations have been made into the combined effect of noise and vibration or, for that matter, of noise and any other environmental physiochemical factor, on the functions of the inner ear.

Today's traffic and industrial environment, in particular, are places where functional deficiencies of the inner ear may increase the incidence of accidents. In terms of increased safety and the ease of carrying out daily work tasks, it is extremely important to understand the functional changes that may be caused in the human body by exposure to combinations of those stimuli most frequently encountered in different environments. In the development and industrialization of the circumpolar areas these questions are of great current interest.

For a correct evaluation of the efficiency of protective devices and technical protection measures it is very important to know how combinations of stimuli occur in the environment, and how the human body responds to the effects of such combinations. The great significance of determining the interactions of environmental factors is also emphasized by the fact that under conditions where multiple stimuli are present, the known specific effects of individual environmental factors may become altered or may even become unimportant as compared with the combined effects of the same factors. The effects of such combined stresses cannot be realistically predicted from single-stress investigations (4, 5, 9, 12, 15).

The International Standardization Organization (ISO) has prepared detailed recommendations on permissible single noise levels and on whole body vibration exposures and the duration of such exposures. The maximum permissible noise and vibration acceleration specified in the recommendations, however, do not include the effects of other factors that may be present simultaneously in the exposure situations involved, nor do they include the effect of exposure repeated at regular or irregular intervals. In order to determine the above items in detail, a series of tests was carried out under controlled conditions. One main aim of the test was to characterize gradual shifts in the temporary hearing threshold when the test subjects were exposed three times in succession to combinations of vibration, noise, temperature and muscular work.

MATERIAL AND METHODS

In order to characterize the main and overall effects of the various factors, a 2x2x3 factorial test was carried out. The total number of combinations of stimuli was thus 12. The effect of each combination of stimuli on temporary threshold shifts (TTS) was tested on the basis of the hearing test results of six subjects selected at random in the cell (i.e. exposure combination) involved. Each ear of each person was treated as an independent observation unit, resulting in a total of 144 observations (ears) in the test.

The subjects were 72 male students of medicine or technology selected from among volunteers. The selection was made on the basis of an initial examination which included hearing measurements, interviews and certain measurements characterizing personal performance. A complete hearing threshold test was carried out on each candidate at 125, 500, 1000, 2000, 4000, 6000 and 8000 Hz using air con-
duction audiometry. Persons accepted for further examination were required to have left and right ear thresholds that did not differ from each other by more than 10 decibels, and a hearing threshold of less than 20 decibels at each of the frequencies tested.

Interviews were carried out in addition to the hearing measurements in order to exclude from the test any persons who had doubtful hearing functions or who had previously been exposed to noise and vibration or to other such factors. The subjects also had to have normal blood pressure and ECG values. All persons accepted as test subjects were thus in good physical condition and health, and had an average age of 22.2 ± 1.7 years, an average weight of 72.4 ± 7.1 kg and an average height of 179.3 ± 5.3 cm.

The test was carried out using an exposure system developed during the method design of the research program; certain general approaches of the system are described in other contexts (10). Fig. 1 contains a diagram of the monitoring and control functions employed in the system. The daily tests were carried out from 8.00 a.m. to 4.00 p.m., with equal numbers of tests carried out during the morning and the afternoon. The subjects wore similar clothing in the exposure tests; before entering the exposure chamber each put on a cotton T-shirt, underpants, track suit trousers and terrycloth socks. Wearing of other clothes was forbidden. The

Fig. 1. Diagram of the monitoring and control set-up employed in the system.

The exposure combinations comprised two dry-bulb temperatures (20°C, 30°C), two physical work loads (2W, 8W) done with the right hand, and three noise levels. The noise levels were no-noise, free field continuous broad-band noise (band width 0.2-16kHz) of 90 dB(A), and free field continuous broad band noise (band width 0.2-16 kHz) of 90 dB(A) with simultaneous sinusoidal (r.m.s.) vibration at a frequency of 5 Hz (acceleration 2.12 m/s^2) along the Z axis.

