Dependence of binaural gain for infrasound on interaural phase difference

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ABSTRACT:
Increasing complaints about infrasound have generated interest in understanding its perception, including binaural effects. This study investigated the level difference between monaural and binaural presentation required for detection and equal loudness (binaural gain) for pure tones with frequencies of 8, 32, and 400 Hz and an 8 Hz sinusoidally amplitude-modulated tone with diotic 400 Hz carrier. Monaural stimuli were compared to binaural stimuli with interaural phase differences (IPDs) of 0°, 90°, and 180° in two experiments: absolute threshold measurements and loudness matching at 40 phons. The latter was repeated with transposed tones (400 Hz carrier multiplied by a half-wave-rectified 8 Hz sinusoid). When expressed as differences in sound pressure level, similar binaural gain was found across all stimulus types under the diotic condition. Confirming previous studies, the gain was larger at supra-threshold levels (40 phons) than at threshold. However, when the loudness-matching results were expressed as binaural gain with respect to the loudness level, they became 17.5, 11.2, and 5.8 phons for the 8, 32, and 400 Hz stimuli, respectively. Results for the 8 Hz pure tone and the transposed stimulus were IPD dependent. © 2022 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1121/10.0012220
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I. INTRODUCTION

In recent years, low-frequency noise has become an important environmental factor due to its potential effect on the quality of life (e.g., Alves et al., 2020; Salt and Lichtenhan, 2014; Clark and Paunovic, 2018). Appropriate actions against noise require knowledge of its perception mechanism, which is, however, not fully understood for infrasound (IS) [frequencies below 20 Hz according to Möller and Pedersen (2004)]. Various studies provide evidence that IS stimulates the auditory system with detectable activity in the auditory cortex (Kühler, 2015b; Behler and Uppenkamp, 2020), although different perception mechanisms are proposed (Koch, 2017). In contrast to sounds in the frequency region well above 20 Hz, IS typically manifests in a rather atonal auditory sensation but is sometimes also reported as sensation of pressure at the eardrums. Further information concerning the perception of IS was provided, e.g., by Möller and Pedersen (2004) and Jurado et al. (2021a,b).

As IS is usually perceived with both ears, it is important to consider the effect of binaural loudness summation. This effect describes the phenomenon that sounds heard with both ears are perceived as being louder than when heard with only one ear. Consequently, at equal loudness, the sound pressure of a binaurally presented sound is usually less than that of the same sound presented monaurally (Whilby et al., 2006; Moore and Glasberg, 2007). Also, the absolute threshold of a binaurally presented sound is usually lower than that of the same sound presented monaurally (e.g., Anderson and Whittle, 1971). We call these sound pressure differences the binaural gain, which was measured in this study for 8, 32, and 400 Hz pure tones and 8 Hz modulated tones under various interaural phase difference (IPD) conditions.

For sounds with frequencies above 100 Hz, binaural gain strongly depends on level. For example, Whilby et al. (2006) found binaural gains between 4 and 8 dB for 1 kHz tones, with the lowest gain close to absolute threshold and the maximum value between 40 dB sensation level (SL) and 60 dB SL. Similarly, the binaural loudness model of Moore and Glasberg (2007), which is based on assimilated data in the literature, predicts a binaural gain below 1 dB at the absolute threshold, rising to 5.3 dB for a loudness level of 40 phons and reaching the highest values of about 6 dB for loudness levels of 60–70 phons.

Only one data set exists for IS; this data set indicates a binaural gain at absolute threshold of approximately 3 dB, which is comparable to the binaural gain for higher frequencies (Yeowart and Evans, 1974). The binaural gain for the IS-frequency range at supra-threshold levels is unknown. Given the very small dynamic range of human hearing at very low frequencies [as reviewed by Möller and Pedersen (2004)], binaural loudness summation may have a significant impact on IS perception. In addition, some published threshold or loudness measurements for IS were obtained

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monaurally via sealed ear-canal sound systems (e.g., Yeowart and Evans, 1974; Kühler et al., 2015a, b; Behler and Uppenkamp, 2020; Jurado et al., 2020), while others were obtained binaurally in a pressure chamber [e.g., Möller and Pedersen, 2004 (review); Suzuki and Takeshima, 2004 (review); Jurado and Marquardt, 2016]. Knowledge about binaural gain in the IS range would facilitate comparison of these data.

