THE MISSING 6 dB: PERCEPTUAL OR PROCEDURAL EFFECT?

Sabine Meunier, Jacques Chatron, Théo Bonetto-Lemaire
Aix Marseille Univ, CNRS, Centrale Marseille, LMA, 4 impasse Nikola Tesla, 13453 Marseille Cedex 13, France
meunier@lma.cnrs-mrs.fr

ABSTRACT

Several studies have shown that, to produce the same loudness, a sound must be played 6 dB louder by headphones than by loudspeaker. Thus, a sound is louder when reproduced by loudspeaker compared to headphones, while the level at the ears are the same in both cases. This phenomenon was called the "missing 6 dB". It was found using methods of direct comparison between loudspeaker and headphones reproductions. In most studies, to make the comparison, the listener had to listen to a sound played by a loudspeaker, then to put the headphones on to listen to the sound played by the headphones, then remove the headphones to listen again to the sound played by the loudspeaker and so on. The purpose of the current study was to test whether the missing 6 dB is found using a procedure that does not require a direct comparison of the two reproducing systems. We measured the loudness functions of one-ERB-wide band of noises centered at 250 and 500 Hz (the missing 6 dB is observed at low frequencies). We used a scale, derived from G. Borg's work, with verbal anchors (from extremely weak to extremely loud, with a special anchor for inaudible). This scale makes it possible to compare the loudness functions measured with the headphones and loudspeaker. The levels at the entrance of the ear canals were measured individually using a small microphone inserted into an ear plug that blocked the ear canal. The experiment took place in an anechoic room. The loudspeaker was visible from the subject in all experiments. We did not find any differences in the loudness functions for the two center frequencies. For the same level at the entrance of the ear canals, the sounds had the same loudness in both reproduction conditions.

1. INTRODUCTION

It has been observed by several authors that, for the same pressure at the ears, a sound played through headphones is perceived less loud than a sound played by a loudspeaker in an open field ([1]–[4]). This effect is called "the missing 6 dB", because, in order to produce the same loudness, a sound played through headphones is adjusted about 6 dB above a sound played by a loudspeaker.
The methods used to highlight this phenomenon were always based on a direct comparison between the sound played via loudspeaker and headphones. In most of the studies, the sounds were equalized in loudness by listening to the loudspeaker, then putting the headphones on the head to listen to the sound played by the headphones, then removing the headphones and so on. ([1]–[5]). In Völk and Fastl [6], the headphones were not remove when listening to the loudspeaker. The missing 6 dB was observed at low frequencies (< 500Hz). According to Rudmose [5], the missing 6 dB may be caused by the vibrations transmitted from the loudspeaker to the listener, the distance of the source, the transducer distortion, the experimental procedure and the monaural balance. From the figures shown in his article, one can conclude that the chair vibrations have an effect of 0 to 2 dB on the difference of the at-ear level between the loudspeaker and the headphones reproductions that yield the same loudness, but only three listeners were tested. He also found an effect of the distance of the loudspeaker on loudness: the difference of the at-ear level between a distant (4-5 m) and a near loudspeaker for equal loudness was found to be from 4 to 5 dB for 4 listeners. Concerning the experimental procedure, in Rudmose's experiment [5], the headphones were always the first source, while in Munson and Wiener's study [1], the loudspeaker was always the first source. In Kohnen and al. [4], the order of stimuli presentation was loudspeaker vs headphones and then headphones vs loudspeaker. According to Rudmose [5] the distortion problem was resolved by using a tapered cone made of a material that make it possible to have a tight seal with the ear canal. When the loudness balancing was done in monaural listening, one ear was occluded with a well fitted earplug and an earmuff over the ear. Rudmose [5] claimed that his results "certainly support the conclusion that, if the procedures used in these experiments are followed, there is no missing 6 dB for loudness balancing test".
Loudness constancy [7] might be an explanation of the missing 6 dB ([5], [8], [9]). Indeed, it is possible that the listener judges the source power (inferring the sound pressure level emitted by the source) rather than the pressure level at the input of the ears. The loudspeaker being far from the listener compared to the headphones, in order to give the same loudness at the ears, its power must be stronger than the power of the headphones, then the loudness at the source is louder for the loudspeaker than for the headphones.
In our opinion, a loudness balancing between loudspeaker and headphones is not the best procedure to assess the missing 6 dB because attentional problems might arise due to the manipulation of the headphones by the listener. Moreover, making the loudness comparison without varying the adapted stimulus induces a systematic bias which is the tendency among subjects to adjust the varying stimulus a little higher than the standard [10].
Thus, the aim of the present study was to determine whether the missing 6 dB can be observed using a method in which the listener does not manipulate the

headphone during the test and that eliminate the bias of the order of presentation.

