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Is there an auditory analogue to Fechner's paradox in binaural loudness perception?

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Summary. In binocular brightness perception a phenomenon called *Fechner's paradox* can be observed. This parádox implies non-monotonicities in the psychometric functions of binocular brightness. Lehky (1983) proposed a model that describes such non-monotonicities. He suggested that Fechner's paradox also exists in binaural loudness perception. However, until now no sufficient data have been collected to test this hypothesis. Therefore, an experiment was conducted in which 36 psychometric functions were obtained using binaural stimuli in the range of intensities in which Fechner's paradox supposedly occurs. As a result, no significant non-monotonicities were found. However, it is shown that jnds derived from the psychometric functions contradict predictions derived from the limited binaural additivity model of Gigerenzer and Strube (1983).

Key words: Binaural loudness, Fechner's paradox, psychometric function.

Gibt es ein akustisches Analogon zum Fechner-Paradox bei der binauralen Lautheitswahrnehmung?

Zusammenfassung. Bei der binokularen Helligkeitswahrnehmung gibt es das sogenannte *Fechner-Paradox.* Dieses Paradox impliziert, daß bei psychometrischen Funktionen der binokularen Helligkeit Nicht-Monotonien auftreten. Lehky (1983) hat ein Modell vorgeschlagen, daß diese Nicht-Monotonien beschreibt. Er vermutet, daß das Fechner-Paradox auch bei der binauralen Lautheit existiert. Jedoch gibt es bis heute nicht genügend Daten, um diese Hypothese zu beurteilen. Aus diesem Grund wurde ein Experiment durchgeführt, bei dem 36 pschometrische Funktionen für kritische binaurale Reizsituationen erhoben wurden. Als Ergebnis wurden keine bedeutsamen Nicht-Monotonien gefunden. Jedoch wird gezeigt, daß die gemessenen ebenmerklichen Unterschiede dem „limited binaural additivity model" von Gigerenzer und Strube (1983) widersprechen.

Schlüsselwörter: Binaurale Lautheit, Fechner-Paradox, psychometrische Funktion.

Introduction

There is a long tradition of investigating the question as to how binaural loudness depends on a two-component stimulus (a, x), with a denoting the intensity of a sound presented to the left ear and x denoting the intensity of a sound presented to the right ear, respectively. In early studies of binaural loudness only stimuli with $a = x$ were used, and the experimental procedure was relying on monaural-binaural loudness comparisons (cf., for example, Fletcher and Munson, 1933; Reynolds and Stevens, 1960). Subsequent investigations, however, also employed stimuli with $a \neq x$ in connection with binaural-binaural comparisons (cf., for example, Irwin, 1965; Levelt, Riemersma and Bunt, 1972; Falmagne, 1976; Marks, 1978; Gigerenzer and Strube, 1983).

A quite general binaural loudness function could be

$$L(a, x) = F[l(a), r(x)],$$

where l, r, and F are continuous functions. Most binaural loudness functions which can be found in the literature are special cases of this general function. One of the first hypotheses assumed some kind of binaural loudness summation: l and r are strictly increasing monaural loudness functions, and F simply is addition:

$$L(a, x) = l(a) + r(x).$$

Further specializations of this summation hypothesis have been proposed concerning the form of the monaural loudness functions l and r. For example, it has been discussed whether power functions are appropriate (for a review see Levelt et al., 1972). Unfortunately, however, there is no agreement on whether the underlying binaural loudness summation hypothesis is valid or not. There is some evidence that this hypothesis is incorrect (Falmagne, 1976) or that it is valid only within a limited range of stimulus intensities (Gigerenzer and Strube, 1983). Therefore, Gigerenzer and Strube (1983) proposed a limited binaural additivity (LBA) model which shall be discussed later.

Most of the binaural-binaural data that have been collected for testing models of binaural loudness are based on stimuli with moderate intensity differences between the two components. As a result, little is known about the binaural loudness of stimuli with large intensity differences. This fact has recently become obvious in connection with a model of binaural loudness suggested by Lehky (1983). He introduced a complex neural model suited for situations in which two sensory inputs are combined. His model, though primarily developed to account for binocular brightness perception (cf. Curtis & Rule, 1978; de Weert & Levelt, 1974), is also relevant for binaural loudness perception. In brightness perception an interesting phenomenon can be observed that is called *Fechner's paradox*. This paradox concerns the fact that if the stimulus component presented to one eye is near threshold, an increase of its luminance must be compensated by an increase of the luminance of the stimulus component presented to the other eye in order to maintain equal binocular brightness. Put differently, increasing the luminance of a stimulus component presented to one eye leads to a decrease in binocular brightness.