Due to the extremely long wavelength when listening to IS, IPDs are negligible under real-world conditions when listening to IS. Nevertheless, IPD dependence is of interest to understand how the synchrony of the phase-locked neural discharges from the left and the right ear influences loudness. This also provides potential insight into the influence of the strongly synchronized neural activity on loudness that occurs in response to IS within a single auditory nerve. Previous research for sounds with frequencies above 100 Hz showed significant effects of IPD on the binaural gain at absolute threshold (Diercks and Jeffress, 1962; Lakey, 1976; Bernstein and Trahiotis, 2008), while smaller or no effects of IPD on binaural gain were found at supra-threshold levels, depending on the frequency and level of the stimulus (Koehl and Paquier, 2015; Berthomieu et al., 2017; Moore et al., 2018). Due to the long periodicity of IS tones, the highly synchronous cycle-by-cycle pressure pulses would be perceptually resolved as separate events (Jurado et al., 2021b). We hypothesize, therefore, that the height of the maxima, produced by each of the pressure pulses in the neural activity pattern after convergence of the activity from the two ears in the brain, determines the binaural loudness of IS. These maxima would be higher for diotic than for dichotic stimulation, thus, leading to lower thresholds and louder sensation. Utilizing separate sound sources, our stimuli were delivered via sealed tubes to the ear canals, so that the synchrony between the phase-locked neural discharges in the left and the right auditory nerve could easily be manipulated by varying the IPD.

Absolute threshold measurements (experiment 1) and loudness-matching experiments at 40 phons (experiment 2) were performed with pure tones with frequencies of 8, 32, and 400 Hz. To investigate the role of long stimulus periodicity, an 8 Hz sinusoidally amplitude-modulated (SAM) tone with a diotic 400 Hz carrier was also employed. After obtaining unexpected results for the SAM stimulus, the loudness-matching experiment was repeated in a supplementary measurement, using a transposed stimulus, which was proposed by van de Par and Kohlrausch (1997), to elicit a phase-locked discharge pattern in high-frequency auditory nerve fibers that resembles the response to a low-frequency tone in a fiber that is tuned to its frequency (see experiment 3 for details).

II. GENERAL METHODS
A. Stimuli

Four stimuli were used: pure tones with frequencies of 8, 32, and 400 Hz and a SAM stimulus with a carrier frequency of 400 Hz, a modulation frequency of 8 Hz, and a modulation depth of 100% (referred to as SAM\text{8Hz} in the following). The 32 Hz stimulus was selected because, even though it does not have a corresponding best frequency on the basilar membrane, it is not considered IS (Jurado and Moore, 2010). The SAM\text{8Hz} stimulus was chosen to investigate whether the long stimulus periodicity per se was responsible for any potential differences observed in binaural gain for the 8 and 32 Hz tones. Each of these stimulus types was presented under six conditions: monaurally to the left or right ear (referred to as L and R) and binaurally with IPDs of 0°, –90°, 180°, or +90° (referred to as B 0°, B –90°, B 180°, and B +90°, respectively). For the SAM\text{8Hz} stimulus, the IPD was applied only to the envelope (i.e., the carrier tone always had zero IPD). The stimulus duration was 1250 ms, including 375 ms cosine ramps at the stimulus onset and offset.

B. Sound system

The sound delivery system for each ear was identical and based on the low-distortion sound reproduction system, developed by Joost et al. (2021). A DD45 earphone transducer (RadioEar, Middelfart, Denmark) was mounted in an air-sealed aluminum housing developed in-house and connected via a polyethylene tube (length 30 cm, inner diameter 1.95 mm) to one of the two sound delivery channels of an ER-10B+ in-ear probe microphone (Etymotic Research Inc., Elk Grove Village, IL). A small amount of sound-absorbing material (synthetic fibers) was inserted at both ends of the tube to flatten the frequency response of the system. The second sound delivery channel of the ER-10B+ earpiece was blocked at the ear-canal end using material from an ER10-14 foam eartip. Stimuli were presented and microphone signals recorded by means of a Fireface UC audio interface (RME, Haimhausen, Germany; 24 bit, 48 kHz). Sound levels corresponding to loudness levels above 80 phons (ISO 226, 2003; Möller and Pedersen, 2004) were prevented by the limited maximum output voltage of the audio interface, taking into account the headphone amplifier gain and the transducer sensitivity, in combination with a low-pass filter (passive, second order, f\text{c} ≈ 30 Hz) between the headphone amplifier (custom-made) and the DD45 transducer. Despite the 12 dB/octave low-pass filter, the presentation of the 400 Hz, which had a much lower sound pressure level (SPL) (less than 50 dB SPL) than the IS stimuli, was possible with the same sound delivery system.