2. PROCEDURE

We measured the loudness functions of the same sounds played via loudspeaker and headphones in order to determine whether the missing 6 dB is observed using a direct method of loudness evaluation. The level is defined as the level at the entrance of the blocked ear canal (see paragraph 2.1).

2.1 Measurement of the sound pressure level at the entrance of the ear canals

The experiment was calibrated for each listener. The listener was seated in the middle of an anechoic room (9.8 x 9.8 x 8.8 m), the loudspeaker (Meyer MM-4XP, self-powered, with a wide operating frequency range from 135 Hz to 17 kHz ±4 dB) was positioned about 2.5 m in front of him/her. The headphones used were Beyerdynamic DT-770 Pro (closed). The sounds were played via a sound cart Babyface Pro RME. Two small microphones (DPA 4060) associated with a preamplifier (DPA MMA6000) were inserted into foam earplugs which were inserted into each ear canal as presented in Figure 1. Due to the configuration of the experimental setup, there was no possible mechanical propagation from the loudspeaker to the chair.

Figure 1: Microphone at the entrance of the ear canal

The microphones were calibrated using a pistonphone (Brüel & Kjaer 4230). The stimuli were narrowband noises with a bandwidth of one ERB and center frequencies of 250 and 500 Hz. The calibration procedure was divided in three different parts, between each part the microphones (with the earplugs) were removed and put back in place into the ears. This was done in order to take into account the influence of the position of the microphones on the sound pressure level measured at the entrance of the blocked ear canals. In each part, the sound pressure levels on the microphones inserted into the ear canals were measured for 30 s, for each center frequency, in the following order: the sounds were played first by the loudspeaker, then by the headphones, again by the headphone after being removed and put back on the head and finally by the loudspeaker. This was done in order to take into account the influence of the position of the headphones on the head and of the relative position of the loudspeaker regarding the head. Thus, we obtained 6 level values for each center frequency and each system (loudspeaker, headphones). These values were averaged and used to calibrate the experiment. When using the loudspeaker, the calibration levels were determined by the average of the levels measured on the left and right ears.

2.2 The CR100 scale

Loudness was judged by listeners on a continuous scale with verbal anchors (see Figure 2). This scale was inspired by the work of E. and G. Borg [11]–[13]. The idea behind the construction of this scale was to obtain ratio data and exponents of the power functions (the scale has predominantly been used for perceived exertion and pain assessment) that mimic what is obtained with magnitude estimation. According to E. and G. Borg this scale permit interindividual comparisons by placing verbal labels on the scale in congruence with the ratio scale.

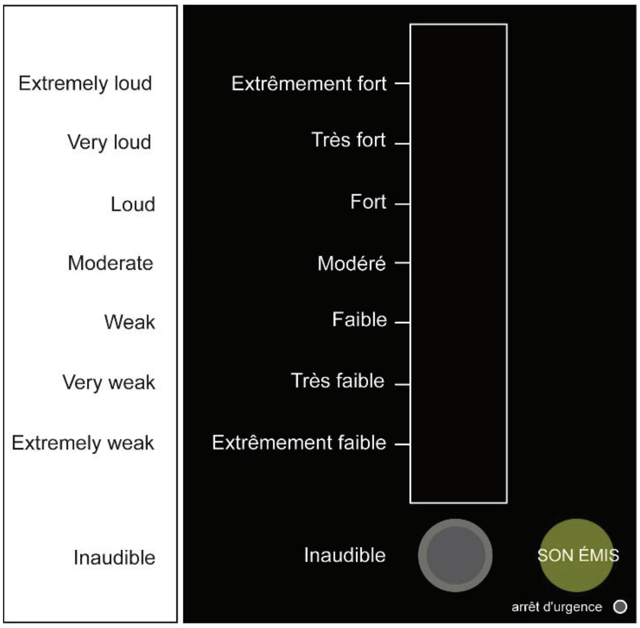

Figure 2: The CR100 scale

In our scale, the labels went from extremely weak (corresponding to the number 100) to extremely loud (corresponding to the number 700), with the possibility to exceed the extreme situations in order to avoid as much as possible edge effects. The corresponding numbers for the extremes were 0 (Inaudible) and 800 (Extremely loud). Each verbal anchor corresponded to a hundred.

The results obtained in this linear scale are converted in CR100 ratio scale using the formula [13]:

$$CR100 = A * B \tag{1}$$

$$\text{with } A = 1.5 * 2.5^{\frac{x}{100}-1}$$

$$\text{and } B = (1-0.082898)^{\left[\left(\frac{x}{100}-1\right)*\frac{\left(\frac{x}{100}-2\right)}{2}\right]}$$

2.3 Stimuli

The stimuli were band of noises that were 1 ERB wide and centered on 440, 500 and 1000 Hz. They had a duration of 1 s, and 20-ms linear rise/fall times. The test levels ranged from 42 to 84 dB SPL by steps of 6 dB.