Depending on the number of the test, the dry-bulb temperature of the exposure chamber was adjusted to either 20°C or 30°C. The average relative humidity during the test cycle was 42.8 ±4.3%. Curtains suspended behind the subject were used to maintain an air flow rate of 0 m/s near the subject’s head. The noise stimulus employed was stable (sound level variation less than 2 dB) A-weighted white noise. The noise spectrum was shaped by means of a variable filter (type Kemo VBF/8), and the resulting signal was stored on low noise magnetic tape (type Scotch 208). The variable filter was used in the band pass mode with the above cut-off frequencies of 0.2 kHz and 16 kHz, and with a slope attenuation of 24 dB per octave. The subjects were exposed to vibration while seated, and the necessary vibration was applied by means of a vibrator system specially developed for exposure tests. The system comprised a vibrator unit complete with servo-cylinders, a monitor and control unit, and a hydraulic pump unit (type Finnhyd). The actuating device of the system, i.e. the servo-cylinder, was electrically controlled by means of a servo-circuit, a displacement transducer and an acceleration transducer. The work included in the test was carried out with the muscles of the right arm. Two different physical work loads were used, corresponding to power outputs of 2 W and 8 W. While seated in the vibration chair, each subject pulled towards himself, in the direction of the armrest, a lever attached to the front end of a double-acting pneumatic cylinder. The work was synchronized.
Fig. 2. Diagram of a manually operated compressed air device for producing loads against muscular work.

by lamps lighting up on a lamp panel. The work load was adjusted by means of the cylinder pressure and non-return throttle valves (Fig. 2), and consisted of two cycles; the actual work was done during the pulling motion, and the rest cycle consisted of returning the lever to its initial position.

During the actual tests the hearing threshold levels were only determined at 1, 4, 6 and 8 kHz (known as limited frequency testing), using the ascending technique developed by Hughson-Westlake, and air conduction audiometry. The sound signals were sent to earphones (type THD-39) connected to a puretone audiometer (type Peters AP-31). The threshold was determined in the same way each time, 2 minutes after the end of exposure (ITS<sub>2</sub>). After receiving a signal, the subject put on the earphones and pressed a signal button to indicate that he heard the test signal. All exposure system equipment was stopped for the duration of the hearing measurements to reduce the sound level in the chamber below 25 dB(A). For clarity, the successive TTS<sub>2</sub> values measured during the test were marked with time subscripts, e.g. TTS<sub>15</sub>, TTS<sub>30</sub>, TTS<sub>50</sub>, TTS<sub>70</sub>, TTS<sub>90</sub> and TTS<sub>105</sub>. The main and overall effects of the factors were examined with the aid of three- and two-way variance analyses. To determine the explanatory degree of the entire model, coefficients of multiple correlation were also calculated. The squares of these coefficients indicate the percentage of TTS variation resulting from the combined effect of the parameters used in the model. To describe the P-values in paired comparison, the two-tailed t-test of unpaired means was used. The subjects themselves provided the control. Before the actual statistical processing of the results, the observed values were corrected by subtracting the threshold value of the second control cycle (TTS<sub>30</sub>) from the threshold values determined immediately after the first, second and third exposures and the subsequent recovery cycle (i.e. TTS<sub>50</sub>, TTS<sub>70</sub>, TTS<sub>90</sub> and TTS<sub>105</sub>). Means and standard errors of means were given for the main observations in the results.

RESULTS

The main and overall effects of the environmental factors tested could be discerned mainly within the 4000 to 6000 Hz range. Among the three variance analysis model parameters, noise was highly significant (p< 0.001) and also had the most distinct main effect on the TTS at both 4 and 6 kHz. Neither temperature nor this type of muscular work seemed to have a main effect on the TTS at 4 kHz, although during each exposure, work seemed to have a significant effect (p < 0.001) on the TTS at 6 kHz. The main effects of the factors on the TTS are shown graphically in Figures 3 to 5.

