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Binaural loudness gain measured by simple reaction time

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Abstract In order to yield equal loudness, different studies using scaling or matching methods have found binaural level differences between monaural and diotic presentations ranging from less than 2 dB to as much as 10 dB. In the present study, a reaction time methodology was employed to measure the binaural level difference producing equal reaction time (BLDERT). Participants had to respond to the onset of 1-kHz pure tones with sound pressure levels ranging from 45 to 85 dB, and being presented to the right, the left, or both ears. Equal RTs for monaural and diotic presentation (BLDERTs) were obtained with a level difference of approximately 5 dB. A second experiment showed that different results obtained for the left and right ear are largely due to the responding hand, with ipsilateral responses being faster than contralateral ones. A third experiment investigated the BLDERT for dichotic stimuli, tracing the transition between binaural and monaural stimulation. The results of all three RT experiments are consistent with current models of binaural loudness and contradict earlier claims of perfect binaural summation.

Keywords Hearing · Psychoacoustics · Simple reaction time

Introduction

When listening to sounds in a natural environment, different sound pressure levels (SPLs) reach the two ears. They are, nevertheless, combined to result in a single binaural loudness. This phenomenon is called *binaural loudness summation*. In the laboratory, it can be carried to an extreme by stimulating one ear only (monaural presentation) or both ears (binaural or diotic presentation), using headphones. When sounds are listened to with headphones, binaural stimulation sounds considerably louder than monaural stimulation. The amount of summation can be expressed in the binaural level difference required for equal loudness (BLDEL). That is the level difference between the monaural and the diotic presentations that sound equally loud.

The numerous studies that have been performed on this phenomenon (see Sivonen & Ellermeier, 2011, for a review) have used either loudness matches (e.g., adjusting a binaural tone to sound equally loud as a monaural one; Whilby, Florentine, Wagner, & Marozeau, 2006) or some variety of direct scaling (e.g., magnitude estimation by assigning numbers; Marks, 1978). Both of these methods have inherent problems. When making matches, for example, participants often find it difficult to compare two qualitatively very different auditory events—that is, binaural tones that produce a broad sound image in the center of the head and monaural ones that are lateralized and confined to an area close to the ear of stimulation. Comparing the two involves the risk of the listener setting arbitrary response criteria for establishing subjective equality. Not surprisingly, estimates of the BLDEL have varied considerably in the research literature, ranging from 10 (e.g., Fletcher & Munson, 1933; Marks, 1978) to a mere 4–5 decibels or even less at certain overall levels (e.g., Whilby et al., 2006).

Direct scaling methods, by contrast, particularly those involving one stimulus and one response—like magnitude estimation—avoid these issues but entail other problems related to the lack of uniqueness of the resulting scales: These studies have yielded binaural-to-monaural loudness ratios ranging from 2.0 (e.g., Hellman & Zwislocki, 1963; Marks, 1978) through 1.5 (Zwicker & Zwicker, 1991) and 1.3 (Marozeau, Epstein, Florentine, & Daley, 2006), to 1.16 with loudspeaker presentation (Epstein & Florentine, 2012). According to

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Stevens's power law, the latter corresponds to a BLDEL as small as 2 decibels.

Given this unsatisfactory state of affairs, the present study sets out to investigate whether simple reaction time (RT) to the onsets of tones, a method that assumably taps the underlying sensory processing in a more direct manner than do psychophysical methods involving explicit judgment or adjustment, might yield an unbiased estimate of the gain produced by binaural stimulation. Reaction time has been suggested as a surrogate measure of the strength of sensation since the times of Wilhelm Wundt (e.g., Cattell, 1886; Wundt, 1874). For the auditory domain, a number of researchers established that RT is inversely related to sound level (Chocholle, 1940, 1944; Kohfeld, 1971; Piéron, 1920). More important, it has been shown to reflect loudness and not SPL per se, since equally loud tones (of differing SPLs) produce approximately equal RTs (Kohfeld, Jeffrey, Santee, & Wallace, 1981; Marshall & Brandt, 1980). In addition, the different growth of loudness with SPL for wideband versus narrowband noise—that is, spectral summation—is properly reflected in RT (Wagner, Florentine, Buus, & McCormack, 2004), and sensory adaptation effects due to changing stimulus context (loudness recalibration, also known as induced loudness reduction) affect RT in the same manner as they affect direct loudness estimates (Arieh & Marks, 2003). Minor discrepancies between loudness and RT have occurred at low SPLs only (e.g., Kemp, 1984; Kohfeld et al., 1981), where the effects of hampered detectability appear to complicate the attempt to measure loudness via RT (for a review, see Marks, & Florentine, 2011). At present, no agreed-upon model of how sensory strength is translated into simple RT exists, but the evidence seems to suggest that RT reflects more than mere energy summation at onset, since variations of sound level and stimulus duration affect both response speed and response force well beyond the initial triggering stage (Heil, Neubauer, Tiefenau, & von Specht, 2006; Ulrich, Rinkenauer, & Miller, 1998), as would be expected from loudness integration.