C. Calibration

Particularly for low frequencies, the sound level in the occluded ear canal varied across subjects or even within the same subject across different insertions, critically depending on the seal achieved by the eartip. To correct for individual differences, an \textit{in situ} calibration using the calibrated ER-10B+ microphones was performed for each sound system after placing the system in the ear canal. This procedure was
peated at regular intervals during the measurements and before removing the system. Adjustment of the electrical signal ensured the correct SPL and phase of the signal in the individual ear canal. The ER-10B+ microphone was calibrated by means of a B&K 4157 occluded ear simulator (Brüel & Kjær, Nærum, Denmark) via the DB-2012 adapter.

D. Subjects

The same 16 otologically normal subjects participated in experiments 1 and 2 (3 female, 13 male; aged 17–29 years; average 21 years). Only eight (new) subjects (two female, six male; aged 22–43 years, average 26 years) participated in experiment 3 due to limited resources and restricted access to the previous subjects. Normal hearing was confirmed via standard pure-tone audiometry [125 Hz to 8 kHz, maximum hearing threshold of 15 dB hearing level (HL)] and tympanometric peak pressure within ±50 daPa. The 8 Hz data set for one subject had to be excluded from the analysis because very high thresholds resulted in levels that exceeded the ethical limit of 80 phons [based on Möller and Pedersen (2004)]. The study was approved by the local ethics committee (approval PTB2020-2).

III. EXPERIMENTS

A. Experiment 1: Absolute thresholds

1. Procedure

Absolute thresholds were measured using a two-alternative forced-choice (2-AFC) paradigm with a 1-up-3-down tracking procedure. Each trial consisted of two observation intervals, separated by 100 ms. The subject indicated which of the two intervals they thought contained the stimulus by pressing either “1” or “2” on a numerical keyboard. The next trial was started after the “Enter” key was pressed.

The starting values were at 25, 82, and 117 dB SPL for the 400 Hz (and SAMstim stimulus), 32 Hz, and 8 Hz pure tones, respectively. At these levels, all subjects confirmed that they clearly perceived the stimulus. The measurements started with a fast descent with a 1-down rule and 3 dB steps until the first incorrect response occurred, which led to a 3 dB step-up. Subjects were instructed to press “0” when the stimulus became barely detectable, indicating their individual threshold was close. Then a 1-up-3-down rule was applied with 2 dB steps. After another two reversals, the step size was reduced to 1 dB, and six more reversals were obtained. The threshold was calculated as the average level at these six reversals. Feedback was provided.

The measurements were performed in the following order: L, R, B 0°, B 180°, B −90°, B +90°. To measure the binaural gain under normal listening conditions, the same stimulus level was used for the two ears during the subsequent binaural threshold measurements. The measurements for the six conditions required approximately 45 min. Each stimulus type was used in a separate session, in which subjects had the opportunity to familiarize themselves with the particular stimulus type and the tracking procedure before the actual measurements began. The order of the stimulus types was randomized.

2. Results and discussion of absolute thresholds

The L and R monaural thresholds differed by 1.4, 1.3, and 2.3 dB for the 400 Hz, SAMstim, and 8 Hz stimuli, respectively (median values of the individual absolute differences, [L-R]). For the 32 Hz stimulus, however, the median difference was 6.2 dB. As we could not identify an underlying problem in the experimental setup, we suspect that differences in the resonances in the L and R middle-eartransfer functions near 32 Hz (see Jurado and Marquardt, 2016) might have affected the thresholds at 32 Hz in very different ways. We therefore excluded the 32 Hz threshold data from the analysis.

