Cross-Modal Frequency Matching: Sound and Whole-Body Vibration

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Abstract. Interest in human responses to whole-body vibration has grown, particularly due to the increasing usage of vehicles, e.g. cars, trucks, and helicopters etc. Another reason for growing interest in recent years is the importance of the vibrations generated by the performance of music for multimedia reproduction systems. There is a strong relationship between the frequency of the auditory stimulus and the frequency of the tactile stimulus, which simply results from the physical processes that generate the stimuli. The recordings in different vehicles or in different concert situations show that the whole-body vibration signal is like a low-pass filtered audio signal. The spectral contents, particularly low frequencies, are matched with each other. This correlation plays an important role in our integration mechanism of auditory and tactile information and in the perception of an immersive multimodal event.

In this study, psychophysical experiments were conducted to investigate, if subjects are able to match the frequencies of two different sensory modalities with each other. In this experiment, sinusoidal sound and vibration signals were used. The auditory stimuli were presented to the subjects via headphones and the tactile stimuli were presented through a vibration seat. The task of the subject was to match the frequency of the whole-body vibration to the frequency of the auditory stimuli. The results show that the subjects are able to match the frequency of both modalities with some tolerances.

Keywords: Whole-body vibration, frequency, cross-modal-matching, audiotactile perception.

1 Introduction

Human response to vibration (or to tactile feedback) and sound is strongly dependent on the frequency of the stimulus. Measurements in vehicles and in concert situations confirm that the spectra of sound and whole-body vibration have strong correlations at low frequencies [1,2]. It has been shown that synchronous presentation of vertical whole body vibrations during concert DVD reproduction can improve the perceived quality of the concert experience [3]. From the view of a sound engineer, the following question arises: how sensitive are humans to the content of the vibration stimuli? This question is also interesting for a vehicle acoustician who would like to optimize the vibration and sound in vehicles and provide a comfortable and enjoyable environment

R. Nordahl et al. (Eds.): HAID 2010, LNCS 6306, pp. 37–45, 2010.

to driver and passengers. Noise and vibration play an important role in what is called the overall harmony of the vehicle.

Sounds that are audible to the human ear fall in the frequency range of about 20-20,000 Hz, with the highest sensitivity being between 500 and 4,000 Hz. Our perception of music is influenced by how the auditory system encodes and retains acoustic information [4]. Auditory perception of frequency is logarithmic in nature. It is well known in acoustics that, given any note as a starting point, subjects can single out certain others, which bear a definite relationship to the first, and are known as its octave, etc. In order to determine the sensory capacity of the auditory system, measurements of the human ability to discriminate the changes in frequency of a pure tone were conducted. Just-noticeable frequency differences for the auditory system were reported e.g. by [5]. Zwicker and Fastl found that, at frequencies below 500 Hz, we are able to differentiate between two tone bursts with a frequency difference of only about 1 Hz. This value increases in proportion to frequency and is approximately 0.002*f above 500 Hz.

The range of frequencies most often associated with effects of whole-body vibration in the context of health, activities and comfort is approximately 0.5 to 100 Hz [6]. However the vertical whole-body vibrations in the frequency range of about 1-500 Hz can be perceived by the human body. The tactile sense is rather poor at discriminating frequency in comparison to the ear (auditory system). Just-noticeable frequency differences for whole-body vibrations were measured by Bellmann [7]. Humans are able to differentiate between two vibrations of 5 and 5.4 Hz ($\Delta f = 0.4$). Above 5 Hz Δf increases in proportion to frequency and is about $0.34 * f - 1.25$ Hz. This equation is applicable for reference frequencies between 5 and 40 Hz.

Two recent studies have discussed cross-modality frequency matching between audio and tactile stimulation of the hand [8,9]. They found that the subjects tend to prefer pairs having the same frequency for the auditory and tactile stimuli. In most cases, subjects judge also the second harmonic of the vibration frequency to be suitable for the auditory frequency. Are people able to match the frequency of whole-body vibration to the frequency of auditory stimuli, although they have poor tactile frequency discrimination? The purpose of this study is to explore how accurate is the cross-modal frequency matching capability of human for sound and whole-body vibration. In order to approach this aim in a systematic way, psychophysical experiments were conducted.