The spectral summation study cited is illustrative of the approach taken when RT is used to measure loudness, much in the way the present study does: Using an adaptive procedure, Wagner et al. (2004) had their participants produce loudness matches of wideband versus narrowband noise stimuli at selected sensation levels. The same stimuli and levels were used to collect simple RTs from the participants. Subsequently, Wagner et al. determined the level difference between the two noises that yielded equal RTs. Results showed the same (inverted-U) pattern as the level difference required to obtain a loudness match using the adaptive procedure, with the exception of minor discrepancies emerging at low SLs.

The goal of the present study is to apply RT methodology to the issue of binaural summation. Except for measurements on 3 participants reported in Chocholle's (1944, Section II.E.) classic study that demonstrate its general feasibility and one recent study focusing on binaural redundancy gains in RT (Schröter, Ulrich, & Miller, 2007), this approach has not been taken in loudness research. By presenting listeners with binaural and monaural (monotic) tones to elicit simple RTs and through a wide range of levels, the binaural level difference required for equal RT (BLDERT) will be determined and compared with the binaural gain typically measured via loudness matches or direct scaling methodologies, as well as with current models of (binaural) loudness. Experiment 1 is basic in comparing RT for monaural versus binaural sounds; Experiment 2 further extends the scope by exploring an issue related to the hand used for responding, and Experiment 3 explores dichotic sounds constituting transitions between monaural and binaural stimulation.

General method

Participants

Twenty listeners (age, 19–30 years; median age, 21; 13 female, 19 right-handed) participated in Experiment 1, 16 in Experiment 2 (20–42 years; median age, 28.5; 12 female, 13 right-handed), and 16 in Experiment 3 (age, 19–44 years; median age, 22; 8 female, 11 right-handed). Each of them passed a hearing test, confirming that their threshold was better than 20 dB HL for all frequencies from 125 Hz to 8 kHz, measured in octave steps. Handedness was tested using the Edinburgh Inventory (Oldfield, 1971) in Experiment 2, where all participants showed a laterality coefficient greater than 0.6 or smaller than −0.6, indicating a clear tendency. In the other experiments, handedness was self-reported, and participants were asked to use their dominant hand. The majority of listeners in Experiment 1 were international students, whereas most of the other ones participated for course credit.

Apparatus and stimuli

The stimuli were generated with 48-kHz sampling rate at a resolution of 16 bit, D/A converted by an RME Hammerfall DSP Multiface II audio interface, amplified by a Behringer HA8000 Powerplay Pro-8, and presented via Beyerdynamics DT-990 250 Ω headphones to the participants, who were seated in a double-walled sound-proof chamber manufactured by the Industrial Acoustics Company. In all experiments, the stimuli had Gaussian rise and fall times of 5 ms. All stimuli were 1-kHz pure tones with a duration of 200 ms.

The signals were calibrated using a Brüel & Kjær 4153 coupler with a DB 0843 adapter. It was determined that 1 V produces 100 dB SPL, which is 2 dB less than the manufacturer's data. Discrepancies between the left and the right channels were corrected via the software settings of the audio interface, although they amounted to less than 1 dB.

The telegraph key was custom-made and offered a resistance comparable to that of a computer mouse. It was connected to a custom-made electronic timer constructed according to the prototype of Kerber (2008). Its high-precision counter has a clock rate of 1 ms, is triggered directly by the acoustic signal, and is stopped by the telegraph key. The value thus measured is read and reset after each trial via USB.

