Vibratory sensation induced by low-frequency noise: The threshold for "vibration perceived in the head" in normal-hearing subjects

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Our previous study, in which we measured the threshold levels for vibratory sensation induced by low-frequency noise under the condition that the subjects were allowed to perceive vibration in any part of the body, showed that the head was very sensitive to the vibratory sensation. In the present study, in which the head was designated as the body part that would perceive the vibration, we measured the threshold levels for experiencing "vibration perceived in the head" within the 16- to 80-Hz frequency range. The threshold levels for "vibration perceived in the head" were found to be very similar to the threshold levels measured in our previous study, which indicated the superior sensitivity of the head to vibratory sensation induced by low-frequency noise. A gap appeared around 40-50 Hz in the threshold level contour for "vibration perceived in the head". In addition, the threshold levels for "vibration perceived in the head" increased when a subject wore an active noise cancelling earmuff. These results suggested the possibility that experiencing "vibration perceived in the head" was related to the pressure change in the ear.

INTRODUCTION

The loudness of low-frequency noise is generally very low, because the hearing threshold levels and the equal-loudness levels of human beings increase rapidly as the frequency decreases [1]. However, low-frequency noise can cause a person to perceive vibration [2]. In a questionnaire survey conducted by Møller and Lydolf, for example, many persons reported that they felt vibration in their bodies when they were exposed to low-frequency noise in living environments [3]. Inukai et al. carried out an experimental study using factor analysis and showed that 'vibration', in addition to 'sound pressure' and 'loudness', was one of the main factors contributing to the human psychological responses to low-frequency noise [4]. In addition, an experimental study carried out by Yamada et al. showed that deaf subjects could become aware of low-frequency noise by sensing vibration in their bodies [5]. Thus, the induction of vibratory sensation is a particular characteristic of low-frequency noise, and clarifying the characteristics of the vibratory sensation should be useful for assessing the effects of low-frequency noise appropriately.

Nakamura and Tokita exposed subjects to 14 kinds of low-frequency tonal stimuli and found that the subjects perceived vibration most sensitively when they were exposed to stimuli within the 40- to 80-Hz range [6]. However, the detailed characteristics of the vibratory sensation induced by low-frequency noise have not been widely investigated.

In our previous study [7], after defining the vibratory sensation as the subjective perception of vibration occurring either in the whole body or in a specific part of the body, we measured the threshold levels for inducing the vibratory sensation in subjects exposed to low-frequency tones at five test frequencies (20, 25, 31.5, 40, and 50 Hz). Additionally, we asked each subject about the part of the body in which he or she felt the vibration when determining the threshold level. The threshold levels for inducing the vibratory sensation were found to be 5-17 dB(Z) higher than the hearing threshold levels. Almost all of the subjects reported that they felt vibration in the head, suggesting that the head was the part of the body most sensitive to the vibratory sensation induced by low-frequency noise. Moreover, the threshold level at 40 Hz was found to be lower than those at 31.5 and 50 Hz. This dip at 40 Hz in the threshold level contour was an interesting finding. However, it remained unknown how the threshold level for inducing the vibratory sensation changed at frequencies higher than 50 Hz.

In the present study, as a first step in investigating the sensitivity of the head to the perception of vibration in persons exposed to low-frequency noise, we measured the threshold levels for experiencing "vibration perceived in the head". To verify whether a 40-Hz dip appeared in the threshold level contour when experiencing "vibration perceived in the head" and to investigate how the threshold level changed at frequencies higher than 50 Hz, we used pure tones over a wider frequency range (16-80 Hz) as test stimuli. For comparison, we also measured the hearing threshold levels and the threshold levels for experiencing "vibration perceived in the head" for subjects wearing an active noise cancelling (ANC) earmuff.

DEFINITION OF KEY TERMS

In the present study we defined the "head" as the part of the body above the neck. Based on this definition, we defined the "vibration perceived in the head" as the subjective perception of vibration in either the whole of the "head" or any part of the "head" that was independent of other sensations, such as the hearing sensation and the perception of vibration in any other part of the body. We told subjects that they were allowed to experience the "vibration perceived in the head" simultaneously with any other sensations when determining the threshold level for the "vibration perceived in the head". In addition, we instructed the subjects that they were required to differentiate the "vibration perceived in the head" from other sensations.