2 Experiment

2.1 Subjects

Eighteen subjects, eight men and ten women, aged between 20 and 49 years, participated in the experiment. The subjects were undergraduate students and university staff. They were paid on a hourly basis. All subjects had normal hearing, with no known back disorders.

2.2 Experimental Set-up

Whole-body vibrations have been reproduced using a self build electro-dynamical vibration seat (Fig. 1). The system is capable of producing vertical vibrations in a frequency range from 5 Hz to 1000 Hz. The transfer characteristic of the shaker loaded with a seated person has been measured using a semi-rigid pad with a triaxial accelerometer (B&K 4322). This frequency response depending on the individual test person is called the Body Related Transfer Function (BRTF) [10]. All stimuli have been compensated for the transfer characteristic of the seat in vertical direction by using inverse filters in MATLAB.

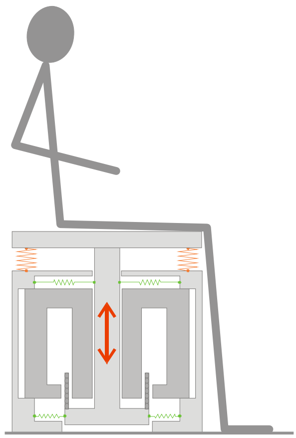

Fig. 1. Electro-dynamical vibration seat. The participant was sitting on a flat hard wooden seat with both feet standing on the ground.

The auditory stimulus was presented from a PC. The noise was amplified and delivered diotically through Sennheiser HDA 200 closed-face dynamic headphones which has a very high sound isolation level and therefore damped the sound radiated by background noise of the shaker. The experiments were conducted in a sound-attenuated room.

2.3 Stimuli and Procedure

In this experiment, sinusoidal sound and vibration signals were used. Auditory stimuli were pure tones at nine different frequencies (50, 63, 67.5, 80, 100, 112.5, 125, 160, 200 Hz). To avoid an influence of stimuli intensity, the loudness of the stimulus for different frequencies was equalized according to ISO 226:1987. The loudness level was 60 phon.

The task of the subjects was to match the vibration frequency to the frequency of the auditory tone. A Matlab graphical user interface was used for the experiment. Subjects could increase or decrease the frequency of the tactile stimulus pressing two buttons. The step size of the frequency increment and decrement was one-third- octave frequency intervals (0,26*f) which is comparable to the JNDF for whole-body vibrations. The acceleration level of the vibration stimuli was equalized for different frequencies to a reference vibration level (100 dB for 50 Hz). If the subject felt that she/he found the best matched vibration frequency, she/he should press a decision button. The decision was recorded after each adjustment and a next stimulus was presented in different random order for each subject.

Tactile and auditory stimuli were presented simultaneously. Each comparison was repeated eight times for each test person. Two different initial frequencies were chosen to avoid the secondary effects of initial value (low or high). For four repetitions, the initial frequency was 8 Hz. For other four repetitions, the initial frequency was 300 Hz. Before the start of the experiment, three anchor stimuli were presented to the subjects so that they could become familiar with the system and the experiment (The anchor stimuli don't belong to the stimuli dataset of the experiment. Frequencies: 30 Hz, 90 Hz, 200 Hz). Each experimental session lasted approximately half an hour including the training session.

3 Results and Discussions

In this study subjects can control the frequency of the vibration, but not continuously, rather in steps (quasi-continuously). Therefore the results of the experiment are plotted in histograms for each auditory frequency separately. The percentages of cross-modality frequency matching responses are shown in Fig. 2 to 9 as a function of the whole-body vibration frequency. Since the histograms have frequently two peaks, a check of the data regarding the Gaussian distribution makes little sense.

The maximum of the responses histogram for a 50 Hz auditory signal is found at vibration frequency of 50 Hz with a percentage of 35 (Fig. 2). Although 35% is very small in comparison to expected higher matching rates (75% or higher), it is possible to say that the participants have a tendency to match the same frequency in both modalities. Interestingly the results show that 25 Hz (an octave lower than the test frequency of 50 Hz) was found as best suitable vibration frequency after 50 Hz.

