Vibratory Sensation Induced by Low-Frequency Noise: A Pilot Study on the Threshold Level

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The induction of vibratory sensation is a characteristic of low-frequency noise. In this pilot study we measured the threshold levels to induce a vibratory sensation in normal-hearing subjects exposed to pure tones within a narrow frequency range (20-50 Hz). The threshold levels necessary to induce a vibratory sensation were found to be 5-17 dB(SPL) higher than the hearing threshold levels; these vibratory sensation levels were lower than the sensation threshold levels in deaf subjects previously measured by another research group. This difference suggested the possibility that the function of the hearing organs is related to the perception of vibration in normal-hearing persons exposed to low-frequency noise. Our study showed that the head was the part of the body in which the vibratory sensation was most often experienced, which supported the idea that the hearing organs may contribute to the normal-hearing person's perception of vibratory sensation. Another interesting finding of our study was a dip appearing in the threshold level for the vibratory sensation at 40 Hz. This was broadly in agreement with another group's result that sensitivity to vibration was greatest at frequencies between 40 and 80 Hz.

Key words: Low-frequency noise, Vibratory sensation, Threshold levels, Sensitivity to vibratory sensation

1. INTRODUCTION

The induction of vibratory sensation is one of the characteristics of low-frequency noise [1]. Møller and Lydolf carried out a questionnaire survey and reported that low-frequency noise in living environments could cause persons to feel vibration in their bodies [2]. An experimental study by Inukai et al. showed that human psychological responses to low-frequency noise resulted mainly from three contributing factors: 'sound pressure', 'vibration', and 'loudness' [3]. These results indicate that not only hearing sensation but also vibratory sensation are important factors for assessing the psychological effects of low-frequency noise.

Clarification of the detailed characteristics of the vibratory sensation should be useful for more appropriate assessments of low-frequency noise. According to Nakamura and Tokita [4], persons perceive vibration most sensitively when being exposed to noises within the 40-80 Hz frequency range. However, the characteristics of vibratory sensation induced by low-frequency noise have not been widely investigated.

In this pilot study, as a first step toward clarifying the range of frequencies and sound pressure levels at which the effects of vibratory sensation should be considered, we measured the threshold levels necessary to induce a vibratory sensation in normal-hearing subjects exposed to low-frequency noise within a narrow frequency range (20-50 Hz). In addition, we administered a questionnaire to determine in which body parts the subject perceived the vibration during the threshold determination.

2. MATERIALS AND METHODS

Seven middle-aged subjects (35-44 yr, mean ± SD = 39.7 ± 3.1 yr) participated in this study. They were 3 males (35-43 yr, mean ± SD = 39.3 ± 3.3 yr) and 4 females (36-44 yr, mean ± SD = 40.0 ± 2.9 yr). Prior to the experiments, we confirmed that their hearing abilities were normal within the 125-8000 Hz range by means of conventional air-conduction audiometric tests. Throughout the experiments, the subjects wore no hearing protection so that they could sense low-frequency noise stimuli under the same conditions as in real environments.

As shown in Fig. 1, the experiment was carried out in a sound-insulated test chamber [3.16 m (W) × 2.85 m (L) × 2.80 m (H)] equipped with 12 loudspeakers (TL-1801, Pioneer, Japan). We used pure tones at five test frequencies (20, 25, 31.5, 40, and 50 Hz) as test tones. The sound sources of the test tones were sinusoidal signals generated by a low-distortion function oscillator (E-1011, NF Circuit Design Block, Japan). After amplification, each test tone was reproduced by the loudspeakers. Sitting on a stool in the center of the test chamber, each test subject was able to control the sound pressure level of the reproduced test tone by manually changing the volume of a mixer (MG10/2, Yamaha, Japan) located between the function oscillator and the power amplifiers. To measure the sound pressure level of the reproduced test tone, a low-frequency microphone (UC-26, Rion, Japan) was installed at a position 30 cm from the left ear of the subject. By inserting booster cushions beneath the subjects, we could adjust their height such that their ears had the same elevation as the microphone (1.2 m from the floor). The microphone was connected to a low-frequency sound level meter (NA-17, Rion, Japan), and the meter's output was recorded on DAT by a data recorder (PC208Ax, Sony Precision Technology, Japan). The DAT recording was sent to a personal computer through an audio data interface (AD216, Nittobo Acoustic