MATERIALS AND METHODS

The experiments in the present study comprised three measurement sessions. Fourteen normal-hearing subjects (20-47 yr, mean ± SD = 33.4 ± 9.9 yr) participated in Sessions 1 and 2. They included seven males (20-41 yr, mean ± SD = 25.0 ± 6.9 yr) and seven females (37-47 yr, mean ± SD = 41.7 ± 3.1 yr). In Session 3, which was an additional measurement session, we used six subjects (21-45 yr, mean ± SD = 34.7 ± 9.6 yr) who were randomly selected from the 14 subjects who participated in Sessions 1 and 2. Three of them were males (21-41 yr, mean ± SD = 28.0 ± 9.2 yr) and three were females (37-45 yr, mean ± SD = 41.3 ± 3.3 yr).

Figure 1 shows the experimental setup used in the present study. The experiments were carried out in a sound-insulated test chamber [3.16 m (W) × 2.85 m (L) × 2.80 m (H)]. We used pure tones at eight test frequencies (16, 20, 25, 31.5, 40, 50, 63, and 80 Hz) as test tones. The sources of the test tones were sinusoidal signals generated by a low-distortion function oscillator (E-1011, NF Circuit Design Block, Japan). After being amplified by power amplifiers (PC4002M, Yamaha, Japan), each test tone was reproduced by 12 loudspeakers (TL-1801, Pioneer, Japan) installed in a wall in front of the subject. The subject's location was changed from the center of the test chamber in our previous study [7] to a position 1 m from the center of the test chamber. This change was made to improve the spatial uniformity of the sound pressure

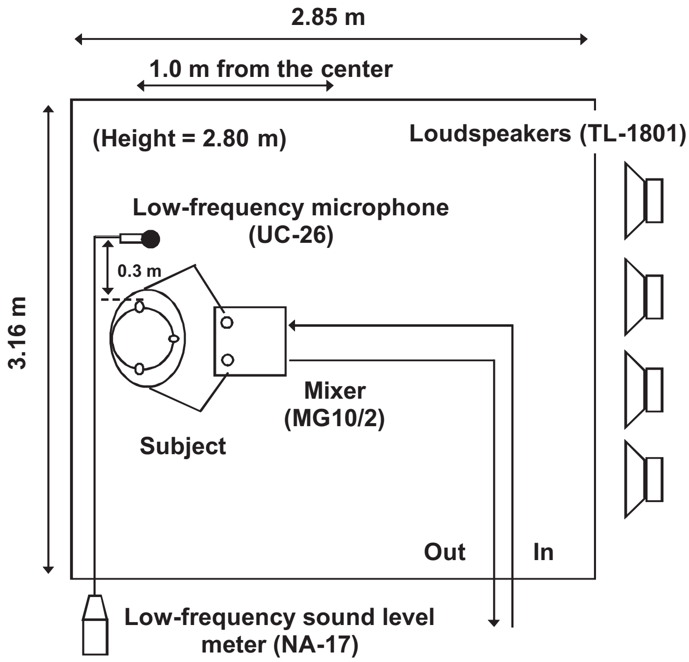

Figure 1. Experimental setup used in the present study.

levels of test tones in the vertical direction at the subject's location.

Sitting on a stool, the subject was able to control the sound pressure level of the test tone by manually changing the volume of a mixer (MG10/2, Yamaha, Japan). The sound pressure level of the test tone reproduced in the test chamber was measured by a low-frequency sound level meter (NA-17, Rion, Japan) with a microphone installed at a position 30 cm from, and as high as, the subject's left ear. The meter's output was recorded on DAT by a data recorder (PC208Ax, Sony Precision Technology, Japan). By off-line analysis, a one-third-octave band sound pressure level corresponding to the test tone was obtained.

The one-third-octave band levels of the background noise in the test chamber were lower than 30 dB(Z) within the 6.3- to 80-Hz frequency range. They were adequately lower than the hearing threshold levels standardized in ISO 389-7 [8] and did not affect this study.

