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INTENSITY PERCEPTION FOR COMPLEX VERTICAL WHOLE-BODY VIBRATION

Anna Schwendicke, Shuyue Cheng, Xudong Yu, M. Ercan Altinsoy
Chair for Acoustic and Haptic Engineering
Technische Universität Dresden
01062 Dresden, Sachsen
Germany
anna.schwendicke@tu-dresden.de

ABSTRACT

Whole-body vibrations are an integral part of daily life experience. A thorough understanding of human vibration perception is necessary, e.g., for both the design of multi-modal virtual environments as well as the evaluation of comfort in the automotive industry. In this study, intensity perception for whole-body vibrations near threshold has been measured using amplitude modulated signals as well as narrow band noises. Stevens' exponents have been calculated showing a significant dependence on frequency between 31.5 Hz and 125 Hz with higher frequencies leading to lower Stevens' exponents. Amplitude modulation does not have an effect on intensity perception. The use of narrow band noise leads to bigger differences among Stevens' exponents compared to those of sinusoidal signals. It is concluded that perceptual data from experiments with sinusoidal signals can be used to model the intensity perception of modulated signals, but adjustments have to be made for noisy signals.

INTRODUCTION

Whole-body vibrations (WBV) are vibrations transmitted to a person's entire body via his/her contact with a vibration source, usually through sitting or standing on a vibration surface [1]. Many every day situations involve the combination of sound and vibration. Most often, both of them are generated by the same source, e.g., a moving vehicle, construction sites, or concerts. Research on multi-modal perception of auditory-tactile events has a long history. With the advent of virtual realities and increased sophistication of home entertainment systems it is becoming increasingly popular. For example, while playing back a recording of a musical concert, adding vibration to the chair can improve the overall listening experience [2]. The use of the same principle allows for the reduction of the bass level when playing back music in vehicles [3]. In order to best profit from multi-modal effects, the fundamental understanding of each single modality is the key, putting a stronger focus on WBV perception, as auditory perception has already been studied extensively.

Additionally, technical development reduced the overall levels of vibration and sound emitted by vehicles and machines, putting vibration closer to threshold into focus. This is also reflected in the shift of research focus of whole-body vibrations from health issues towards comfort and quality, especially in the automotive sector [4, 5]. However, quality and comfort are situation dependent, while it is preferable to have measures that are context insensitive. A few examples of non-context sensitive measures, known from the auditory domain, are loudness, sharpness, and harshness [6–8]. The equivalent to loudness perception in the auditory domain is intensity perception of whole-body vibration. Recent studies [9, 10] suggest the use of further perceptual descriptors defined by frequency content, vibration level and other additional signal parameters such as amplitude modulation or bandwidth. The suitability of frequency dependent descriptors depends on modulation frequency as well as bandwidth. Differences in bandwidth for signals with the same overall acceleration level can change the perception. Knowing the influence of those two parameters on intensity perception can help to distinguish the different parameters influencing WBV perception.

INTENSITY PERCEPTION

Stevens' power law defines the relationship between the perceived intensity of a stimulus Ψ and its physical magnitude ϕ:

$$\Psi = k\phi^n, \tag{1}$$

where n - the Stevens' exponent - is a characteristic exponent that depends on the specific sensory modality tested, and k is a proportionality constant that depends on the units of measurement used.

Taking into account the detection threshold ϕ_0 [11] the equation can be extended to

$$\Psi = k(\phi - \phi_0)^n. \tag{2}$$

Plotting the relationship between Ψ and ϕ on a log-log-plot allows for an easy determination of the Stevens' exponent via linear regression as n is now the slope of the line.

For acoustical signals n is dependent on frequency, while results for vibration signals are inconsistent and differ depending on the methodology used. Stevens [12] uses vibro-tactile matching between different frequencies at the finger. Both a method of adjustment as well as a tracking method lead to significantly declining exponents with increasing frequency, although absolute values for n vary depending on the method used. Hempstock and Saunders [13] used cross-modality matching for whole-body vibration and auditory noise. The results of their study show that the Stevens' exponent is greatly influenced by the dependent variable, but seems to be independent of frequency. A recent study using magnitude estimation for WBV with 10 participants shows varying results over frequency, although none of the differences are significant [14].