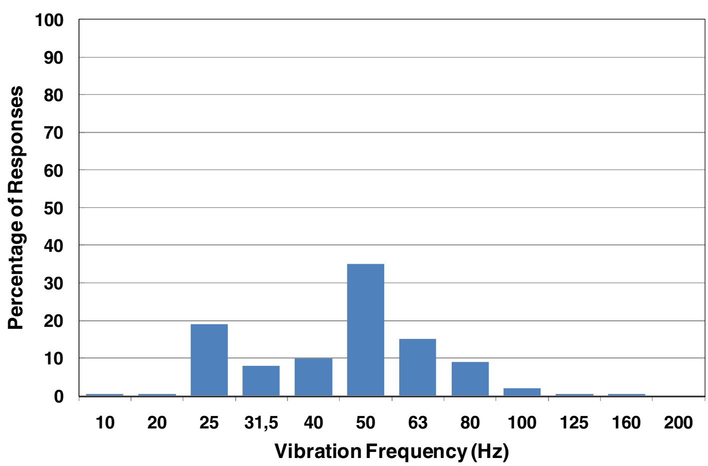

Fig. 2. The percentage of cross-modality frequency matching responses for auditory frequency 50 Hz

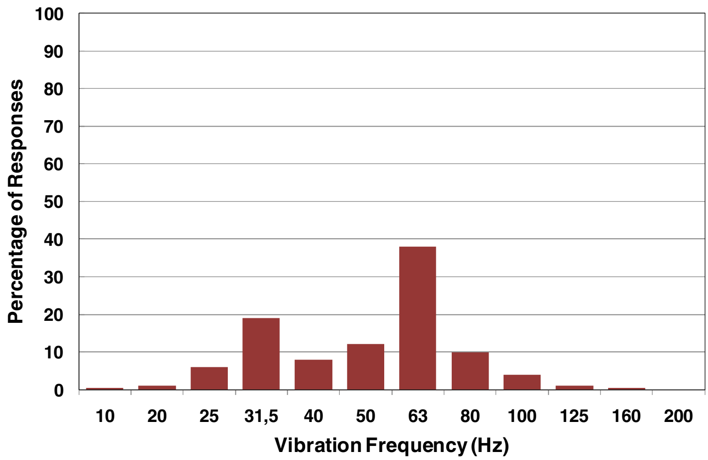

Fig. 3. The percentage of cross-modality frequency matching responses for auditory frequency 63 Hz

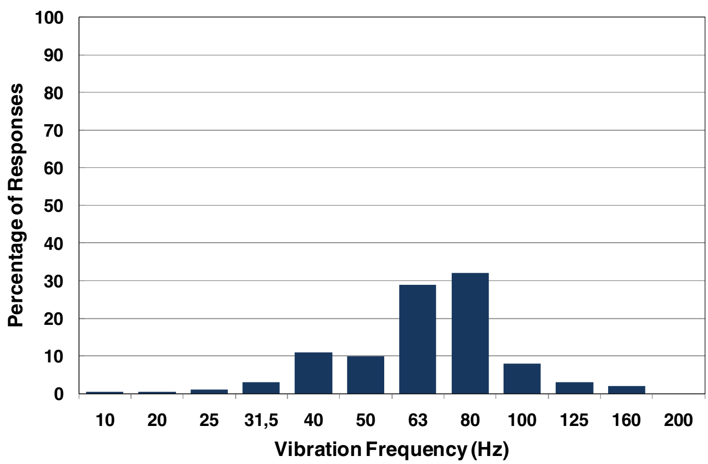

Fig. 4. The percentage of cross-modality frequency matching responses for auditory frequency 80 Hz

The results of the 63 Hz (Fig. 3) have very similar character in comparison to the results of the 50 Hz (Fig. 2). Figure 3 shows that 63 Hz vibration signal was found as the most suitable for the 63 Hz auditory stimuli. The lower octave of 63 Hz (31,5 Hz) shows an increase of the percentages of responses as neighboring 1/3 octave band frequencies.