The L and R monaural thresholds were averaged for each subject, resulting in the following median monaural thresholds: 4.8 dB SPL [interquartile range (IQR) 5.3 dB] for the 400 Hz stimulus, 5.7 dB SPL (IQR 4.3 dB) for the SAMstim stimulus, and 105.7 dB SPL (IQR 4.1 dB) for the 8 Hz stimulus. The monaural thresholds at 400 Hz are somewhat lower than those determined previously for the Etymotic ER-3A insert earphone (13 dB SPL; ISO 389-2, 1994). At 8 Hz, our threshold is in excellent agreement with the monaural threshold of 104.7 dB SPL determined by Yeowart and Evans (1974) by means of the method of limits, while a lower value around 102 dB SPL was obtained by Kühler et al. (2015a) by means of a two-alternative unforced-choice up-down adaptive staircase procedure (Kaernbach, 2001).

We define the reduction of the binaural threshold relative to the monaural threshold for the better ear of each subject as the binaural gain, which is a conservative estimate compared to the difference between binaural thresholds and the average of L and R thresholds (in this case, the binaural gains would be 0.7 dB higher, on average). The binaural gains are shown in Fig. 1. B 90° represents the thresholds for B −90° and B +90°, averaged for each subject. For B 0°, the binaural gain of 2.2 dB at 400 Hz agrees well with the 2.5 dB obtained by Anderson and Whittle (1971), while the 3.8 dB at 8 Hz is consistent with the results of Yeowart and Evans (1974), who obtained 3.2–4.0 dB, depending on method.

An analysis of variance for repeated measures (r-ANOVA) with factors presentation condition (i.e., better monaural threshold, B 0°, B 90°, B 180°) and stimulus type showed a significant effect of presentation condition [F(3, 42) = 21.4, p < 0.001]. There was no significant effect of stimulus type [F(2, 28) = 0.7, p = 0.50] but a significant interaction [F(6, 84) = 2.5, p = 0.027]. Post hoc Tukey tests showed significant binaural gains of between 1.3 and 3.8 dB for all conditions (median values; p < 0.05, indicated by the asterisks at the top of Fig. 1; see also Table I).

To test the hypothesis that the IPD has no influence on the binaural threshold, another r-ANOVA was conducted only on the thresholds for binaural presentation (i.e., B 0°, B 90°, B 180°). There were no effects of both the stimulus
type \( F(2, 28) = 0.7, p = 0.50 \) and the presentation condition (IPD) \( F(2, 28) = 2.9, p = 0.073 \). However, the interaction was significant \( F(4, 56) = 3.6, p = 0.010 \). Post hoc Tukey tests revealed a dependence on presentation condition only for the 8 Hz stimulus. B 180°/C14 yielded 2.5 dB lower binaural gain than B 0°/C14 \((p < 0.001)\) and 1.2 dB lower gain than B 90° \((p = 0.033)\), as indicated at the bottom of Fig. 1.

### B. Experiment 2: Binaural loudness matching

#### 1. Procedure

Data for the four stimulus types were obtained in separate sessions of approximately 70 min each. The order of the stimulus types was randomized.

Loudness matching was performed for ten stimulus pairs, as listed in Table III. The L/R match (#1) was done first, and matches with binaural stimuli (#2–#10) were subsequently presented interleaved on a trial-by-trial basis in randomized order. The initial L/R match was used for training purposes as well as to adjust the R level so that loudness was equal for the two ears during the subsequent loudness matches involving binaural stimuli (#2–#10). The left and right stimulus levels, adjusted to equal loudness, differed by less than 1.3 dB (on average) for all stimulus types (including 32 Hz). Such compensation for across-ear differences was not done for the threshold measurements (experiment 1) but was used here to maximize the binaural gain to allow possible IPD dependencies to become more apparent.

For presentation of the stimuli at supra-threshold levels, the increasing compression of the phon-to-SPL relationship toward lower frequencies was taken into account. The reference stimuli, L, were set at a level above the individual’s left monaural threshold from experiment 1 that corresponded to the level difference between the threshold curve and the corresponding points of the 40 phon equal-loudness-level contour at the stimulus’ frequency as defined in ISO 226 (2003) at 32 and 400 Hz (and SAM8Hz) and Møller and Pedersen (2004) at 8 Hz. The corresponding average levels in dB SL and dB SPL are given in Table II.