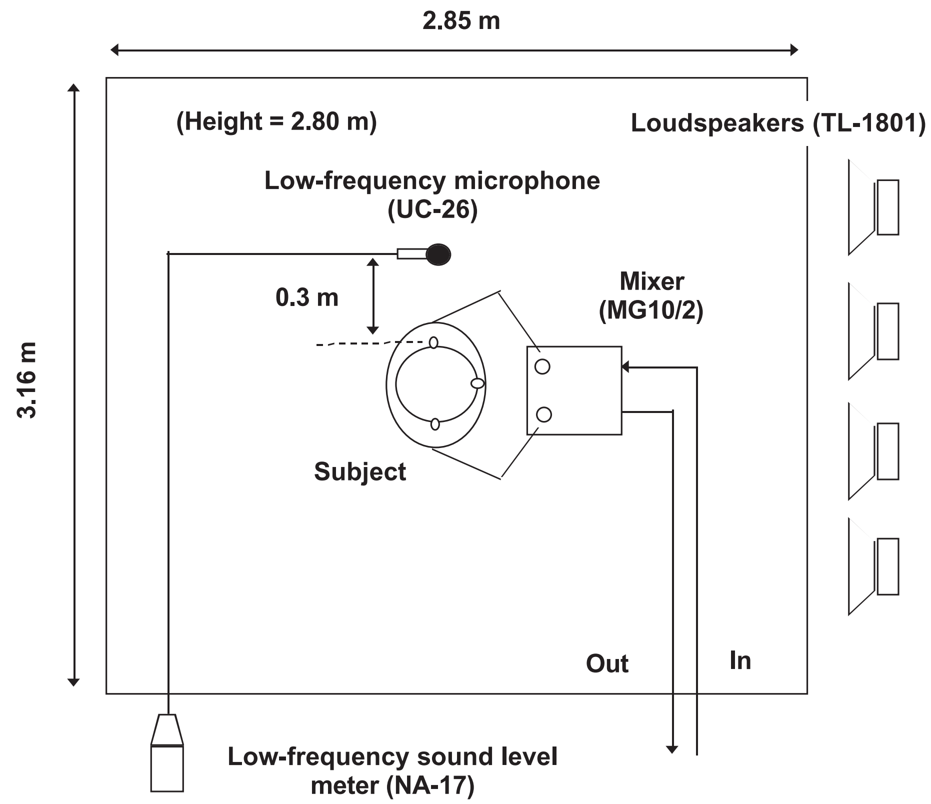

Figure 1. Experimental setup of this study.