2.4 Method

Ten listeners participated in the experiment.

The listener was seated at the center of the anechoic room facing the loudspeaker (about 2.5 m from the center of the head of the listener). Its position was exactly the same as for the calibration session (paragraph 2.1). The loudspeaker used (Meyer MM-4XP) has a compact size (10 x 10 x 15 cm). We were afraid that the small size of the loudspeaker would induce an estimate of the source power too weak, avoiding loudness constancy to play any potential role in the loudness evaluation. In order to be able to possibly highlight loudness constancy, we added two larger loudspeakers (Genelec 1031) on each side of the small loudspeaker so that the listener thinks that it was these two loudspeakers that were playing the sounds (see Figure 3) while they were not playing any sound, they were just acting as a decoy. Listening to headphones was done in diotic.

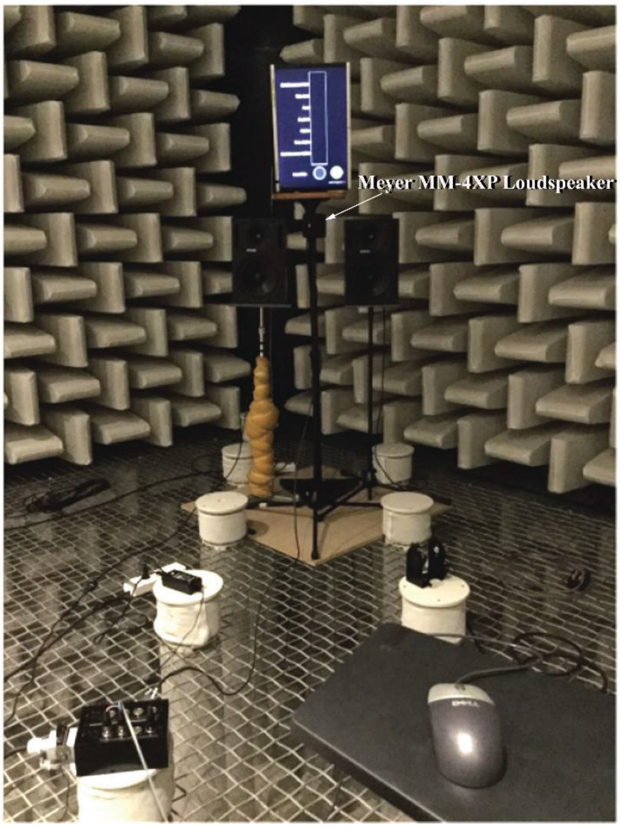

Figure 3: experimental set up.

The test was divided into 7 blocks. The first one, was a procedural training block with a one-ERB wide band of noise centered on 440 Hz. This center frequency was not used later on in order to avoid any training effect on the results. We used the calibration done for the 500-Hz center frequency as we did not need to have very precise levels for the training. The following 6 blocks were run for center frequencies of 250 and 500 Hz. Each block consisted of the presentation of bands of noises of the same central frequency and played by the same restitution system. Three blocks were run for each restitution system: 2 for a center frequency of 250 Hz and 1 for a center frequency of 500 Hz. The order of presentation of the blocks was randomized among the listeners. In one block, the stimulus was played at the 8 levels (42, 48, 54, 60, 66, 72, 78 and 84 dB SPL) presented in a "quasi-random" order to reduce assimilation effects, as proposed by Cross [14]. Each level was preceded by all the other 7 levels. Thus, all levels were presented 7 times, except the level played first, which was presented 8 times because at the beginning of the block it was preceded by any other sound. The listener judged the loudness using the CR100 scale that was displayed on a big screen positioned behind the loudspeaker in order to interact as less as possible with the acoustic field between the loudspeaker and the listener. He/she had to use a mouse to click on the CR100 scale at the place corresponding, according to him/her, to the loudness of the sound. The mean of the seven estimates was calculated for each listener.

3. RESULTS

Figure 4 and Figure 5 show the means of the estimates of the 10 listeners as a function of the level at the entrance of the ear canal for the band of noise centered on 250 Hz and 500 Hz respectively. They are reported on the CR100 scale. The blue squares correspond to the loudness measured with the headphones and the red circles to the loudness measured with the loudspeaker.

It can be observed that there is no difference between the loudness of the sounds played by the loudspeaker and by the headphones for the two center frequencies. An analysis of variance (ANOVA) with repeated measures shows any significant effect of the restitution system ($F(1, 9)=0.27$, $p=0.6$). Moreover there is no interaction between the restitution system and the level ($F(7, 63)=1.34$, $p=0.25$) neither between the restitution system, the level, and the center frequency ($F(7, 63)=1.65$, $p=0.14$).