Fechner's paradox implies that there are non-monotonicities in binocular brightness perception. Important with respect to this paper, however, is Lehky's (1983) suggestion that such non-monotonicities also occur in binaural loudness. If Lehky's hypothesis is true, it would follow that not only all simple binaural loudness summation models, but also the LBA model must be false. Unfortunately, no appropriate data are available which could serve to test this hypothesis.

Therefore, this paper addresses the question as to whether there exist non-monotonicities in binaural loudness perception. One efficient method to test this hypothesis is to consider psychometric functions (cf. Irtel, 1986). If one considers a stimulus (*s*, *c*) where the component *c* has an intensity near threshold, then one would usually expect that increasing the intensity of *c* corresponds to an increase in loudness. That is, loudness increases monotonically with stimulus intensity. However, if Fechner's paradox holds, then there must be a range in which a *decrease* in the intensity of *c* leads to an increase in binaural loudness. Between these two intensity ranges lies a minimum such that increasing as well as decreasing of the intensity leads to an increased binaural loudness. Or, to put it another way, the corresponding psychometric function is non-monotonic. To obtain such a psychometric function one chooses a standard stimulus (*s*, *c*) and several comparison stimuli (*s*, *x*) with *x* varying. If there are non-monotonicities and a c' is chosen such that the standard stimulus (s, c') is the unique minimum with respect to (*s*, *x*), then the relative frequencies of „louder" judgements must increase, no matter if the component *x* of the comparison stimulus is more or less intense than c' of the standard. Therefore, it is important to find that minimum c', if there is one.

As mentioned earlier, the LBA model shall be considered in more detail. According to this model additivity only holds within a limited range of intensity differences between the two components of a binaural stimulus. Beyond this limit only the more intense stimulus determines binaural loudness. Formally, the model is written as:

$$L(a^*, x^*) = max\left[\frac{a^* + x^*}{2} + \delta, max(a^*, x^*)\right],$$

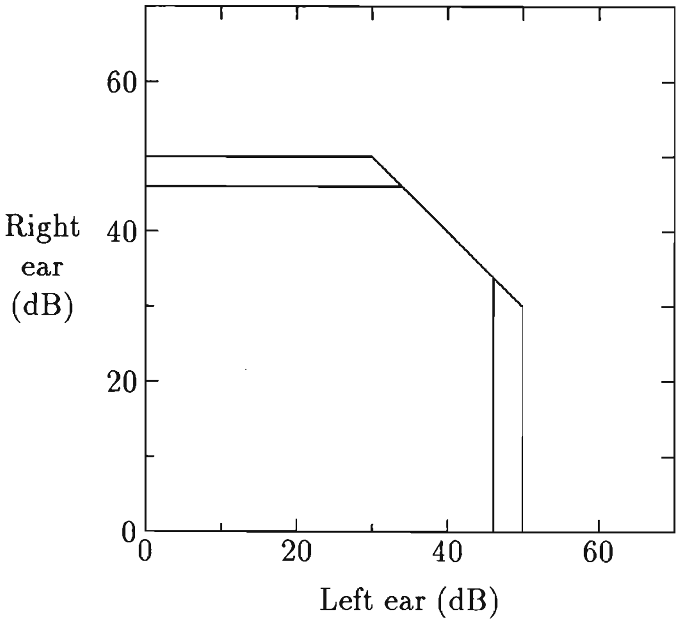
where, a^*, x^* are sound pressures levels (dB SPL), and δ is a constant.

However, the LBA model has at least two unsatisfactory features which deserve mention. First, if one considers stimuli with a SPL of 0 dB in one component as monaural stimuli, the LBA model implies that monaural loudness corresponds to the dB scale which is known to be wrong.

Second, the authors present a theoretical equal loudness contour derived from the LBA model. Since they specify a lower bound of 6 and an upper bound of 10 dB for delta, it follows that there is a tolerance field for deltas between 6 and 10 dB in the non-dominance area in which additivity holds (see Fig. 1 in Gigerenzer and Strube, 1983). However, an equal loudness contour is always related to a given standard stimulus. Consequently, the LBA model is reasonable only for standard stimuli from the dominance area. To make this clear, consider a stimulus with equal sound pressure levels for each component. Rather than specifying a unique loudness for this stimulus, the LBA model preditcts a tolerance field in the dominance area. Take, for example, the stimulus (40,40). For $\delta = 6$

we have a corresponding loudness of 46 and for $\delta = 10$ a loudness of 50. Moreover, the tolerance field in the non-dominance area disappears. The resulting curious equal loudness contour is shown in Fig. 1.