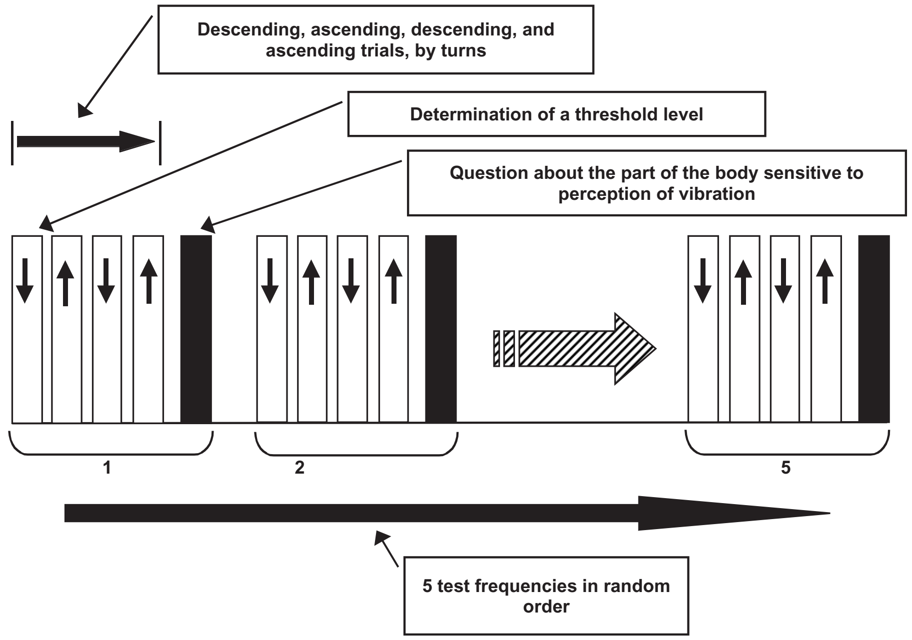

Figure 2. *Experimental procedures used in this study. It should be noted that a questionnaire was used only in Session 2.*

Engineering, Japan), and a one-third-octave band sound pressure level corresponding to the test tone was obtained by off-line analysis.

The one-third-octave band levels of the background noise in the test chamber were lower than the hearing threshold levels standardized in ISO 389-7 [5] below 100 Hz, and caused no difficulty in the execution of this study.

The experiment comprised two sessions (Session 1 and Session 2). In Session 1, the subject's hearing threshold levels were measured at the five test frequencies. In Session 2, which started about 10 min after the end of Session 1, the threshold levels at which vibratory sensation was first induced in the subject were measured at the same five test frequencies.

The experimental procedures are shown in Fig. 2. In Session 1, the subject's hearing threshold level was measured four times (descending, ascending, descending, and ascending trials, by turns) at each test frequency. In the first trial (a descending trial), we initially presented the subject with a test tone at a sound pressure level that he or she could hear clearly. Then, the subject sought his or her hearing threshold level by manually decreasing the sound pressure level of the test tone gradually until he or she could not hear it. The hearing threshold level thus found was recorded by the data recorder. In the second trial (an ascending trial), the test tone was initially presented at a sound pressure level the subject could not hear it at all. The subject then sought his or her hearing threshold level by manually increasing the sound pressure level of the test tone gradually until he or she could hear it. The hearing threshold obtained in this trial was likewise recorded. We used the same experimental procedures in the third (descending) and fourth (ascending) trials, respectively. We did not limit the time allowed to determine the hearing threshold level so that each subject could determine his or her hearing threshold level calmly. We treated the average value of the four threshold levels as the subject's hearing threshold level at each test frequency. The hearing threshold levels at the five test frequencies were measured in random order.

In Session 2, the threshold levels for inducing a vibratory sensation at the five test frequencies were measured using the same method. In this study, we defined the vibratory sensation as the subjective perception of vibration in the body, either the whole body or a specific part. In addition, by defining the vibratory sensation as being independent of a hearing sensation, we instructed the subject to differentiate the vibratory sensation from the hearing sensation. As in Session 1, the threshold level for inducing the subject's vibratory sensation was measured four times (descending, ascending, descending, and ascending trials, by turns) at each test frequency. Again, we did not limit the time allowed to determine the threshold level for inducing the vibratory sensation. The average value of the four threshold levels was treated as the threshold level for inducing a vibratory sensation in the subject at each test frequency. The threshold levels at the five test frequencies were measured in random order.

In Session 2, after the fourth determination of the threshold level to induce the vibratory sensation at each test frequency, each subject responded to a questionnaire about the part of the body in which he or she perceived the vibration during the threshold determination (Fig. 2). Ten choices were given: "head", "chest", "abdomen", "hips", "back", "arms", "hands", "legs", "feet", and "other". The subject was allowed to select multiple choices in response to this question.