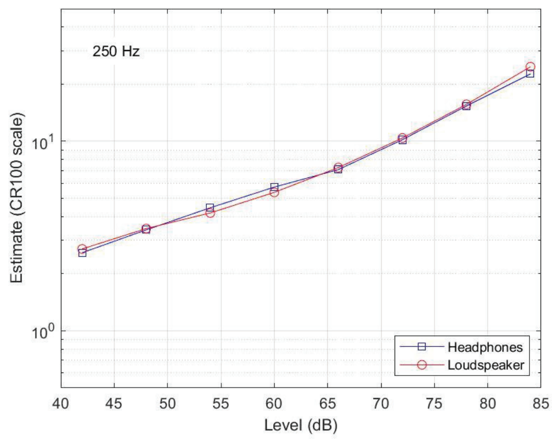

Figure 4: Loudness estimate as a function of the level at the entrance of the blocked listener's ear canals for the 1-ERB band of noise centered on 250Hz.

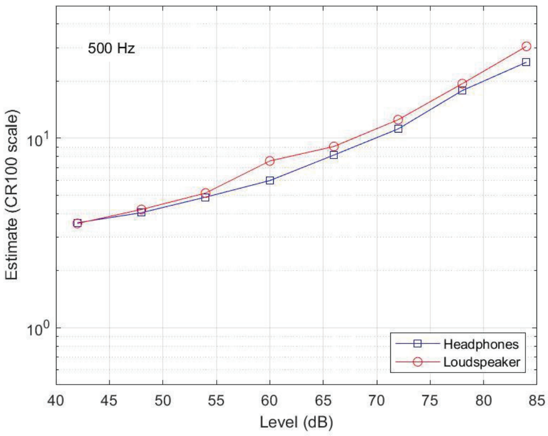

Figure 5: Loudness estimate as a function of the level at the entrance of the blocked listener's ear canals for the 1-ERB band of noise centered on 500Hz.

4. DISCUSSION AND CONCLUSION

Using a direct method to evaluate loudness, we did not find the missing 6 dB. So far, the missing 6 dB was observed when the sounds played by the loudspeaker and the headphones were directly compared.

Although attentional problems may come into play in this type of procedure, we do not believe they can explain the missing 6 dB. The bias introduced by a fixed order of sound presentation does not seem to explain the missing 6 dB either. Indeed, by varying the order of presentation Kohnen et al. [4] still observed the effect.

One of the possible cause of the missing 6 dB could be loudness constancy [7]. However Berthomieu and al. ([9], [15]) have shown that loudness constancy is obtained when the instruction given to the listener directs him/her toward a loudness judgment based on the sound source power. In the majority of previous studies, it seems that the instructions have not directed the listener toward a judgment based on sound source power. Rudmose [5] describes the task of his experiment as follows: "…simultaneously with removing the earphones, the subject switched the sound to the loudspeaker to compare the loudness of the two sounds". In Völk and Fastl [6] the task was "to continuously adjust the level of the BS (binaural synthesis) so that equal loudness is elicited by the synthesis and the real loudspeaker". In Kohnen et al. [4], "participant had to rate whether they perceived the loudspeaker or the headphone reproduction as louder". The only study where it is clear that the source has been evaluated is described in Munson and Wiener [1]: "He (the listener) then indicated which source was louder".

Moreover, one can wonder, if a phenomenon of loudness constancy is responsible for the missing 6 dB, why are the missing 6 dB only observed at low frequencies?

For these two reasons, it is difficult to argue for loudness constancy as an explanation for the missing 6 dB.

Völk and Fastl [6] have shown that when the signals were in phase on both ears, in both headphones and loudspeaker reproductions, there was no difference in loudness at equal levels in the auditory canals. They used binaural synthesis and compared the loudness of sounds played by virtual loudspeaker (binaural synthesis) to the loudness of sounds played by the corresponding real loudspeaker. If the phase difference between the two ears is the cause of the missing 6 dB, the loudness measurement method should have no influence on the effect and we should have found a difference of loudness between loudspeaker and headphones reproductions. One difference between Völk and Fastl [6] and Kohnen et al. [4]'s studies is the signal, Völk and Fastl used pure tones, and Kohnen et al. bands of noises (as us), which might explain the effect of the phase in Völk and Fastl which cannot be found with bands of noises.

The results of the present study do not explain the missing 6 dB, but allow us to provide lines of thought. The missing 6 dB is not observed in a direct loudness estimation task. What, in a comparison task, can induce a difference in loudness between a sound emitted by a loudspeaker and a sound emitted by headphone, when the at-ear pressures are identical? It therefore seems necessary to reflect on the task in order to understand the origin of the missing 6 dB.

5. REFERENCES

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