In addition to these curious results new empirical evidence will be provided in this paper which shows that the LBA model is not valid.



Figur 1: Theoretical equal loudness contours resulting from the LBA model with a (40, 40) comparison stimulus.

Method

Procedure and Stimuli

The method of constant stimuli (cf. for example Bock and Jones, 1968) was used. The stimuli were pairs of 1000 Hz tones. The duration of the stimuli was 400-ms (rise-fall time 10-ms), and the inter-stimulus interval within a pair lasted 700-ms. The subjects had to press one of two buttons to indicate the louder stimulus, or randomly, if they perceived equal loudness. There was no time limit for their decision. The presentation order of comparison and standard stimulus was randomized.

The standard stimuli consisted of all 16 combinations of the SPLs presented to the left ear (20, 30, 40, 50 dB) with the SPLs presented to the right ear (-8, 5, 10, 20 dB). The comparison stimuli consisted of a fixed left-ear SPL identical to that of the respective standard stimulus and 10 right-ear SPLs. For example, the subjects had to respond to the pair:

$$(20, -8) \gtrapprox (20, x).$$

The 10 values of x were chosen to cover a range of 20 dB, and to show an increase in the relative frequencies of the „louder" judgements in the right part of the psychometric function. The respective values were found by individual pre-tests.

Each stimulus pair was presented 40 times. The combinations of all left-ear SPLs with the right-ear SPLs of -8 and 5 dB are referred to as stimulus condition 1. The remaining combinations are condition 2.

Subjects

Listeners were four normal hearing psychology students (3 female, 1 male) between the ages of 21 and 28. All received training sessions prior to the actual data collection. Two subjects (1 female, 1 male) participated in condition 1, and two subjects (2 female) in condition 2.

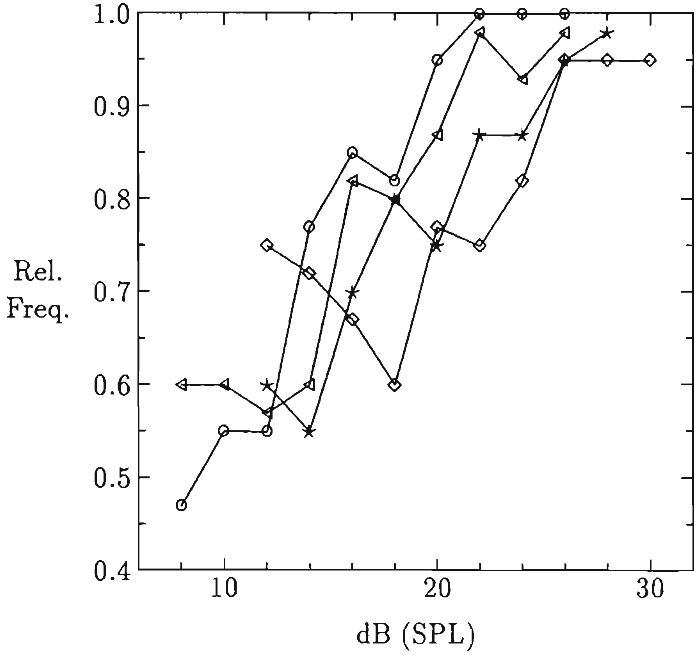
Apparatus

Stimuli were generated by a 12 bit D/A converter (40 kHz sampling rate) controlled by a personal computer. After low-pass filtering, the signal was divided into a left and a right channel. Subsequently, the signals were attenuated by a two-channel attenuator (two AD 7111), amplified by a standard amplifier (KS 33), and presented through earphone (Beyer DT-48A). An artificial ear (Brüel & Kjaer type 4153) and a measurement amplifier (Brüel & Kjaer type 2607) served for calibration. The subjects were seated in a double-walled sound-proof room. A control panel with two LED's indicated which signal corresponded to each of the two buttons.