For statistical analysis, we used a statistical software package (SPSS for Windows 17, SPSS Japan, Japan) and adopted a p-value less than 0.05 as the criterion for statistical significance.

The protocol of this study was approved in advance by the Research Ethics Committee of the National Institute of Industrial Health, Japan (presently, the National Institute of Occupational Safety and Health, Japan). Informed consent was obtained from each subject before the measurements.

3. RESULTS

No statistically significant difference was found at any test frequency between the threshold levels for inducing vibratory sensation measured in the four trials (two descending trials and two ascending trials) (by the Friedman test). Similarly, no statistically significant difference was found between the hearing threshold levels measured in the four trials (again by the Friedman test). These results indicated that the two different ways to change the sound pressure level of a test tone caused no clear systematic difference in either type of measurement. Therefore, it was considered valid that we treated the average threshold level measured in the four trials (two descending and two ascending trials) as the threshold level measured in this study.

Figure 3 shows the threshold levels for inducing vibratory sensation (means and SD) measured in this study. For comparison, the hearing threshold levels (means and SD) are also shown in this figure. To simplify the figure's appearance, error bars for both threshold levels are depicted only on one side (only upward for the former and only downward for the latter). The hearing threshold levels measured in this study were higher than the hearing threshold levels standardized in ISO 389-7 [5]. This was presumed to be due to the different methods of measuring the threshold level. The threshold levels for inducing vibratory sensation ranged from 68 to 87 dB(SPL), which were higher than the hearing threshold levels measured at all test frequencies. The difference between these two types of thresholds ranged from 5 to 17 dB(SPL) and diminished at lower frequencies (Fig. 4). This difference was statistically significant at all test frequencies ($p<0.05$, by the Wilcoxon signed-rank test). In only one of the 35 cases (7 subjects ? 5 test frequencies) was the threshold level to induce vibratory

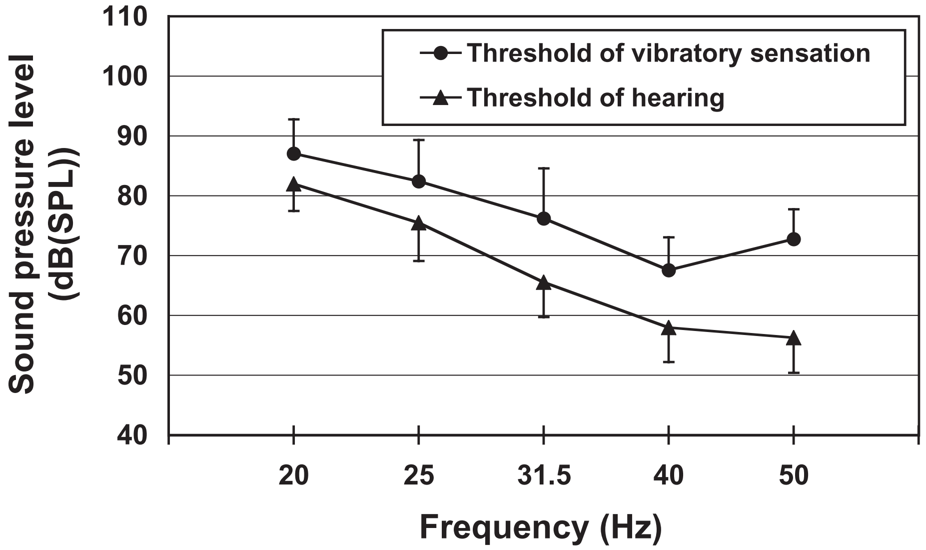

Figure 3. The threshold levels for inducing vibratory sensation (means and SD) and the hearing threshold levels (means and SD) measured in this study. For simplification, error bars for both thresholds are depicted only on one side.

sensation lower than the hearing threshold level, indicating that the subjects could differentiate the vibratory sensation from the hearing sensation without serious difficulty.