EXPERIMENTAL SETUP

The intensity perception for whole-body vibration was measured for two different signal classes, i.e., amplitude modulated signals and narrow band noise, using the same experimental setup. In order to keep the overall time for each volunteer at reasonable length, different test subjects were used. The individual detection threshold for WBV was determined for each test participant prior to assessing the intensity perception.

Apparatus

The basis for all experiments is a self-constructed vibration seat, based on an electro-dynamic shaker as shown in Fig. 1a. The participant sits upright, without a backrest, on a flat wooden board, mounted on top of the coil of the shaker. Strong springs between the chassis and the board support the weight of the subject and keep the coil approximately in middle position. Optional wooden plates below the subject's feet keep the thighs level with the seat. The hands are positioned in the lap. A keyboard is used to give feedback during the experiments.

Throughout the experiment participants wear closed headphones to attenuate ambient sounds. Additionally to visual feedback, indicating which stimulus is played at which point in time, pink noise is used as an auditory key simultaneously with each stimulus during both parts of the experiment. The noise also masks potentially emitted sound for higher frequencies of the shaker.

The internal sound card of the computer is used for playing and recording the signals. One channel of the stereo output signal is used for the vibration signal, the other one for audio reproduction. The vibration signal is amplified separately with an external amplifier. The transfer characteristic of the overall system, including the person on top, is not linear. This effect is known as body related transfer function (BRTF) with the individual person having a significant influence on the position of the peaks and dips of the BRTF [15].

To compensate for this effect all signals are pre-processed using the individual BRTF of each subject, recorded at the beginning of each session, and inverse filters in Matlab. Fig. 1b shows the result of vibration reproduction before and after compensation. The BRTF is measured using a 30 second band-limited white noise, which leads to consistent results verifying levels for individual sinusoidal signals afterwards. The spectral difference between a compensated and an uncompensated signal is measured at the base of the coil of the electro-dynamic shaker (1/12th octave smoothing). Compensation leads to a smooth frequency response across the whole frequency range from 20 to 500 Hz, differing less than 1.5 dB from the original signal. To illustrate the dynamic range of the vibration chair, additional lines are plotted for various levels of the compensated signal. They range from being barely perceivable (-10 dB relative to the calibration signal) to already causing significant discomfort (+ 20 dB). This shows that the overall system operates almost linear over the whole dynamic range.

Subjects

Two groups of 20 subjects each participated in the experiments. All subjects were students of the Technische Universitt Dresden, participated voluntarily, and indicated that they did not know of any spinal disorders.

Group 1 evaluated amplitude modulated (AM) signals. The 20 subjects were between 21 and 32 years old (mean = 24.7 years). Five of the subjects were women. The average body height was 1.75 m (STD = 10.6 cm) and and they had an average weight of 68.4 kg (STD = 10.7 kg)

Group 2 evaluated narrow band noise (NBN) signals. They were between 23 and 29 years old with an average age of 26.3 years. Again, out of the 20 subjects five were woman, 15 men. The average body height was 1.71 m (STD = 6.7 cm) and the average weight was 67.2 kg (STD = 13.53 kg).

Stimuli and Experimental Methods

The aim of this study was to measure intensity perception relatively close to the detection threshold. A frequency range of 31.5 Hz to 125 Hz was chosen, covering the middle to high frequency range of WBV perception in half-octave steps. Subjects used a magnitude estimation method to rate the different stimuli against a fixed reference. Both reference and the test stimulus were presented before the subject judged the test stimulus. Subjects were free to repeat the presentation of reference and test as often as they liked before judging.

The reference signal for all intensity perception experiments was set to a pure sine at 45 Hz and 10 dB sensation level (SL), i.e., 10 dB above detection threshold, and assigned the value of 100. A total of 60 different test stimuli were judged in each experiment, i.e. the combination of five different frequencies (31.5. 45, 63, 90, and 125 Hz) at three different levels (5, 10, and 20 dB SL) for four different signal variations.

The four different signal variations in the AM experiment were modulation with two, four, and eight Hertz as well as unmodulated pure sinusoidal signals. Reference and test stimulus had a duration of two seconds and were separated by a pause of one second. Test stimuli were presented in a randomized order and each stimulus was evaluated five times. The overall experiment lasted approximately an hour, subjects were allowed to take a break, when feeling fatigue.