In Session 1, we measured the subjects' hearing threshold levels at eight test frequencies. The 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 low-frequency sound level meter and the data recorder. In the second trial (an ascending trial), the test tone was initially presented at a sound pressure level at which 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 level 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 for determining the hearing threshold level so that each subject could determine his or her hearing threshold level calmly. The average value of the four determined threshold levels was treated as the subject's hearing threshold level at the test frequency. The subjects wore no hearing protection so that they could be exposed to low-frequency noise stimuli under the same conditions as in real environments, and the hearing threshold levels at the eight test frequencies were measured in random order.

In Session 2, using experimental procedures similar to those used in Session 1, we measured the subjects' threshold levels for experiencing "vibration perceived in the head" at the same eight test frequencies. The threshold level was measured four times (descending, ascending, descending, and ascending trials, by turns) at each test frequency, and the average value of the four determined threshold levels was treated as the subject's threshold level for experiencing "vibration perceived in the head" at the test frequency.

In Session 3, the subjects' threshold levels for experiencing "vibration perceived in the head" were measured while the subjects wore an ANC earmuff (PA-3000, Foster NCT Headset, Japan). According to the manufacturer's specification, expected noise suppression by the ANC earmuff ranges from approximately 15 dB at 16 Hz to approximately 25 dB at 80 Hz. Although the noise suppression performance changes monotonously at frequencies between 16 and 80 Hz, this non-uniformity was not a critical point in executing the study. The experimental procedures used in this measurement session were similar to those used in Session 2, except for the number of subjects and the usage of the ANC earmuff.

Statistical analysis was performed using a statistical software package (SPSS Statistics for Windows 19.0, SPSS Japan, Japan). We adopted a p-value less than 0.05 as the criterion for statistical significance.

The protocol of the present study was approved in advance by the Research Ethics Committee of the National Institute of Occupational Safety and Health, Japan, and informed consent was obtained from each subject before study participation.

RESULTS

Figure 2 shows the threshold levels for "vibration perceived in the head" (means ± SD, n = 14) measured in the present study. For comparison, the hearing threshold levels (means ± SD, n = 14) measured in the present study are also shown in the figure. The threshold levels for "vibration perceived in the

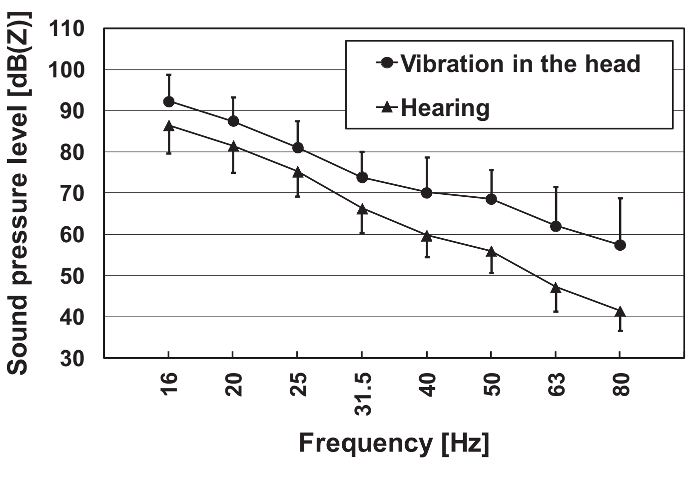

Figure 2. The threshold levels for "vibration perceived in the head" (means ± SD, circles) and the hearing threshold levels (means ± SD, triangles). For simplification, the error bars for the two thresholds are depicted only upward or downward.

head" ranged from 57 dB(Z) at 80 Hz to 92 dB(Z) at 16 Hz, and were higher than the hearing threshold levels at all eight test frequencies. The difference between the two threshold levels were within the 6- to 16-dB(Z) range and tended to increase with frequency. At all eight test frequencies, the difference was statistically significant ($p<0.01$, by Wilcoxon signed-rank test). It was in only 11 out of 112 cases (14 subjects × 8 test frequencies) that the threshold level for "vibration perceived in the head" was lower than the hearing threshold level.