Procedure

The participants were instructed to press a telegraph key as soon as they heard any sound through their headphones. Each trial was started by presenting a red square on the screen for 200 ms. The foreperiod between the warning signal and the onset of the sound consisted of two parts: a fixed part of 500 ms and a randomly varying part drawn from an exponential distribution having a mean value of 1 s. The entire waiting time was limited to 5 s. If the value drawn exceeded this limit, it was recalculated before the trial. After pressing the telegraph key, the participants received visual feedback on the screen through a depiction of a button being pressed, thus telling them the response had been registered. The intertrial interval between a reaction and the start of the next warning signal was 1.5 s. Trials resulting in RTs of less than 100 ms or more than 1 s were repeated at a random position in the same block. With latencies of less than 100 ms, we assumed that the listener had anticipated the sound, whereas latencies greater than 1 s were taken to mean that he or she had missed its onset.

In order to prevent fatigue, the participants were allowed to take breaks after blocks of about 100 trials. In addition, each experiment was split into two sessions with at least 1 h in-between. Within each block, the conditions occurred equally often and in random order.

Experiment 1: Binaural gain

Stimuli and procedure

The aim of Experiment 1 was to determine the BLDERT. This is hereby defined as the difference in level that is needed to obtain the same RT for monaural and diotic sound presentations. For this purpose, a 200-ms 1-kHz pure tone was presented at nine levels between 45 and 85 dB SPL with a 5-dB spacing diotically to both ears, to the right ear only, or to the left ear only. Each listener completed 40 trials for each of the 27 (9 levels × 3 presentation modes) conditions. This means that one data point in Fig. 1 represents 800 trials (20 participants × 40 trials).

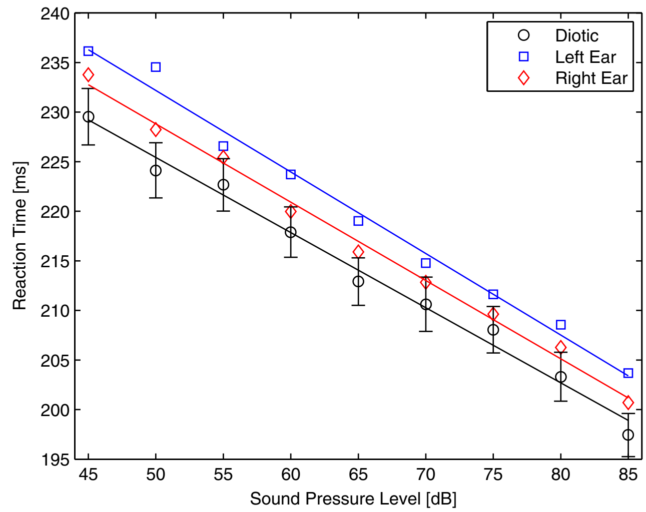

Fig. 1 Geometric mean reaction times of 20 listeners to the onsets of 1-kHz pure tones as a function of sound pressure level and aural presentation mode. Linear regression lines were fitted separately to the left ear (squares), right ear (diamonds), and binaural (circle) conditions. Standard errors of the mean are shown for the binaural conditions

Results

Because of the skewed distribution of RTs, the overall geometric mean was computed across trials and participants. It has the advantage of reducing the effect of the occasional longer RTs regarded as outliers. Errors occurred rarely: The cutoffs of 100 and 1,000 ms were exceeded on only 0.2 % of all trials.