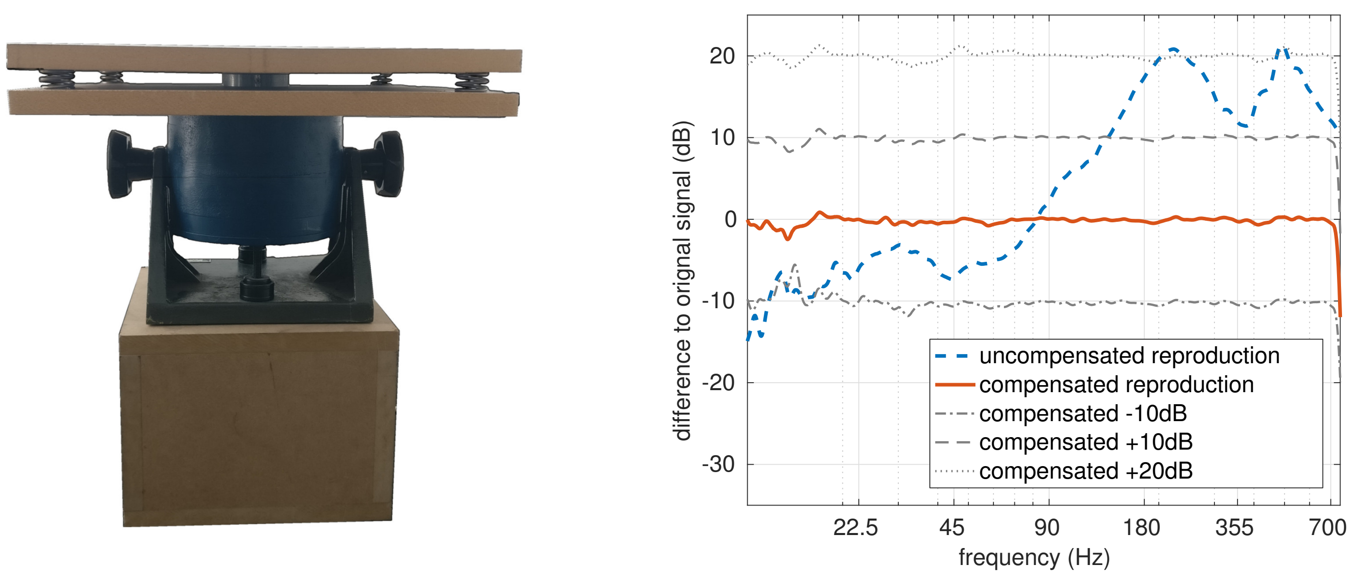
For NBN stimuli bandwidth is varied between 1/3th, 1/6th and 1/12th octave, additionally, sinusoidal signals at the center frequencies were tested for comparison. Test and reference stimulus had a duration of 1.5 seconds. They were separated by a 0.5-second pause. Again, test stimuli were presented in a randomized order. The number of repetitions was reduced to three, as subjects of group 1 showed a consistent rating across all repetitions. This reduces the length of the magnitude estimation experiment to approximately 30 minutes. Throughout all experiments acceleration levels were adjusted according to the overall root mean square (rms) value of the signal.

Prior to the magnitude estimation, the detection threshold of each subject was measured for the five main frequencies of the main experiment using an adaptive 3AFC 1up-2-down algorithm. Each stimulus had a length of one second, separated by a 500 ms pause. The task of the subject was to indicate during which of the three stimuli they felt the vibration. Tactile thresholds depend on stimulus length [16], but do not change for frequencies above 16 Hz for duration of one second and longer [4]. All signals were blended in and out using a 50 ms Hanning window. This session lasted approximately another 30 minutes.