Fig. 3. Main effect of dry-bulb temperature on temporary threshold shifts at 4 kHz, plotted against duration of exposure. Block diagrams drawn on the basis of arithmetic means. *<sup>1</sup><sup>st</sup> exposure = TTS<sub>50</sub> values, 2<sup>nd</sup> exposure = TTS<sub>70</sub> values, 3<sup>rd</sup> exposure = TTS<sub>90</sub> values, post-exposure = TTS<sub>105</sub> values.

Among the paired combinations of stimuli, noise (intensified by vibration) and work seemed to have a significant effect (p < 0.025- p < 0.01) on threshold shifts at 6 kHz only (Fig. 6). The
combined effect of all the three (four) factors was significant at the 5% level (df = 2; 132; F value = 3.53) after the third exposure at the 6 kHz audio frequency. The squares of the coefficient of multiple correlation ($R^2$) based on variance analysis further show that the total explanatory degree of the factors increased with prolonged duration of the exposure; this was particularly evident in the threshold shifts at 4 kHz. The squares of the coefficients, in the order of the exposure sequence, were 58, 69, 72, 54 (at 4 kHz) and 55, 55, 63, 48 (at 6 kHz). When examined by combination, the percentage increase in the explanatory degree of the multiple coefficients was largely explained by the increased significance of those combinations that included noise. In fact, this was already observed from the main effects produced by variance analysis and from the statistics listed in Table I.

Table I gives the TTS means and standard errors of the means determined for 4 kHz. The broad-band 90 dB stable noise and the 5 Hz whole-body vibration had a particularly clear combined effect on threshold shifts when the subjects were working at the 2 W power output at both 20°C and 30°C. With the same power output and the same dynamic muscular work at 20°C the temporary threshold was on average 1.1 times (1st exposure), 1.4 times (2nd exposure) and 1.2 times (3rd exposure), and at 30°C 1.1 times (1st exposure), 1.3 times (2nd exposure) and 1.2 times (3rd exposure) higher than when stable noise was the only factor. At four times the above workload (i.e. 8 W) noise
TABLE I  Means (X) and standard errors of means (S.E.M.) at 4 kHz by exposure combinations, presented against duration of exposures. This plot system is intended to point out an interesting finding of TTS variations caused by vibration and temperature.

<table>
<thead>
<tr>
<th>Noise level</th>
<th>20°C</th>
<th>30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2W Work load</td>
<td>2W Work load</td>
<td>2W Work load</td>
</tr>
<tr>
<td>0.0 ± 0.6</td>
<td>0.8 ± 0.6</td>
<td>-0.4 ± 0.4</td>
</tr>
<tr>
<td>0.2 ± 0.6</td>
<td>0.8 ± 0.6</td>
<td>0.2 ± 0.0</td>
</tr>
<tr>
<td>-0.4 ± 0.8</td>
<td>1.3 ± 0.9</td>
<td>0.8 ± 1.0</td>
</tr>
<tr>
<td>-0.4 ± 1.0</td>
<td>0.8 ± 1.0</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>0.8 ± 0.8</td>
<td>0.8 ± 0.8</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>-0.4 ± 0.8</td>
<td>1.3 ± 0.8</td>
<td>0.4 ± 1.0</td>
</tr>
<tr>
<td>0.8 ± 1.0</td>
<td>1.0 ± 1.0</td>
<td>1.0 ± 1.0</td>
</tr>
</tbody>
</table>

§ 1=1st Exposure, 2=2nd Exposure, 3=3rd Exposure, 4=Post-Exposure

and vibration were not found to have the same combined effect; the mean threshold values seemed rather to remain roughly the same or even become reduced by two or, three decibels. Perhaps the most important difference for further research, however, was in the threshold shifts upon exposure to the combinations 90 dB(A)/2 W/20°C and 90 dB(A) + 5 Hz(2.12 m/s²)/2 W/30°C (see Table I and Fig. 7). Although the variance analyses showed no significant interactions in this respect, the results would seem to indicate that the additional effects of exposure to vibration while seated are in one way or another related to the ambient temperature.