The results are illustrated in Fig. 1 as a function of SPL and ear of stimulation. It can be seen that in the range studied, RT decreases linearly with SPL and that the least-square regression lines for the three aural presentation modes are almost parallel, having slopes of 0.76 ms (binaural), 0.79 ms (right ear), and 0.82 ms (left ear) per dB. Furthermore, diotic presentation yields faster reactions than the monotic conditions, as was expected because of binaural loudness summation. However, there is also an unexpected difference in RT between right-ear stimulation and left-ear stimulation, favoring the right ear. All of these effects are statistically significant, as confirmed by a 9 × 3, SPL × aural presentation mode (APM), within-subjects analysis of variance performed on the geometric means calculated for each listener. The main effects of SPL, $F(8, 152) = 127$, $p < .001$, $\eta_p^2 = .87$, and of APM, $F(2, 38) = 21.3$, $p < .001$, $\eta_p^2 = .53$, are both highly significant. Subsequent pairwise t-tests confirm that the diotic configuration results in faster RTs than does the mean of the two monotic configurations, $t(19) = 4.6$, $p < .001$, but also indicate a significant difference between right ear and left ear stimulation, $t(19) = 4.7$, p < .001. The interaction between SPL and APM is not significant, $F(16, 304) = 0.446$, $p = .97$, $\eta_p^2 = .02$, meaning that the decrease of RT with SPL is very similar for the three types of aural configuration.

In order to estimate the BLDERT, the horizontal distance in dB between the diotic and the monotic regression lines was determined and is shown in Table 1. The SPLs given are those of the approximated value for the binaural condition. The average BLDERT is about 5–6 dB, showing a slight decrease with sound pressure level.

Discussion

The objective of Experiment 1 was to show that binaural loudness summation can be observed when measuring simple RT to the onset of a stimulus. Listeners responded faster in the case of diotic stimulation, when compared with monaural stimulation of either ear. Thus, the present experiment complements earlier studies showing that RT is dependent not only on SPL, but also on spectral loudness summation (Wagner et al., 2004) and, to some extent, on frequency (e.g., Chocholle, 1940; Epstein & Florentine, 2006). All of these studies suggest that simple RT is related to loudness, not to physical intensity.

The results further permit us to quantify the amount of loudness summation and imply that the BLDERT comes quite close to what has been measured using other methodologies. They disagree with early studies (e.g., Marks, 1978), which found a binaural gain of 10 dB, which would mean perfect loudness summation across the two ears, or a doubling of loudness when binaural was compared with monaural stimulation. A binaural gain of 5–6 dB, by contrast, is consistent with more recent measurements employing modern psychoacoustical methods (reviewed in Sivonen & Ellermeier, 2011): An extensive study by Whilby et al. (2006) found average gains of between 6 and 8 dB in the level range studied in the present investigation; experiments by Zwicker and Zwicker (1991) yielded a loudness ratio of 1.5, corresponding to a gain of 6 dB.

The present study is also consistent with current models of binaural loudness summation. Moore and Glasberg's (2007) model, incorporating contralateral inhibition, proposes a gain of about 6 dB for binaural presentation. Model predictions for the stimulus parameters studied are listed in Table 1 and are very close to the present measurements. The power summation model of Sivonen and Ellermeier (2006) suggests a smaller gain of 3 dB on the basis of experiments conducted in an anechoic chamber with free-field listening to narrow-band noise. Indeed, the summation of two identical signals also yields a gain in intensity of 6 dB—certainly a special case that may apply to the diotic presentation via headphones. Recent studies by Epstein and Florentine (2009, 2012), using both tones and speech as stimuli, found that loudspeaker presentation and concurrent video of the talker all tended to reduce the binaural gain, suggesting a role for "binaural loudness constancy" to operate under these more realistic conditions. The present study, producing a somewhat larger binaural gain using pure tones and headphone presentation thus fits into this line of reasoning.

Table 1 Binaural level difference for equal reaction time

	Binaural Level [dB SPL]		
	50	65	80
Binaural vs. left	8.2	7.0	5.9
Binaural vs. right	4.3	3.7	3.1
Average	6.3	5.4	4.5
Moore & Glasberg (2007) model	5.9	6.1	5.6

Experiment 2: Hand–ear interactions

A surprising finding in Experiment 1 is that the two monaural conditions differed; that is, right-ear stimulation produced significantly shorter RTs than did left-ear stimulation. Since the vast majority of participants (19 of 20) were right-handers, it was hypothesized that presenting sound to the right ear facilitates responding with the right hand, as if participants were inadvertently considering the location of the stimulus, even though it was irrelevant to the simple RT task. This phenomenon might bear some resemblance to the Simon effect observed in choice RT (Lu & Proctor, 1995; Simon, 1969). Simon and Rudell (1967), for example, had participants press right- or left-hand keys in response to the commands "right" or "left," which could be presented to either ear. They found RT to be significantly faster when the meaning of the command agreed with the task-irrelevant ear of stimulation. Recent evidence has shown that this effect may extend to a simple RT task as well (Spera, 2010). This might suggest that the present right-ear advantage in RT is mediated by responding with the right (ipsilateral) hand. Therefore, if participants were asked to respond with their left hand, the unexpected monaural effect should reverse.