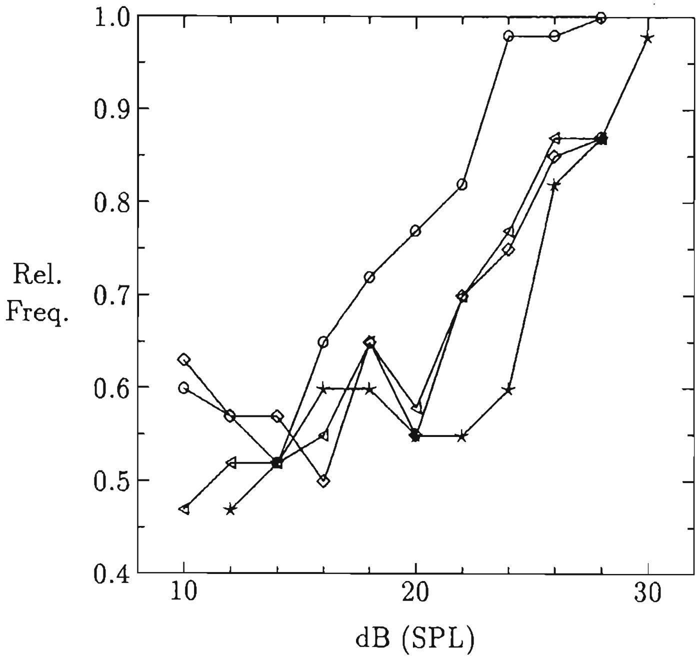
Results

Only few of the resulting 32 psychometric functions show the expected non-monotonicities. Take, for example, the data of Subject 1 from condition 2 corresponding to standard stimuli of $(c, 10)$ with $c = \{20, 30, 40, 50\}$ (see Fig. 2). Here, two of the four curves first decrease to a minimum and then increase.

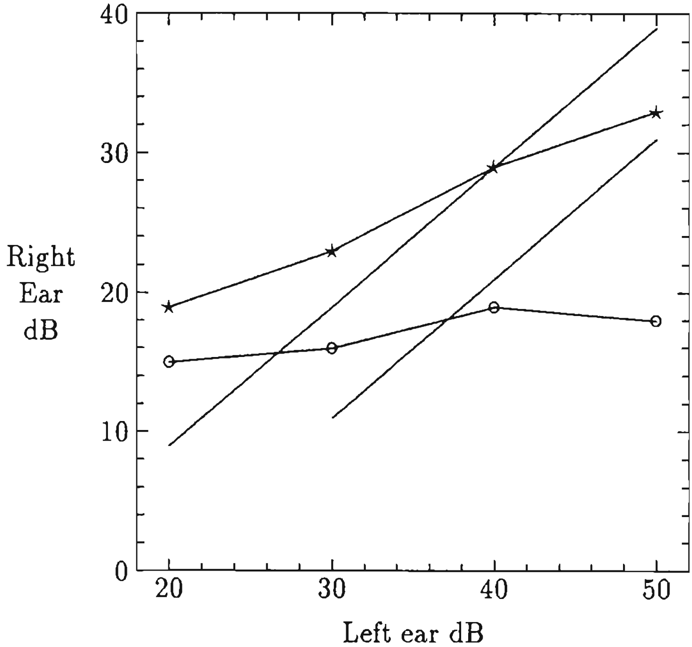
A similar result is evident in the data of Subject 1 from condition 1 corresponding to standard stimuli of $(c, 5)$ (see Fig. 3). Here, the curve depicted by squares shows a considerable non-monotonicity. However, these are the only functions out of 32 showing the kind of non-monotonicity to be expected on the basis of „Fechner's Paradox". As can be sen, there are several non-monotonicities other than the expected ones, particularly in Fig. 2. This seems to indicate that all non-monotonicities are due to random fluctuations in the data. Furthermore, attempts to replicate the functions showing the expected non-monotonicity while shifting the range of comparison stimuli to smaller intensities did not confirm the hypothesis. On the contrary, the non-monotonicities usually vanished. Thus, there is no evidence for an analogue to Fechner's paradox in binaural loudness perception.