As shown in Fig. 2, the threshold level for "vibration perceived in the head" decreased monotonously as the frequency became higher, and a 40-Hz dip did not appear in the threshold level contour. However, the decreasing step from 40 Hz to 50 Hz was narrower than the decreasing steps over other frequency intervals. As shown in Fig. 3, the individual threshold level contours of 7 subjects showed a dip at 40 Hz, and almost all of the individual threshold levels showed a common tendency for their changes with frequency to be subtler at frequencies around 40-50 Hz than at other frequencies, except in the case of a few individual data. These results can be elucidated by hypothesizing that the threshold level contour for "vibration perceived in the head" has a "gap around 40-50 Hz" rather than a dip at 40 Hz. In our previous study [7], we did not measure the threshold level for inducing the vibratory sensation at frequencies higher than 50 Hz. Provided that a "gap around 40-50 Hz" appeared to be a dip at 40 Hz due to the limited measurement frequencies, the above hypothesis is not inconsistent with the 40-Hz dip found in our previous study.

It should be noted that we use the terms "gap" and "dip" just because of the appearance of the threshold level contour for experiencing "vibration perceived in the head". The change with frequency in the threshold level contour for experiencing "vibration perceived in the head" looks characteristic at frequencies around 40-50 Hz. To emphasize this characteristic appearance, we use the two terms "gap" and "dip". However, there is no scientific reason for using these terms and for distinguishing the "gap" from the "dip".

Figure 4 shows a comparison between the threshold levels for "vibration perceived in the head" (means ± SD, n = 14) and the threshold levels for vibratory sensation measured in our previous study (means ± SD, n = 7) [7]. In the previous study, under the condition that any part of the body was permitted to perceive vibration induced

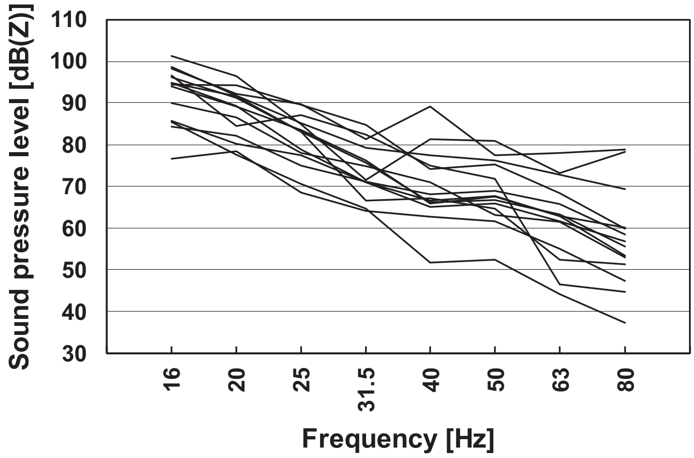

Figure 3. The threshold levels for "vibration perceived in the head" in individual subjects.

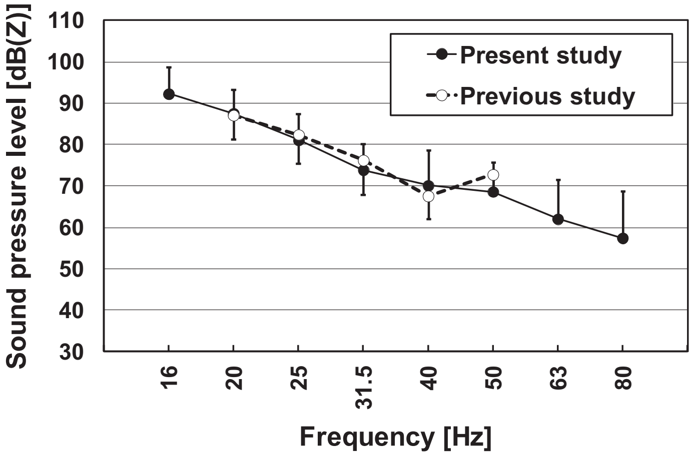

Figure 4. Comparison between the threshold levels for "vibration perceived in the head" (means ± SD (n = 14), black circles) measured in the present study and the threshold levels for vibratory sensation (means ± SD (n = 7), white circles) measured in our previous study. For simplification, the error bars for the two thresholds are depicted only upward or downward.

by low-frequency noise, we measured the threshold level for vibratory sensation within the 20- to 50-Hz range. As shown in Fig. 4, except for the appearance of a 40-Hz dip, the threshold levels for "vibration perceived in the head" in the present study were very similar to those for vibratory sensation recorded in the previous study. At all five common test frequencies (20, 25, 31.5, 40, and 50 Hz), no statistically significant difference was found between the two threshold levels (by Wilcoxon rank-sum test). This is consistent with our hypothesis that the threshold level contour for "vibration perceived in the head" has a "gap around 40-50 Hz".