RESULTS AND DISCUSSION

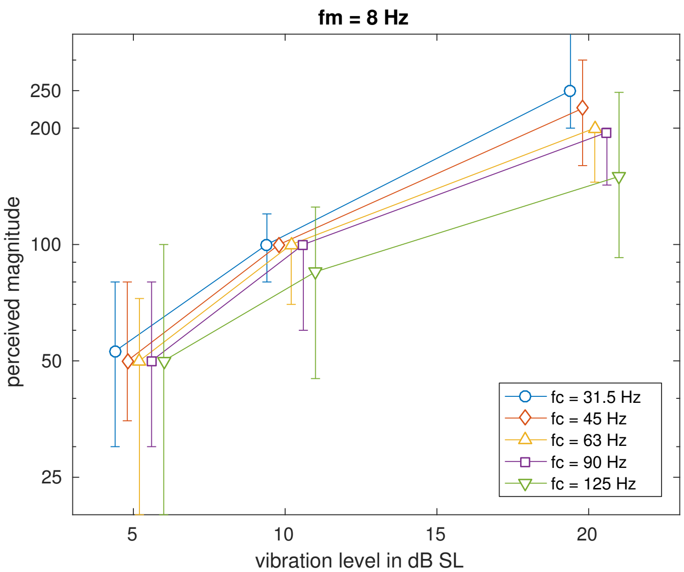
Intensity Perception of WBV

The median perceived intensities were calculated for each signal averaging the repetitions for each participant. Fig. 2 shows