Stimuli and procedure

To investigate this hypothesis and the potential role of handedness, Experiment 2 was conducted. The same stimuli and aural presentation modes as in the first experiment were used. However, they were presented at 50, 65, and 80 dB SPL only. This time, participants were asked to switch their hand used for keypressing between blocks. The order of left hand (L) and right hand (R) in the ten blocks was LRRLLRLLRR or the other way round. This constitutes 18 conditions (3 levels × 3 presentation modes × 2 hands), each being repeated 60 times per listener.

Results

Figure 2 shows RTs for all 16 listeners as a function of SPL, APM, and hand used for responding, separately for the three SPLs employed. Since results for the 13 right-handers did not differ markedly from those of the 3 left-handers, their data were combined in a 3 × 3 × 2 (SPL × APM × hand) within-subjects analysis of variance of the geometric means per participant.

First of all, the results confirm the outcome of Experiment 1: There is a significant effect of SPL, $F(2, 30) = 142$, $p < .001$, $\eta_p^2 = .90$, and of APM, $F(2, 30) = 10.3$, $p < .001$, $\eta_p^2 = .41$, with the binaural conditions producing shorter RTs than the mean of the two monaural ones, $t(15) = 4.8$, $p < .001$. The mean binaural gain at 65 dB SPL when responding with the right hand is 5.8 dB, essentially the same as in Experiment 1. Including the responses made with the left hand, the binaural gain at 65 dB SPL is 4.9 dB, which is still close to the 5.4 dB of Experiment 1.

The point of Experiment 2, however, was to inspect monaural RTs as a function of the hand used for responding. As in Experiment 1, when participants pressed the key with their right hand, RTs were shorter for tones presented to the right ear, as compared with the left ear (see the plots labeled "RH" in Fig. 2). When, by contrast, they responded with their left hand, the effect reversed, showing shorter RTs to tones presented to the left ear (plots labeled "LH" in Fig. 2). This consistent advantage for the ipsilateral ear is highlighted by the gray bars in Fig. 2. The interaction between hand and APM is statistically significant, $F(1, 15) = 4.7$, $p < .05$, $\eta_p^2 = .24$, in an analyis of variance involving the monaural conditions only. All other interactions—for example, those involving SPL as a factor—were not statistically significant, nor was the overall main effect of hand of responding.

Discussion

The results of Experiment 2 suggest that the difference between stimulation of the right and left ears observed in Experiment 1 is not due to a lateral sensitivity difference in the hearing system but is caused by an ipsilateral advantage with respect to presentation and response modes. It appears that a stimulus presented to one auditory hemifield primes a response on the corresponding side via a direct, automatic route (see Lu & Proctor, 1995), an advantage not present when responding with the contralateral hand. The effect is much smaller, however, than the one observed in the Simon effect, since in a given block, responding is always with one hand only, thus missing the element of response competition in the Simon task. Given that the effect is not auditory in nature, it seems reasonable to take the average of the two monaural conditions to calculate the binaural gain.