Figure 5 shows our comparison of the threshold levels for "vibration perceived in the head" (means ± SD, n = 6) with the threshold levels for "vibration perceived in the head" (means ± SD, n = 6) measured with the

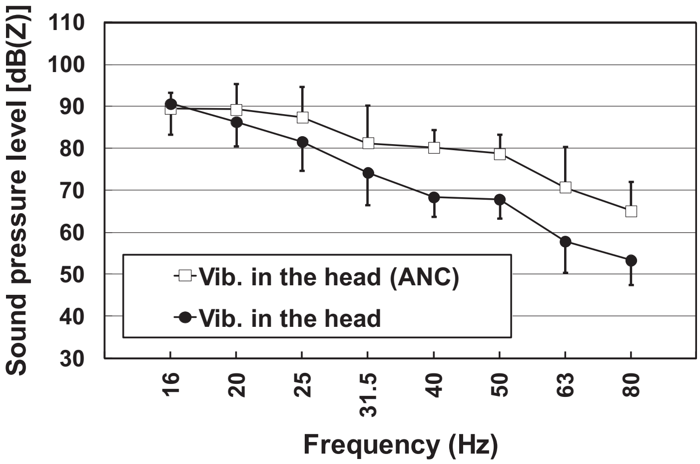

Figure 5. The threshold levels for "vibration perceived in the head" (means ± SD (n = 6), black circles) measured with the subjects not wearing an ANC earmuff and the threshold levels for "vibration perceived in the head" (means ± SD (n = 6), white squares) measured with the subjects wearing an ANC earmuff. For simplification, the error bars for the two thresholds are depicted only upward or downward.

subject wearing the ANC earmuff. For the two types of threshold level in this figure, we used only the data obtained from six subjects participating in both Sessions 2 and 3. The threshold levels for "vibration perceived in the head" measured with the subjects wearing the ANC earmuff (Session 3) ranged from approximately 65 dB(Z) at 80 Hz to approximately 90 dB(Z) at 16 Hz and, on the whole, were higher than the threshold levels for "vibration perceived in the head" measured without the ANC earmuff (Session 2). The differences between these two types of threshold level were approximately within the 0- to 15-dB(Z) range and tended to increase with frequency. At 31.5 Hz and higher frequencies, the differences were statistically significant ($p<0.05$, by the Wilcoxon signed-rank test), indicating that wearing the ANC earmuff clearly reduced the subject's sensitivity to "vibration perceived in the head". It was interesting that the "gap around 40-50 Hz" appeared even in the threshold level contours measured with the subjects wearing the ANC earmuff.

Figure 6 shows the correlation between the threshold levels for "vibration perceived in the head" and the hearing threshold levels in 112 cases (14 subjects × 8 test frequencies). The threshold levels for "vibration perceived in the head" are, on the whole, in close correlation with the hearing threshold levels, suggesting that the experience of "vibration perceived in the head" is related to some functions of the hearing organs. At frequencies higher than 40 Hz, the correlation became more divergent. The mechanisms by which people experience "vibration perceived in the head" at lower frequencies (40 Hz and lower) may be different from those at higher frequencies (50 Hz and higher), and the different perceptual mechanisms may be a cause of the "gap around 40-50 Hz" that appears in the threshold level contour for "vibration perceived in the head".

DISCUSSION

The threshold levels for experiencing "vibration perceived in the head" were in good agreement with those for inducing vibratory sensation measured in our previous study (Fig. 4). This result supports our previous result that a feeling of vibration in the head contributes strongly to the total subjective experience of vibratory sensation in persons exposed to low-frequency noise.