A distinct dip in the mean threshold level for inducing vibratory sensation was found at 40 Hz (Fig. 3). This dip was not found in the mean hearing threshold level. Figure 5 shows the threshold levels for inducing the vibratory sensation in individual subjects. A clear 40-Hz dip was found in 6 of the 7 individuals' data, suggesting that the appearance of the 40-Hz dip in Fig. 3 was an actual rather than spurious effect.

Although the inter-individual difference in the threshold levels for inducing vibratory sensation was large (Fig. 5), all of the individual data showed a common tendency; namely, that vibration was perceived more sensitively around 40 Hz (within the 31.5-50 Hz range). This implied that all the subjects experienced vibratory

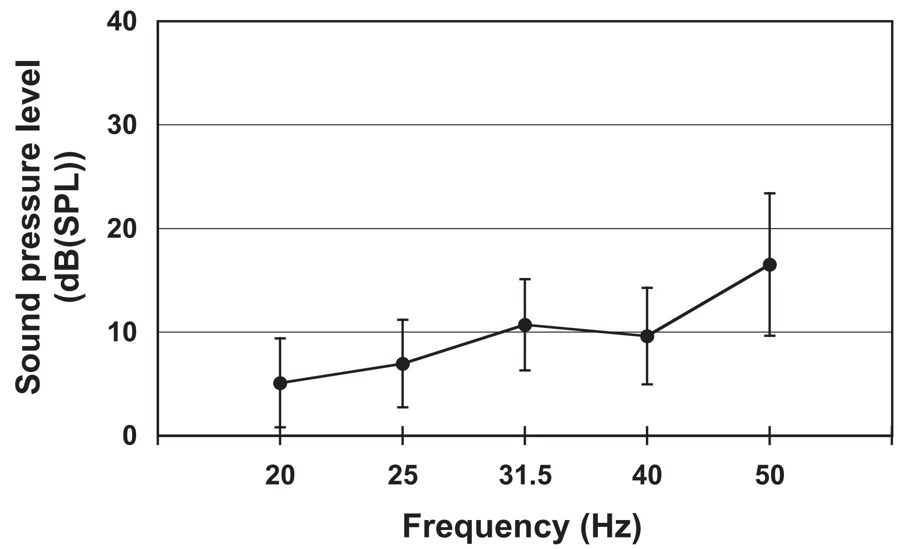

Figure 4. Difference between threshold levels for inducing vibratory sensation and hearing threshold levels (means ± SD).

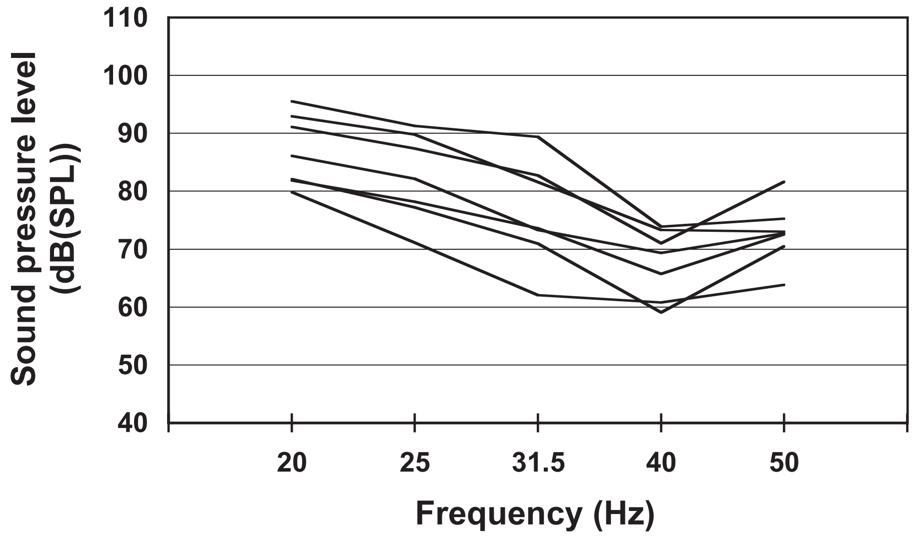

Figure 5. The threshold levels for inducing vibratory sensation in individual subjects.