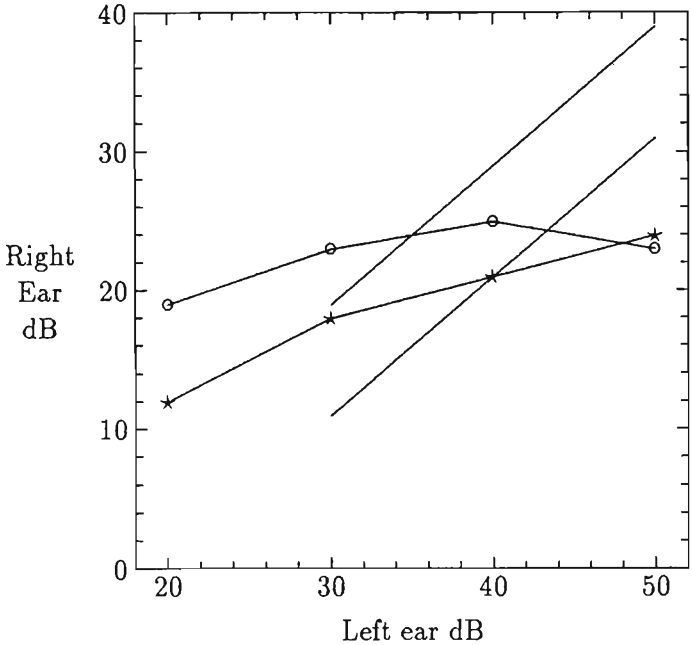
Figur 2: Psychometric functions of subject 1 in condition 2 obtained with standard stimuli of (20, 10) (circles), (30, 10) (triangles), (40, 10) (asterisks), and (50, 10) (squares).



Figur 3: Psychometric functions of subject 2 of condition 1 obtained with standard stimulio of (20, 5) (circles), (30, 5) (triangle), (40, 5) (asterisk), and (50, 5) (square).



Figur 4: Just noticeable differences of subjects 1 and 2 in condition 1 obtained with standard stimuli (c, 5) with c = {20, 30, 40, 50}.



Figur 5: Just noticeable differences of subjects 1 and 2 in condition 2 obtained with standard stimuli (c, 10) with c = {20, 30, 40, 50}.

Implications for the LBA model

The results of the experiment indicate that there is no Fechner's paradox in binaural loudness perception, contrary to Lehky's (1983) suggestion. This implies that the „true" psychometric functions can be regarded as monotonic which is consistent with the LBA model. There is another aspect of the data, however, that clearly contradicts the LBA model. Although the model does not make explicit statements concerning loudness discrimination, they can be inferred. The LBA model assumes that there is some sort of contralateral inhibition in the dominance area. Consequently, the stimuli from this area should equal in loudness and their discrimination should be impossible. Discrimination should be possible only among stimuli in the non-dominant area, or among stimuli from the non-dominant and the dominant area. The transition from non-discrimination to discrimination depends on the constant δ. Therefore, discrimination is possible if the intensity difference between the two ears is less than 2δ. For example, it is not possible to discriminate between the stimuli (50, 10) and (50, 20). However, given $\delta = 10$, it should be possible to discriminate between either stimulus and (50, 31). Another assumption of the LBA model is that the delta values are constant over the whole range of intensities. This implies a linear relationship with slope 1 between the intensity (in dB) in one ear and the corresponding intensity (in dB) in the other ear from which onward the discrimination of a stimulus from the respective dominance area is possible.

To test the last prediction the just noticeable differences (jnds) of those psychometric functions were estimated for which the standard stimulus lies in the predicted dominance area. This restriction was imposed to avoid the aforementioned tolerance field of the dominant area. To estimate the jnds, logistic functions were fitted to the data by means of linear regression (cf. Bock and Jones, 1968).

Figs. 4 and 5 show the results of the data analysis for standard stimuli (c, 5) and (c, 10), respectively. The straight lines correspond to the predictions of the LBA model. As can be seen, the data do not agree with the model. However, at least three of the four curves are approximately linear. One subject behaves differently but mainly at the highest intensity.

Discussion

The results of this investigation lead to the conclusion that in contrast to binocular brightness perception there is no evidence of Fechner's paradox in binaural loudness perception. This seems to be true at least for 1000 Hz tones. Thus, Lehky's (1983) suggestion could not be confirmed. This shows that some caution is necessary in transferring concepts from vision to audition and vice versa. A hint towards explaining the discrepancy might be sought in the phenomenon that the brigtness of some source usually does not change if one closes one eye, while the loudness of a sound source decreases if one covers one ear. Perhaps this may be one reason for the existence of Fechner's paradox in binocular brightness perception as opposed to binaural loudness perception.

However, it should be noted that the empirical results presented here rely only on samples of the whole stimulus range. Even though it seems highly unlikely, it is still possible that there are non-monotonicities but that they were not found.

In addition, the data collected demonstrate that the LBA model of Gigerenzer and Strube (1983) seems to be correct in suggesting that additivity only holds within a limited range. However, the data show that the model is too simple with respect to the predicted starting points of the suggested limits. Although there seems to be a linear relationship between intensity (in dB) and discrimination, i e. a linear increase of the jnds with SPL, it turns out to have a smaller slope than predicted by the LBA model. This implies that the delta values cannot be constant over the whole range of intensities.

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