The perceptual mechanisms of "vibration perceived in the head" remain to be clarified. One hypothesis is

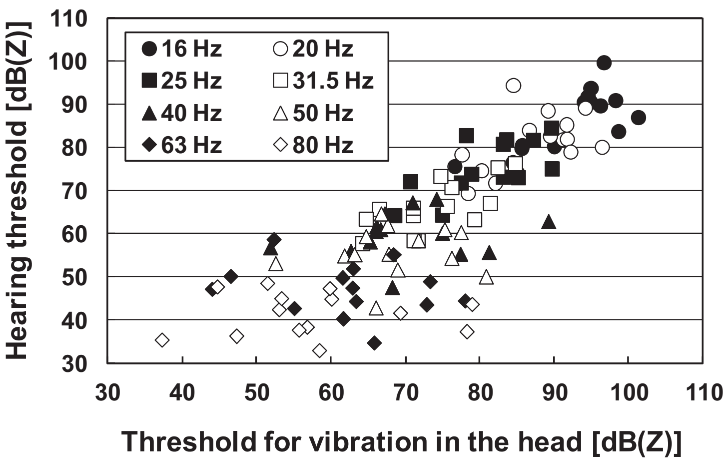

Figure 6. Correlation between the threshold levels for "vibration perceived in the head" and the hearing threshold levels.

that low-frequency noise generates vibration in the tympanic membrane or the basilar membrane and then, through the hearing organs, the vibration generates a secondarily perceivable pressure change in the fluid in the head. In fact, almost all of the subjects in the present study reported that, after the experiment, they felt vibration not in the surface area of the head but in the deep area of the ear or in the inner area of the head, including the brain. As shown in Fig. 5, wearing an ANC earmuff clearly raised the threshold levels for experiencing "vibration perceived in the head". In general, wearing an ANC earmuff not only prevents sound from entering into the external auditory canal but also causes the pressure change in the external auditory canal to decrease. This result does not contradict the hypothesis mentioned above.

There is one point to note. The "gap around 40-50 Hz" was found even in the threshold levels for "vibration perceived in the head" measured for the subjects wearing the ANC earmuff (Session 3, Fig. 5). Provided that the above speculation is exactly right, this characteristic change should not have been found in the threshold level measured in Session 3. One possible explanation for this incongruity is that adequate sealing of the external auditory canal was not achieved by wearing the ANC earmuff.

Pedersen and Marquardt measured the forward middle-ear transfer function (FMETF) and found a resonance feature around 40-65 Hz in the FMETF [9]. The resonance feature they found is very similar to the "gap around 40-50 Hz" found in the threshold levels for "vibration perceived in the head" measured in the present study. This similarity supports the idea that the pressure change in the external auditory canal or in a deeper area of the ear may contribute to the perception of vibration in the head in subjects exposed to low-frequency noise.

As shown in Fig. 6, the threshold levels for "vibration perceived in the head" were, on the whole, in close correlation with the hearing threshold levels. Provided that the subjects sensed the "vibration perceived in the head" by detecting vibration in the tympanic membrane or the basilar membrane whose levels were slightly higher than the levels required to induce the hearing sensation, the close correlation in Fig. 6 is consistent with the above speculation. The correlation shown in Fig. 6, however, becomes more divergent at frequencies higher than 40 Hz. At such frequencies, human beings sense air-borne vibrations clearly as sound. Namely, sound is a dominant sensation caused by low-frequency noise at such frequencies and at a sound pressure level around the threshold for experiencing "vibration perceived in the head". It is possible that the clearer sensing of sound at higher frequencies is a confounding factor for experiencing "vibration perceived in the head".

According to Landström et al. [10], the threshold levels for inducing vibrotactile perception in subjects exposed to low-frequency noise stimuli were 110 dB(Z) or higher within the 16- to 25-Hz frequency range. The locations in which their subjects experienced the vibrotactile sensation were chiefly the back and legs. There was no difference in these threshold levels between the normal-hearing and deaf subjects. On the other hand, Yamada et al. reported that, within the 16- to 80-Hz range, deaf subjects could be aware of low-frequency noise by sensing vibration chiefly in their chests and that the threshold levels for the sensation ranged from approximately 90 to 120 dB(Z) [5]. The threshold levels for the sensation in the normal-hearing subjects were reported to be approximately 10 dB(Z) lower than in the deaf subjects. In contrast, our present results suggested that the head was the most sensitive part of the body for experiencing vibratory sensation induced by low-frequency noise and that the threshold levels for "vibration perceived in the head" were much lower than the sensation threshold levels measured by Landström et al. and Yamada et al. The threshold levels for "vibration perceived in the head" measured in the present study might have been influenced by the hearing sensation and the functions of the hearing organs. In addition, different definitions of the target sensations should be considered to be a cause of the differences between others' results and ours.