The results for 80 Hz show some differences in comparison to the results of 50 and 63 Hz (Fig. 4). The maximum of the responses histogram is found at vibration frequency of 80 Hz with a percentage of 32. However the 63 Hz vibration signal also obtained a comparable matching percentage (28%). One reason for this phenomenon can be the high JNDF values for 80 Hz. The subjects cannot easily differentiate both signals. However 100 Hz vibration signal which is also very near to the 80 Hz, did not obtain comparable matching percentage. Interestingly the lower octave of 80 Hz (40 Hz) has very low matching percentage (11%).

The histogram of 100 Hz auditory stimuli is shown in Figure 5. A distinct peak is not recognizable in this histogram, the results have ambiguous character. High JNDF values in high whole-body vibration frequencies can be a reason. The participants have found that the vibration signals in the frequency range of 63-125Hz are suitable for 100 Hz auditory stimulus.

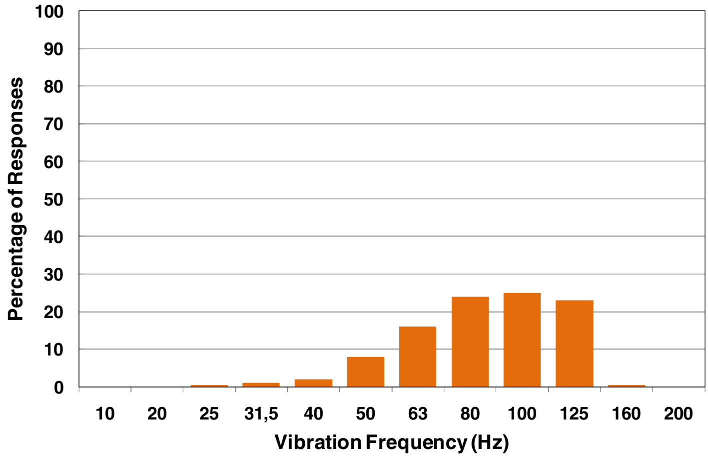

Fig. 5. The percentage of cross-modality frequency matching responses for auditory frequency 100 Hz

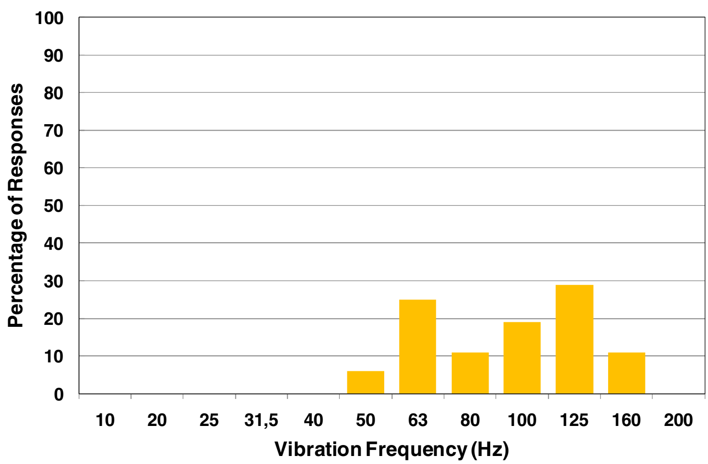

Fig. 6. The percentage of cross-modality frequency matching responses for auditory frequency 125 Hz

The histogram of 125 Hz auditory stimuli is shown in Figure 6. There are two peaks which are found 125 Hz (29%) and 63 Hz (25%). 100 Hz signal has also relatively high matching rate (19%).

The participants have found that 160 Hz vibration is the most suitable signal for the 160 Hz auditory stimuli (Fig. 7). Again 80 Hz (an octave lower of 160 Hz) has obtained high matching rate as neighboring 1/3 octave band frequencies.