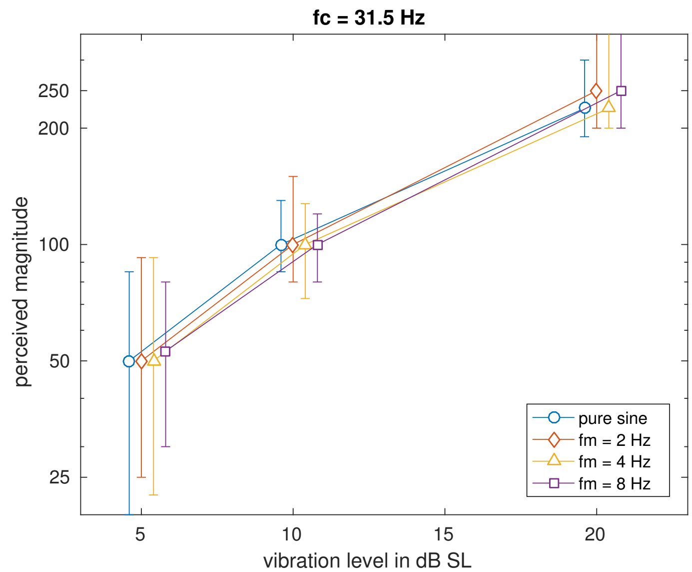


(a) Vibration seat (b) Compensation

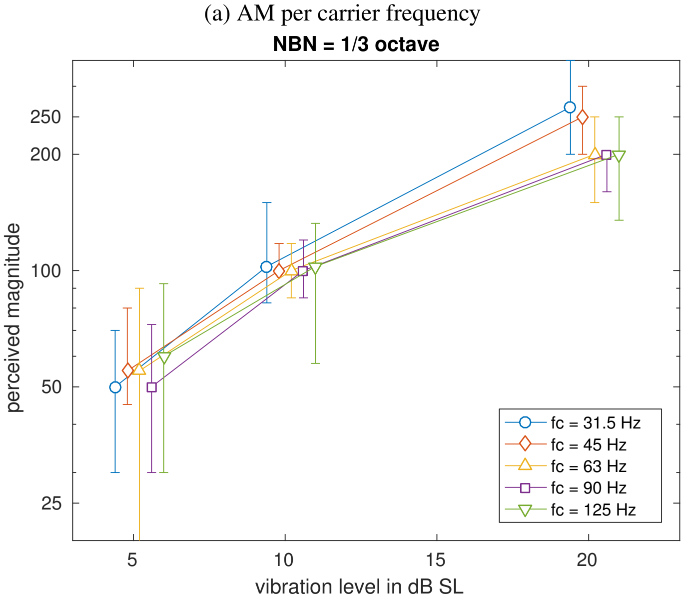
FIGURE 1: VIBRATION SEAT AND EXEMPLARY COMPENSATION FOR ONE PARTICIPANT



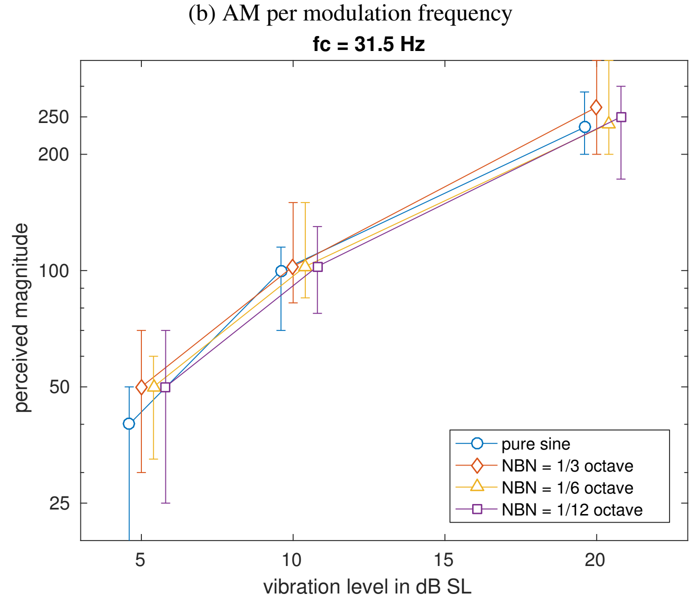
(a) AM per carrier frequency



(b) AM per modulation frequency



(c) NBN per center frequency

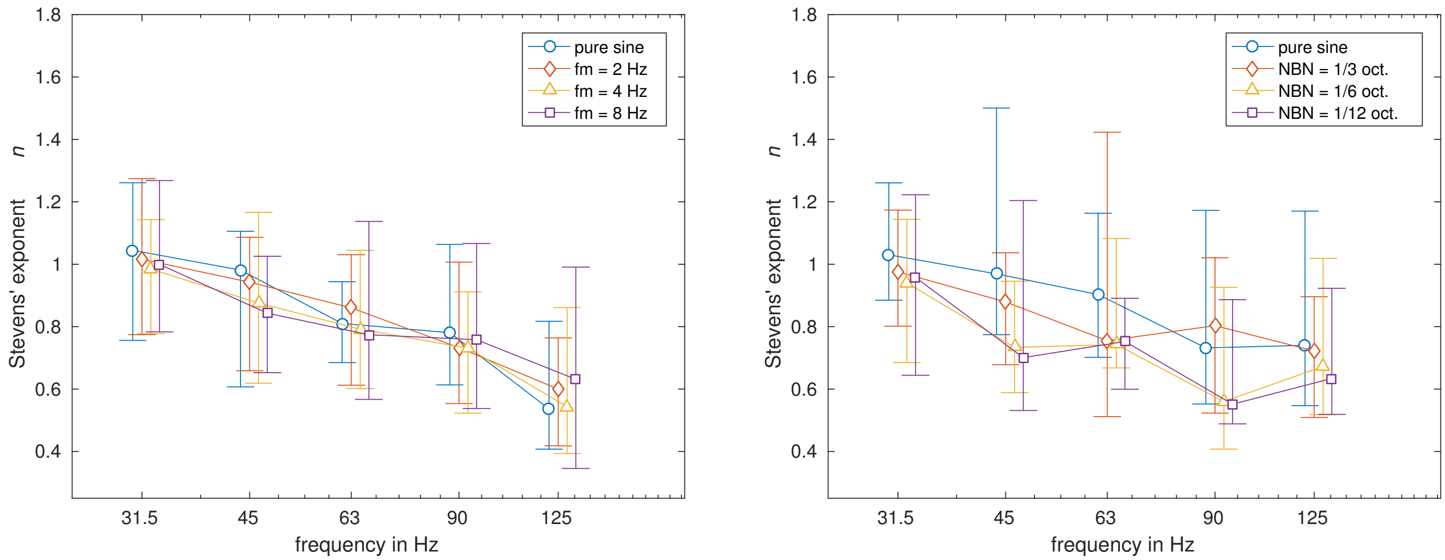


(d) NBN per bandwidth

FIGURE 2: EXAMPLES OF PERCEIVED MAGNITUDE

exemplary plots for all modulation frequencies or bandwidths of NBN for a single frequency, as well as the results for all modulation frequencies for one carrier frequency or all bandwidths for one center frequency. Median and interquartile ranges are plotted across all subjects. Data points are slightly shifted for better visibility. While the perceived magnitude does not seem to be dependent on the modulation frequency or the bandwidth used, the center or carrier frequency influences the intensity perception consistently with higher frequencies leading to a shallower slope.