At the frequencies tested with the audiometer, the greatest relative increase in hearing threshold was at 6 kHz. It was highest, i.e. 25 ± 8.0 dB (X ± s.d.), after the third exposure, during which the combination of stimuli was 90 dB(A) + 5 Hz(2.12 m/s²)/8 W/30°C, and second highest, i.e. 23.5 ± 5.4 dB, when the combination was 90 dB(A)/8 W/30°C. The mean threshold values measured after successive exposures repeated at regular intervals of four minutes differed by a maximum of 7.0 (at 4 kHz) - 9.2 (at 6 kHz) decibels. Depending on the combination of stimuli, the average difference between the mean thresholds measured after the first and third exposures was 5.7 (at 4 kHz) - 6.1 (at 6 kHz) decibels. On the other hand, the post-exposure threshold values were resumed in almost direct proportion to the stimulus combinations and to the threshold values measured after exposure to
DISCUSSION

Noise, vibration, temperature and (both mentally and physically stressing) work are perhaps the most common factors whose specific characteristics are quite frequently being classified for evaluating the quality of the environment. In modern artificial mini-environments (e.g. cabs of vehciles) the various factors form a complicated entity, in which none of the factors can be summarily omitted or isolated for separate evaluation. The temporary threshold shifts observed in subjects examined after such test exposure situations as the one described in the above are one indication of the integral fabric formed by the various factors.

Researchers in the field of noise-induced hearing impairment have for decades been aware of the distinct notch on the audiogram in the 4 to 6 kHz frequency range (8). As Schucknecht and Tonndorf (14) point out, the phenomenon can be explained in two different ways. The first is based on the effect of the mechanical forces exerted during acoustical exposure on the area of the organ of Corti, while the second is based on the higher susceptibility of the organ of Corti to damage at about 4000 Hz. According to the survey made by Brandy and Studebaker (3), most researchers today hold the first view. Excessive strain could therefore be a reason for the notch at 4 to 6 kHz. Considering the changes in the hearing functions, observed in different degrees and on different levels, the two views are not necessarily conflicting; in fact they clearly support each other.

Other factors may, naturally, contribute to the rise of the hearing threshold at the 4000 to 6000 Hz frequencies. Another explanation could perhaps be found in changes in the inner ear metabolism or in some other physiological balance (7, 11). Functional disorders of, and damage to the auditory organ could thus be caused by the effects of noise and vibration on blood circulation in the inner ear or on the vascular wall structure (2, 13, 16).

Peripheral circulation in the brain and the inner ear could be further impaired if exposure to noise and vibration were combined with the pooling of a large quantity of blood. In either the seated or standing position, vibration occurring in the vertical direction of the body (Z axis) would probably cause maximum pooling. An examination of the effects of vibration acceleration (+G<sub>z</sub>) at varying temperatures (1) reveals that the peripheral vasodilation resulting from the exposure to vibration contributes to the accumulation of blood in the lower body and in the lower extremities. As the hydrostatic pressure increases in the lower limbs, the blood vessels become more and more dilated (6).

The additional effects of the pooling of blood may, however, be eliminated to some extent by changing the body's position and, at relatively low vibration accelerations and low temperatures, by some suitable dynamic work carried out by the exposed persons. As is well known, work done by limb muscles, in addition to increasing blood flow, also mobilizes fats and increases the rate of glucose metabolism. The results obtained in the present study provide interesting support for this view. One item of interest is the optimum limits of the work rate to be recommended for this.
purpose.

To summarize, it can be noted that the combined effects of noise, vibration, temperature and work on hearing functions are results of a very complicated chain of events. Owing to the complex nature of the effects, a good deal more research is required before detailed conclusions can be reached. The present research program will proceed gradually to more complicated exposure models, which will reconstruct real exposure situations better in both spectrum and the mutual interactions available. Detailed knowledge of the effects of such exposure combinations could help to prevent any excessive irritation of the hearing mechanism, particularly in cases not caused by the detrimental effects of sound alone.

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REFERENCES


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