sensations induced by low-frequency noise on the basis of some common kinds of perceptual mechanisms. Table I lists the part of the body in which the subject perceived vibration when determining the threshold level for inducing vibratory sensation. At all the test frequencies, almost all of the subjects reported that they perceived vibration in their head. This suggested that the experience of a vibratory sensation induced by low-frequency noise depended on the body part and that the head was the most sensitive part of the body for experiencing the vibratory sensation induced by low-frequency noise. The second most sensitive part of the body was the chest.

4. DISCUSSION

In this study, the threshold levels for the vibratory sensation induced by low-frequency noises (20-50 Hz) were found to range from 68 dB(SPL) (at 40 Hz) to 87 dB(SPL) (at 20 Hz) (Fig. 3). In a previous study by Nakamura and Tokita [4], the subjects exposed to low-frequency noise perceived a greater degree of vibration at sound pressure levels higher than 70-80 dB(SPL) within the 40-80 Hz frequency range. The threshold levels for inducing vibratory sensation measured in our study are consistent with their finding. Machines prevalently used in living environments do not frequently generate low-frequency noises at sound

Table 1. The part of the body sensitive to perception of vibration when determining the threshold level for inducing vibratory sensation.

Body part	**Number of subjects answering 'Yes'**				
	20 Hz	**25 Hz**	**31.5 Hz**	**40 Hz**	**50 Hz**
Head	6	5	7	7	7
Chest	1	3	2	1	0
Abdomen	2	2	1	1	0
Hips	0	0	0	0	0
Back	0	0	0	0	0
Arms	0	0	0	0	0
Hands	0	0	0	0	0
Legs	0	0	0	0	0
Feet	0	0	0	0	0
Other	0	0	0	0	0

pressure levels higher than 70 dB(SPL) [1, 6, 7]. However, noises generated by large transportation machines such as aircraft, ships, and large trucks often contain low-frequency components at sufficiently high sound pressure levels to induce vibratory sensations [1, 8, 9]. Additionally, in working environments, many machines can be a source of high-level low-frequency noise that can induce vibratory sensation [1, 10, 11]. Thus, investigation of the effect of vibratory sensation should be useful for assessing low-frequency noise in both living and working environments.

The threshold levels for the vibratory sensation measured in this study were only about 5-17 dB(SPL) higher than the hearing threshold levels (Fig. 3). These level differences were smaller than suggested by previous works. Yamada et al., for example, exposed deaf and normal-hearing subjects to low-frequency noise stimuli and measured the threshold levels for sensing low-frequency noise [12]. They reported that, within the 20-50 Hz range, deaf subjects sensed low-frequency noise by detecting vibration chiefly in their chests and that the threshold levels for the sensation ranged approximately from 95 to 120 dB(SPL). It was also reported that the threshold levels for the sensation in normal-hearing subjects were approximately 10 dB(SPL) lower than those in the deaf subjects. In our present study, the threshold levels for inducing vibratory sensation were even lower than the sensation threshold levels in the normal-hearing subjects of Yamada and his collaborators. The different results of these two studies could be due to the different experimental conditions including the definition of the target sensation. Yamada et al. exposed the deaf subject's whole body to low-frequency noise stimuli, while they exposed the normal-hearing subject's whole body, except the head, to low-frequency noise stimuli, using a specially prepared chamber [12]. Namely, for both types of subjects, the sensation threshold levels were measured in conditions in which hearing sensations were minimized. In our present study, on the other hand, we exposed the normal-hearing subject's whole body, including the head, to low-frequency noise stimuli. As a result, almost all of our subjects perceived the vibration in their head (Table I). Our results suggest the possibility that the function of the hearing organs is related to the perception of vibration in normal-hearing persons exposed to low-frequency noise. Nakamura and Tokita also used normal-hearing subjects [4], which may be the reason why their results were not contradictory to ours.