CONCLUSIONS

The threshold levels for experiencing "vibration perceived in the head" in normal-hearing subjects were in good agreement with the threshold levels for vibratory sensation measured under the condition that the subjects were allowed to perceive vibration in any part of the body. This similarity indicated the superior sensitivity of the head to vibratory sensation induced by low-frequency noise.

A 40-Hz dip, which was found in our previous study, did not appear in the threshold level contour for experiencing "vibration perceived in the head" in the present study. It was more appropriate to presume that the threshold level contour for "vibration perceived in the head" had a "gap around 40-50 Hz" rather than a dip at 40 Hz.

Although the perceptual mechanisms of "vibration perceived in the head" remain to be clarified, the present results suggest that the pressure change in the external auditory canal or the deeper area of the ear may contribute to the perception of vibration in the head in subjects exposed to low-frequency noise.

ACKNOWLEDGMENTS

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WIND TURBINE NOISE IS ALL IN THE MIND

In the first study of its kind, the University of Nottingham asked more than 1,000 households living within 0.6 miles (1km) of small wind turbines up to 15m tall if they suffered health problems caused by the renewable technology. It found that around one in ten respondents reported problems like insomnia and headaches because of wind farm noise. However further study found this was not connected to the noise made by the wind turbines - but the personality of the people. "We measured the actual noise from the turbines and used environmental noise modelling software that helped us to predict how much sound is actually heard by those living in the vicinity. We found there was no relationship between the 'real' level of noise and reports of ill health," said Dr Claire Lawrence, who led the study. Instead she said people with so-called, "neuroticism", a personality type prone to worrying will suffer health problems connected to wind turbines. "There is certainly no evidence that if you are living near a noise or can hear a noise that it is causing you ill health," she said. "But there is evidence that if you have a certain personality trait you will report problems."

NOISE RULES WILL FORCE ME OUT OF BUSINESS, SAYS PUB LANDLORD

A Whitehaven town centre nightspot will go out of business if rules about noise and plastic glasses are forced upon it, the owner has warned. The owner of Cap'n Senny's in Whitehaven is appealing against a decision by Copeland council to add new conditions to its licence. The Council want to lower the sound limit and stop punters drinking from glass bottles but owner Peter Watson said the restrictions could lead to him closing. The pub's licence has been up for review several times in the past few years and in December the pub was ordered by the council to reduce noise levels and pour alcohol which comes in a glass bottle into a plastic glass. Mr Watson appealed the council's decision and a hearing, has been adjourned until June 20. Following complaints from neighbouring properties, including the Waverley Hotel, Mr Watson said that in the past two years he has taken a number of steps to reduce the sound at the pub. This has included moving speakers, turning the volume down and putting sound barriers on the roof. He believes the noise is now at an acceptable level. "I have spent a lot of money trying to sort it out and we have done a lot on our side," he said. "We believe the level to be acceptable. "We will be put out of business if we have to turn the sound it down - we won't be able to survive. We run a nightclub and if the music is so low people won't be able to hear."

SAINSBURY'S ACCUSED OF BEING NOISY 'NEIGHBOURS FROM HELL'

Christopher Wallace has launched a one-man protest outside his Sainsbury's Local store in Holloway (London) with a banner proclaiming them "neighbours from hell". Mr Wallace, says the store's three industrial are positioned beneath the bedroom window of his flat and have a low-level buzz which keeps him up at night and are a regular irritation during the day. Police were called during one of his protests but said that he was entitled to carry on provided he didn't encroach on the store's property. Islington Council has sent an environmental health officer to the store in Holloway Road to measure the noise but have yet to produce a report. Mr Wallace said: "This store opened three weeks ago and I haven't been able to get a decent night's sleep since. I've lived here for 13 years but I don't seem to have any rights to peace and quiet. It's like the noise of a distant motorway regularly buzzing in your ears for hours on end. I want them to move these fans to somewhere where they are not disturbing people. I shall continue my protest until I get justice."