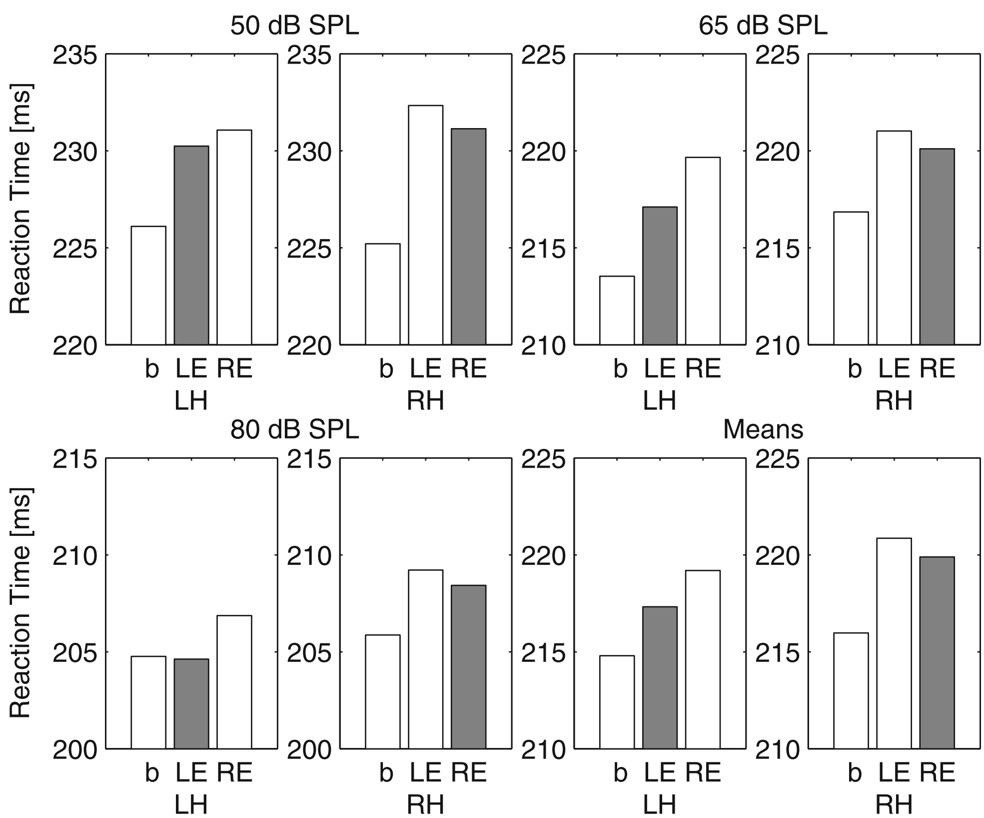

Fig. 2 Geometric mean reaction times of 16 listeners to the onsets of 1-kHz pure tones. The tones were presented binaurally (b) or monaurally to the left (LE) and right ear (RE), respectively. Listeners responded either with their left (LH) or right hand (RH). Gray-colored bars indicate ipsilateral responses

The ipsilateral advantage can be seen for any combination of responding hand and stimulated ear in Fig. 2. Furthermore, binaural mean RTs are shorter than monaural ones, with one exception occurring in the eight configurations studied at 80 dB SPL with the left hand responding. Here, the left-ear and binaural RTs are indistinguishable.

It is rather surprising that no main effect of the hand responding could be found. This means that the right-handers did not react more slowly when using their left hand. The data even show slightly faster responses by the left hand. If these are used to calculate the BLDERT, it becomes somewhat smaller. However, the difference from the BLDERT based on the right hand only is less than 1 dB. A reason why there is no advantage of the dominant hand could be that both stimuli and task are very simple.

Experiment 3: Dichotic gain

Stimuli and procedure

So far, only extreme conditions with respect to interaural level differences—monaural and diotic—have been considered. Therefore, a third RT experiment targeted intermediate (dichotic) conditions. Again, a 1-kHz pure tone was used at a duration of 200 ms. The SPL at the left ear was fixed to 70 dB. Apart from monaural and diotic stimulation, the level at the right ear could be 1, 2, 3, 6, 10, and 20 dB less than that at the left ear, so the right-ear signal was either absent or had SPLs between 50 and 70 dB. Because of the small effects expected, maximally corresponding to the BLDERT, each of the eight conditions was repeated 105 times per participant.