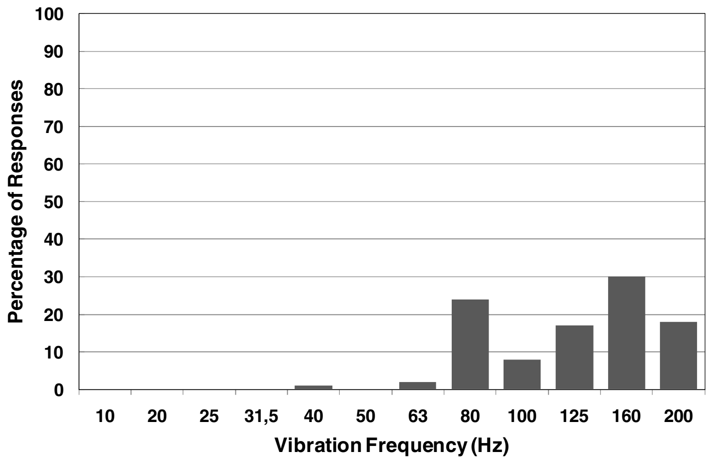

Fig. 7. The percentage of cross-modality frequency matching responses for auditory frequency 160 Hz

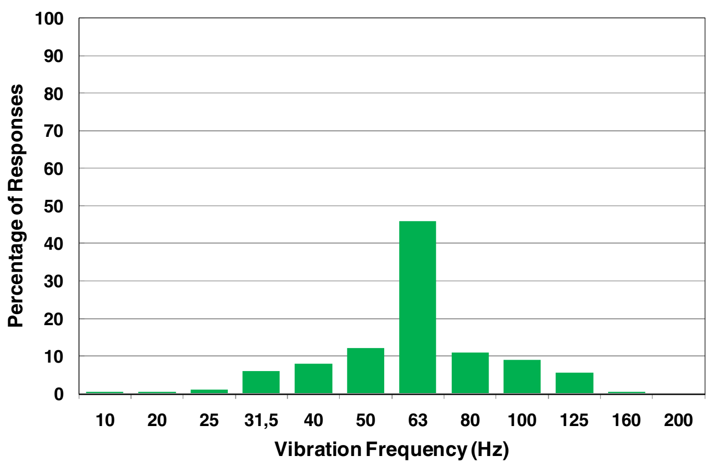

Fig. 8. The percentage of cross-modality frequency matching responses for auditory frequency 67,5 Hz

The cross-modality frequency matching experiment was conducted for an additional auditory frequency 67,5 Hz. However the exact same frequency was not in the pool of vibration stimuli. The reason for this additional investigation was to check if the lower octaves became higher matching rates rather coincidentally. The results of this additional investigation are shown in Figure 8. In this case the participants have selected the next 1/3 octave neighbor as suitable vibration signal. 63 Hz vibration signal was the most suitable one for 67,5 Hz tone (Fig. 8). Interestingly other signals did not obtain a comparable high rating. A possible reason for that can be the lower octave of 67,5 Hz was not in the stimuli pool.

4 Summary and Outlook

It is possible to observe interesting tendencies for cross-modality frequency matching. To find the most suitable frequency for the vibration signal in comparison to auditory signal, the subjects tend to prefer pairs having the same frequency for the auditory and tactile stimuli. In most cases, subjects judge also the lower octave of the auditory frequency to be suitable for the vibration frequency. One reason for that can be that in concert or in vehicle driving situations, we are used to perceive low frequency content mainly through tactile modality and high frequency content mainly through auditory modality. Rao has conducted an investigation on the perception of whole-body vibration frequency and found that if two whole-body vibration stimuli in different octave frequencies were presented, subjects can estimate the frequency ratio [11]. The results of this study confirm his results that octave perception is possibly existent for whole-body vibration similar to auditory octave perception. The results have extensive similarities with the results of audiotactile frequency matching studies for sound and hand vibration. They have also found that subjects tend to prefer pairs having the same frequency for the auditory and tactile stimuli [8,9] and there were some evidences for the octave perception in tactile modality [8].

For further research, it might be interesting to compare the obtained results with another experiment, in which the vibration frequency can be continuously controllable. Another aspect would be to expand the investigated frequency range.

Acknowledgment

The authors wish to thank Prof. Ute Jekosch for her support and informative discussions.

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