The Stevens' exponent is then calculated for every subject and stimulus combination individually. Fig. 3 shows median and interquartile ranges across all subjects. Again, data points are slightly shifted for better visibility. Both graphs show a distinct decline of Stevens' exponent with frequency. Especially for AM signals, there is almost no difference between different modulation frequencies. Not all of the data does pass standard tests for normal distribution as it is slightly skewed. High Kurtosis results indicate leptokurtic distributions. In particular for smaller samples, a leptokurtic distribution increases the power of an analysis of variance [17]. A two-way ANOVA was conducted to compare



(a) AM signals (b) NBN signals

FIGURE 3: STEVENS' EXPONENT OVER FREQUENCY OF DIFFERENT SIGNALS FOR WBV

the main effects of carrier frequency and modulation frequency and the interaction effect between both on the Stevens' exponent. The effect of the carrier frequency is statistically significant at the 5% significance level, while there is no statistically significant effect of modulation frequency of the interaction between carrier and modulation frequency. A post-hoc analysis using Bonferroni critical values shows significant differences between 31.5 Hz and 63 Hz, 90 Hz, as well as 125 Hz and between 45 Hz and 125 Hz. Fig. 3b displays a wider range of exponents across bandwidth for each center frequency tested. With the exception of 90 Hz, median exponents for narrow band noise are smaller than those for pure sine. Mean values (not plotted) for NBN signals are always lower than those for sinosuidal signals. Again, a two-way ANOVA was conducted to compare the main effects of center frequency and NBN widths and the interaction effect between both on the Stevens' exponent. The effect of the center frequency as well as the effect of the bandwidth is statistically significant at the 5% significance level, while there is no statistically significant effect of the interaction between center frequency and bandwidths. A post-hoc analysis using Bonferroni critical values shows significant differences between 31.5 Hz and 90 Hz, as well as 125 Hz for the center frequency and significant differences between sinusoidal signals and 1/6th octave NBN noise as well as 1/12th octave noise, but no significant difference between any of the different NBN widths. Hempstock and Saunders [13] had similar effects for multi-modal intensity perception between an auditory noise signal and sinusoidal WBV signals. The growth parameter of the intensity function differed to a large extent based on which signal class (noise or sinusoidal) was the dependent variable. The effect was much stronger than in this study, and might in part be attributed to the study design which used multi-modal stimuli compared to the uni-modal used here.

One factor leading to stronger variations in Stevens' exponent might be the temporal structure of the actual test stimuli. The irregular fluctuation of the envelope might lead to a different perception than the rather smooth envelope of amplitude modulated signals.

The results for pure sinusoidal signals do not differ significantly between both subject groups (two-sided Wilcoxon rank sum test, $p > 0.05$) and show a trend towards lower exponents for higher frequencies, decreasing by approximately 0.2 per octave. A one-way ANOVA was conducted to compare the effect of the frequency on the Stevens' exponent. There is a statistically significant effect of the frequency at the 5% significance level. A post-hoc analysis using Bonferroni critical values shows significant differences between 31.5 Hz and 125 Hz.

Fig. 4 compares the accumulated results across all 40 subjects of both subject groups in this study for sinusoidal signals with results from a previous study [14] with only 10 subjects and using fixed absolute acceleration levels between 90 dB and 130 dB below 100 Hz and up to 140 dB for higher frequencies, calculating sensation level based on an averaged detection threshold. Average values for the Stevens' exponent are consistent across the frequency range tested in this study. Slight differences might be caused by the choice of a different anchor stimulus and the use of individual detection thresholds versus an averaged detection threshold. Data collected by Stevens [12] using a method of adjustment shows a very similar slope, although

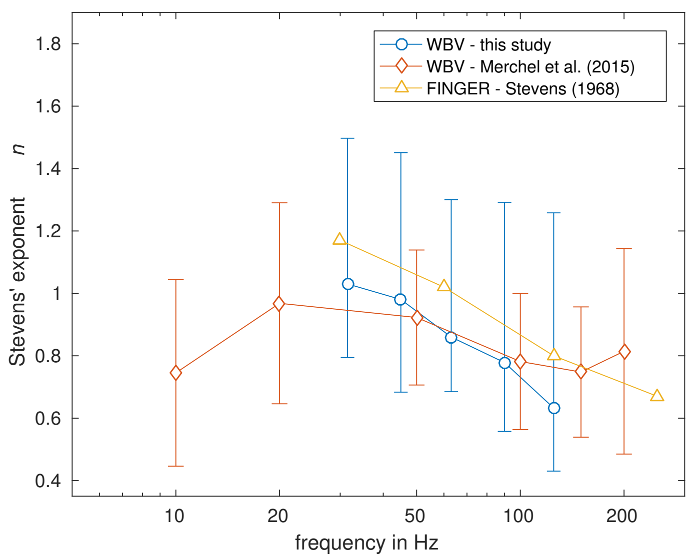


FIGURE 4: STEVENS' EXPONENT OVER FREQUENCY FOR SINUSOIDAL TACTILE STIMULI

absolute values differ. Differences are most likely to be attributed to the different experimental methods used.