Yamada et al. described their target sensation as "body sensation" [12], while we used the term "vibratory sensation". The definitions of these two target sensations might be different from each other. In addition, the instruction given to the subjects in the study by Yamada et al. must have been different from that given to our subjects. These differences between the target sensations may explain the differing results.

Because our definition of the vibratory sensation was not a strict one, each subject might have determined his or her vibratory sensation on the basis of a subjective definition that varied from person to person. In spite of the ambiguity in the definition, however, almost all of the subjects in this study reported that they perceived vibration in the head (Table I). The similarity in their responses implied that the subjects experienced the vibratory sensation induced by low-frequency noise on the basis of some kinds of common perceptual mechanisms. Although the details remain to be investigated, the sensitiveness of the head supports the idea that the function of the hearing organs may contribute to the perceptual mechanisms for vibratory sensation in normal-hearing persons exposed to low-frequency noise.

Another interesting finding in this study is that a dip in the threshold level for inducing vibratory sensation appeared at 40 Hz (Fig. 3). A previous study discovered that the sound pressure levels of a tone reproduced in the test chamber was almost spatially uniform in the direction parallel to the wall in which the loudspeakers were installed, if they were measured at a constant height [13]. In the present study the low-frequency microphone and the subjects' ears were matched in elevation. In addition, the particular frequency responses of the test chamber did not affect the results because we used only pure tones as the test stimuli. Therefore, the 40-Hz dip in the threshold level for inducing vibratory sensation was not considered a spurious effect. As described in the Introduction, Nakamura and Tokita reported that their subjects perceived vibration most sensitively during exposure to noise within the 40-80 Hz frequency range [4]. The 40-Hz dip found in our study was broadly in agreement with their finding. However, the present study was carried out using low-frequency noise stimuli within a narrow frequency range (20-50 Hz). In order to confirm a 40-Hz dip in the threshold level for inducing the vibratory sensation, it is necessary to extend the frequency range of the test tones to frequencies higher than 50 Hz.

In addition, in the future, the contribution of the hearing function to the vibratory sensation induced by low-frequency noise should be investigated. Differentiating the vibratory sensation experienced in one part of the body from that experienced in a different part of the body (e.g., "vibration perceived in the head", "vibration perceived in the chest", and so on) may help to uncover in more detail the mechanisms behind the perception of vibration.

5. CONCLUSIONS

In this pilot study, we exposed normal-hearing subjects to low-frequency pure tones (20-50 Hz) and found that the threshold levels for inducing vibratory sensation ranged from 68 to 87 dB(SPL). In assessing low-frequency noises at such sound pressure levels or higher, the effect of vibratory sensation should be taken into account.

The threshold levels for the vibratory sensation measured in this study were lower than those suggested by a previous work. Taking into account the different experimental conditions used in the previous and present studies, the present results suggested the possibility that the function of the hearing organs is related to the perception of vibration in normal-hearing persons exposed to low-frequency noise. Almost all of our subjects perceived vibration in the head, thus supporting the idea that the function of the hearing organs may contribute to the perceptual mechanisms for the vibratory sensation. Another interesting finding was that a 40-Hz dip appeared in the threshold level for inducing vibratory sensation, which was broadly in agreement with the result obtained by another research group.

However, the results of this study were obtained under limited experimental conditions, including a narrow frequency range of test tones and a small number of subjects. To clarify the detailed characteristics of the vibratory sensation induced by low-frequency noise and to investigate the contribution of the hearing function to the vibratory sensation, further studies need to be conducted in the future.