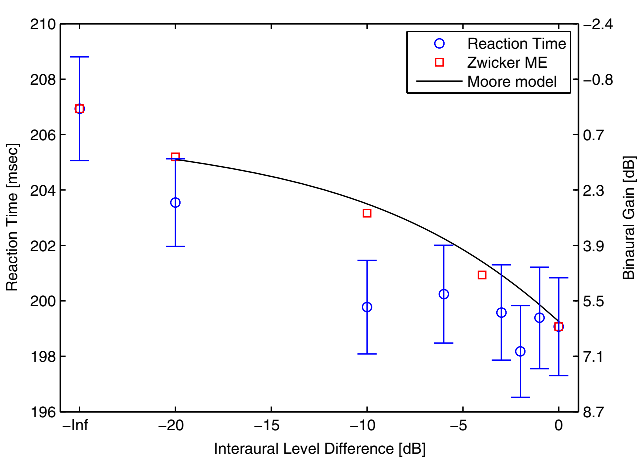

Fig. 3 Geometric mean reaction times (RTs) of 16 participants to the onset of 1-kHz pure tones as a function of the interaural level difference. Error bars show standard errors of the mean. Squares designate mean magnitude estimates for similar stimuli obtained by Zwicker and Zwicker (1991, Table 1) under the assumption that the binaural gain in decibels is a linear function of RT in milliseconds. The prediction by the Moore and Glasberg (2007) model is traced by the solid line. The sound pressure level at the left ear was fixed to 70 dB SPL

Results

Each data point in Fig. 3 represents the geometric mean RT of 1,680 trials (16 participants × 105 trials). A within-subjects analysis of variance shows that the effect of the interaural level difference (ILD) is significant, $F(7, 105) = 8.25$, $p < .001$, $\eta_p^2 = .35$. Post hoc *t*-tests yield the result that the monaural condition differs from the one with an ILD of 20 dB, $t(15) = 10.3$, $p < .001$, and the 20-dB ILD differs from one of 10 dB, $t(15) = 5.00$, $p < .001$. By contrast, a post hoc analysis of variance including the ILDs between 10 and 0 dB does not show any significant differences in that range, $F(5, 75) = 0.57$, $p = 0.72$, $\eta_p^2 = .04$.

Discussion

Analyzed qualitatively and considering that there is no statistically significant difference for ILDs between 10 and 0 dB, RT appears to decrease monotonically when the level delivered to the right ear is increasing. This means that the expected rank order is not violated.

The present data may be further compared with the magnitude estimates reported by Zwicker and Zwicker (1991, Figs. 6 and 9, Table 1), which are also based on a vast amount of data and a medium level of 70 dB SPL but were collected using narrow-band noise at three different center frequencies. Their condition that is closest to that of the present study is a third-octave wide noise centered at 710 Hz and having 70 dB SPL. It results in virtually the same values as the median taken from all conditions studied (Fig. 9 and Table 1). Binaural gains derived from the latter are depicted in Fig. 3 for comparison with the present RTs. The predictions for dichotic stimuli from the binaural inhibition model of Moore and Glasberg (2007) rest upon these previous data.

In order to allow a quantitative comparison between Zwicker and Zwicker's (1991) magnitude estimations (MEs) and the present RTs, it is necessary to transform the MEs into a binaural gain in milliseconds, which requires some assumptions. First, Stevens's power law can be applied to the MEs, which yields a binaural gain in decibels. Second, it is assumed that the BLDERT obtained in the present experiment is equal to the BLDEL of the MEs, which is justified by the findings of Experiment 1, showing that the BLDERT is very close to the BLDEL of Moore and Glasberg's (2007) model and, therefore, the MEs. Thus, the RT of the monotic conditions equals a binaural gain of 0 dB, and the RT of the diotic condition a binaural gain of 6 dB. Finally, the regression lines in Experiments 1 have shown that RT in milliseconds is linearly related to loudness level in the range studied. That is why a linear connection between the right axis of Fig. 3, showing the MEs converted to levels, and the left axis, showing the RTs in milliseconds, appears reasonable.

A discrepancy between the results obtained by simple RT and those obtained by ME can be seen. Both data sets yield a certain binaural gain at an ILD of 20 dB, although they do not agree exactly on its value, which might be somewhere between 1.5 and 2.5 dB. Toward the binaural condition—that is, going from left to right in Fig. 3—the binaural gain approaches its maximum value (i.e., 6 dB). It does so at a faster rate, when considering the RT measurements. These already reach the full binaural gain at an ILD of 10 dB, whereas for the ME data, this constitutes an intermediate condition. Since both studies rely on vast amounts of data, it is questionable whether the difference stems from inaccuracy, although the RT data appear somewhat noisier. In-head lateralization might have different effects on the two methods, as well as the different types of simuli being used—namely, a pure tone versus a narrow-band noise. Nevertheless, both studies agree that an intermediate condition between monaural and binaural stimulation is obtained with an ILD somewhere between 20 and 10 dB.