Looking more closely at the data, the uneven distribution of Stevens' exponents is mainly caused by four individuals, three out of the group testing NBN signals, one of the group testing AM signals. Apart from being all male, they do not share any obvious body characteristics; their age is in line with the rest of the subjects. They have varying weights (50 kg to 90 kg), varying body heights (1.68 m to 1.82 m) and their BMIs range between 17.7 and 31.1. All of these individuals show a very consistent rating across all the repetitions of the magnitude estimation experiment leading to relatively high exponents. While excluding the data of these four subjects would reduce the median less than 0.1 for each frequency, it would reduce the 75% quantile significantly leading to almost symmetrical distribution. Nevertheless a certain percentage of the overall population may have a distinctly differing vibration intensity perception compared to the majority.

WBV Detection Threshold

Figure 5 shows the combined results of the detection threshold measurements for all 40 subjects. Red lines indicate median results, boxes show interquartile ranges and blue circles mean values. The Ordinate is given in dB relative to 1 μm/s^2 as well as in m/s^2. Within the frequency range of 31.5 Hz to 125 Hz, both average values are slightly below 90 dB with a local minimum at 90 Hz.

The reported average values are in line with previous results using a very similar setup [18,19], as well as results by Bellmann using a rigid wooden chair with a backrest mounted on top of a

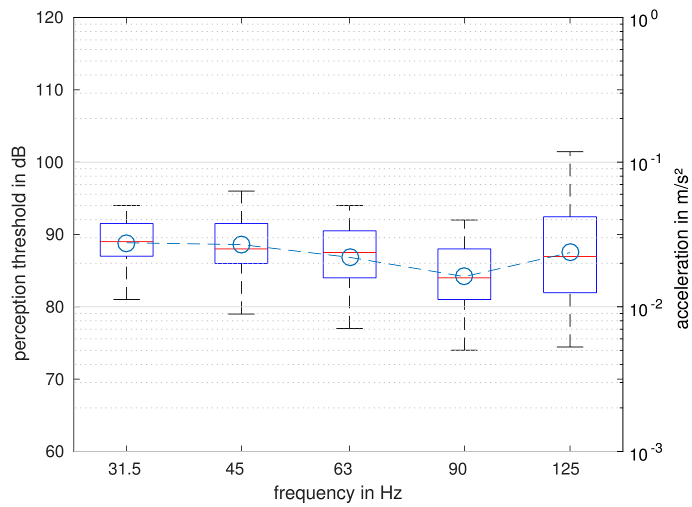


FIGURE 5: DETECTION THRESHOLD FOR VERTICAL WBV

vibration floor [4]. The same holds true for the inter-individual differences. In this study interquartile ranges for the detection threshold are between 4.5 dB and 10.5 dB. Thus presenting all signals for the magnitude estimation at each subject's individual sensation level ensures a consistent rating. The use of an individual threshold avoids the issue where subjects with a rather high detection threshold do not feel a stimulus at low sensation level at all, while others with a low detection threshold perceive it much stronger.

SUMMARY

This study investigated the intensity perception for different parameters of complex vibration signals. The following results were obtained:

- Amplitude modulation does not influence intensity perception.
- NBN slightly decreases Stevens' exponents compared to sinusoidal signals.
- Stevens' exponent is significantly dependent on frequency, decreasing approximately 0.2 per octave between 31.5 Hz and 125 Hz.
- For low vibration intensities Stevens' exponents are between 1.0 and 0.6.

For amplitude modulated signals, only the main frequency and the rms of the vibration acceleration contribute to a change in intensity perception. The intensity perception of complex signals can be predicted by measurements with sinusoidal signals having the same main frequency content, but noise has to be considered as an influencing factor.

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