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WIND FARMS NOISE NOT SPECIAL NOISE, FINDS STUDY

The noise caused by wind farms can make some people ill, according to experts. The study by a panel of independent experts found that the irritation caused by the noise around wind farms can effect certain individuals. Scientists dismissed the idea of a “wind turbine syndrome” where the vibrations in the air or the particular sound waves from wind turbines cause headaches, nausea and panic attacks. Wind Turbine Sound and Health Effects, commissioned by the American Wind Energy Association, found that some people may be “annoyed” by the sound of wind turbines. A major cause of concern is the fluctuating nature of the sound, which is particularly stressful for some people because it is difficult to get accustomed to intermittent noise. Dr Geoff Leventhall, past-President of UK’s Institute of Acoustics and one of the authors of the study, said noise from wind turbines can disturb people in the same way as any other noise pollution, such as an airport nearby. “The conclusions of our report were that the main effects of wind turbines noise is similar to the effect of any other noise and will disturb people if they are listening to a noise they do not want to hear. One of the main effects is sleep disturbance which can lead to other stress related effects.” Presenting the evidence at a Wind Turbine Noise meeting organised by the IOA in Cardiff, he emphasised that only a small number of people find the noise distressing, which can lead to sleep deprivation and psychological problems. “The number of people who suffer these extreme effects are small and if the turbines are designed properly the effects are minimised even further,” he added.

COMPANY PAYS £58,000 FOR HAVS

A welder has received £58,000 in compensation after prolonged use of vibrating tools left his hands permanently damaged. The man was diagnosed with Carpal Tunnel Syndrome and Hand Arm Vibration Syndrome (HAVS), after he found he was unable to use his hands properly. The 56-year-old was first diagnosed with HAVS symptoms in 2004 during a routine examination by the company nurse. His company, based in Willenhall, UK, makes bonnets, tailgates and doors for cars. Although he was showing signs that he had the condition, he was not removed from the job and continued in the same role for another 18 months. He was later made redundant as part of cutbacks in his new department.

ENVIRONMENTAL IMPACT STATEMENT TRUMPS HOME OWNERS DISTRESS

A couple has lost a High Court action claiming they have been exposed to serious noise nuisance from the Luas light rail which runs close to their home. Ms Justice Mary Laffoy dismissed an application requiring the Luas operators to erect a barrier against the noise allegedly endured by Paula and Vincent Smyth, of Cambridge Terrace, Leeson Park, Dublin. The judge found they "had not established nuisance". They brought the proceedings against the Railway Procurement Agency (RPA) and Veolia Transport Ireland Ltd. They claimed the enjoyment of their home was "severely undermined and compromised" due to noise since the line began operating in July 2004. A tram passed their home 330 times between 5.30am and 12.30am every weekday and 254 times daily at the weekend. They claimed they were unable to enjoy their garden or hold a conversation when a tram passed and were unable to sleep properly. Their bedroom faced on to an embankment and they regularly had to sleep with the windows shut and with earplugs. They sought injunctions restraining the defendants from operating the Luas in a manner that causes a noise nuisance and requiring them to erect an appropriate barrier to reduce the noise. They also sought damages. The defendants denied the claims and contended the Luas was being operated in accordance with the terms of the Transport (Dublin Light Rail) acts of 1996 and 2001. They also pleaded the operation of the Luas under those acts could not, as a matter of law, give rise to the nuisance alleged. During the 16-day hearing, the High Court was told the Smyths believed, at the planning stages of the Luas in the late 1990s, that special noise reduction screens would be erected at certain sensitive locations where the light rail would pass. Based on an undertaking by the RPA, they had a legitimate expectation measures would be put in place to reduce noise levels to within acceptable levels, it was claimed. Ms Justice Laffoy described the case as "difficult" and said, despite the fact the RPA had failed to comply with a requirement to set day and night-time noise levels, there were no circumstances in which the Smyths could be entitled to the relief they sought. She said the issue of noise had been dealt with at a public inquiry and had not been challenged. By operating within noise levels predicted in an environmental impact state ment, the rail is being operated without infringing the comfortable and healthy enjoyment of the Smyths' home, she said.