General discussion

Altogether the present experiments have shown that simple RT correlates extremely well with loudness. They complement previous studies that measured loudness by way of RT and investigated the effects of frequency and spectral summation. Potentially, reacting to the onset of a sample sound, rather than having to make a complex cognitive assessment (as on a loudness match, for example) avoids potential biases and constitutes a more natural, direct correlate of loudness.

Furthermore, the present data may be used to investigate binaural loudness summation. Chocholle's (1944, Figs. 11–13 and Table IV) pioneering study had provided initial, qualitative evidence for emergence of a monaural–binaural difference in RT measurements. Consistent with that, a recent study focusing on redundancy gains in RT (Schröter et al., 2007) found a small advantage of some 5–9 ms for binaural stimulation, which—although discounted in their conclusions—corresponds quite well to the effect size observed in the present set of experiments. Note, however, that they used only a single SPL (60 dB), which precludes expressing the effect in units of physical intensity or loudness. By contrast, the present data collection may be used to actually quantify the amount of binaural gain in decibels. It shows the BLDERT to be approximately 5–6 dB. This value falls in the middle of the range of gain factors found by most studies (Marozeau et al., 2006; Sivonen & Ellermeier, 2006; Whilby et al., 2006; Zwicker & Zwicker, 1991) also using headphone presentation or synthetic stimuli but disagrees with older studies having claimed "perfect" binaural loudness summation—that is, a gain of 10 dB.

The present outcome further supports the line of reasoning developed by Epstein and Florentine (2012), who observed that the binaural gain is highest for synthetic stimuli and unnatural (headphone) presentation, while some kind of "binaural loudness constancy" is obtained when listening to natural sounds positioned in real space or rendered with proper auralization. The BLDERT of 5–6 dB obtained in the present study using headphones could be regarded as a maximum for the binaural gain. What remains to be known is whether the BLDERT would be less using a loudspeaker setup in real space. Such an experiment would imply some difficulties. First, the position of the head must be controlled carefully, since 34 cm less distance would shorten RT by 1 ms because of the speed of sound. Second, monotic conditions, realized wearing earplugs, cannot be mixed in arbitrary random order but must be organized in blocks. Thus, it is more difficult to cancel training effects, and the participants clearly know which ear must be paid attention to. However, it does not seem impossible to control these difficulties, and it could be a promising approach to further investigate the concept of "binaural loudness constancy."

A number of researchers (Gigerenzer & Strube, 1983; Levelt, Riemersma, & Bunt, 1972; Schneider & Cohen, 1997) pursued an axiomatic-measurement approach to binaural loudness and emphasized necessary conditions for "binaural additivity." If comparisons include a monaural condition, which in turn contains the zero element, the concept of additivity is extended to that of summation. The results of all three experiments reported here are consistent with the necessary conditions for summation—particularly, RTs for diotic stimulation are shorter than RTs for monotic stimulation at the same level. Under the assumption that loudness grows as the 0.6 power of sound pressure, perfect binaural loudness summation would result in a BLDERT of 10 dB, since this is the level difference required to double loudness according to Stevens's law. Since the effect of the combined (binaural) stimulus is smaller than the sum of the two single (monaural) stimuli would suggest, the present experiments imply that binaural loudness is subadditive.

It is important to consider the hand used to respond, since there appears to be an ipsilateral advantage. However, this was controlled and balanced. The effect is mainly based on the interaction between ear of stimulation and the responding hand and is not of an auditory nature. Furthermore, there is no significant main effect of the responding hand. Thus, it seems viable to just use the dominant hand and average across the two monaural conditions to obtain the BLDERT.

In conclusion, the binaural gain, as measured via RT, is quite consistent with recent models of binaural summation (see Moore & Glasberg, 2007; Sivonen & Ellermeier, 2006, 2008) for both diotic and dichotic sounds—most notably, the model by Moore and Glasberg, which predicts a 6-dB binaural gain.

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