![FIG. 1. (Color online) Binaural gain at threshold for the different binaural conditions with respect to the better-ear monaural thresholds. The asterisks on top of the boxes indicate that the binaural gain of the corresponding presentation condition is significant. The brackets below the boxes indicate significant differences between the thresholds for the corresponding binaural conditions. The significance levels are indicated by ** for \( p < 0.01 \) and * for \( p < 0.05 \). Data are from 16 subjects (15 subjects for the 8 Hz stimulus). The boxes cover 50% of the measured values, while the lower and upper edges indicate the first and third quartiles, respectively. Median values are indicated by thick lines. Whiskers indicate minimum and maximum values that are less than 1.5 times the interquartile range outside the box. All other data points are considered outliers (circles).](https://doi.org/10.1121/10.0012220)

### TABLE I. Binaural gain (median values) at threshold and at supra-threshold levels (see experiments 2 and 3, as described in Secs. III B and III C, respectively).

| Stimulus Type | 400 Hz | SAM8Hz | 32 Hz | 8 Hz | 400 Hz | SAM8Hz | 8 Hz |
|---------------|--------|---------|-------|-----|--------|---------|-----|
| B 0°/dB       | 2.2    | 2.6     | 3     | 2.8 | 5.4    | 6.6     | 4.8 |
| B 90°/dB      | 1.7    | 2.1     | 2.5   | 2.5 | 5.9    | 6.4     | 6.2 |
| B 180°/dB     | 1.9    | 2.2     | 1.3   | 1.3 | 6.5    | 5.9     | 5.2 |

### TABLE II. Supra-threshold levels for the stimuli as used in experiment 2.

| Stimulus Type | 400 Hz | SAM8Hz | 32 Hz | 8 Hz |
|---------------|--------|---------|-------|-----|
| B 0°/dB       | 39     | 39      | 29    | 12  |
| B 90°/dB      | 59     | 44.7    | 93.9  | 115.6|
| B 180°/dB     | 6.5    | 3.9     | 7.2   | 4.9 |
In each trial, the reference and variable stimuli were randomly assigned to the two intervals, which were separated by 100 ms. The subject indicated which of the two stimuli seemed louder by pressing either “1” or “2” on a numerical keyboard. The next trial was started by pressing “Enter.” The level of the variable stimulus was adjusted based on the subject’s answer to the previous trials and was randomly chosen at either the 80% point or the 20% point of the currently most likely PMF [for reasons and further details, see Jurado et al. (2020)]. The track was terminated after 16 trials, and the 50% value of the psychometric function was taken as the LDEL for that stimulus pair. Runs resulting in PMF slopes of less than 15%/dB were ignored and repeated until the PMF slope met this condition.

2. Results and discussion for loudness matching

These experiments were designed with some redundancy to allow the data consistency to be investigated. The first redundancy was that each binaural condition was matched to L and R separately (i.e., the following matches were paired: #2 and #3, #4 and #5, #6 and #7, #8 and #9; see Table III). A direct LDEL comparison of each match pair showed no significant differences (less than 1.0 dB on average; confirmed by Tukey tests), and the matches for L and R were therefore averaged for each subject.

The second redundancy was the inclusion of B 0° and B 180°. An r-ANOVA of the binaural gains for B 0° and B 180° was conducted to investigate IPD dependence. There were significant effects of presentation condition \( F(2,28) = 8.9, p < 0.001 \) and stimulus type \( F(3,42) = 18.3, p < 0.001 \) and their interaction \( F(6,84) = 5.5, p < 0.001 \). Post hoc Tukey tests revealed highly significant \((p < 0.01)\) differences only among the three IPDs at 8 Hz; these differences are indicated in Fig. 3 by the green brackets at the bottom. In contrast, there was no significant effect of IPD for the 400 Hz, SAM8 Hz, and 32 Hz stimuli.

The significant variation in the binaural gains with IPD only at 8 Hz was supported by the binaural loudness match

| Match no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-----------|---|---|---|---|---|---|---|---|---|----|
| Reference stimulus | L | L | R | L | R | L | R | L | R | B 0° |
| Variable stimulus | R | B 0° | B 0° | B 180° | B 180° | B −90° | B −90° | B +90° | B +90° | B 180° |

FIG. 2. (Color online) Binaural gain determined from the LDEL between monaural and binaural presentations for the various stimulus types (the following matches were combined: B 0° #2 and #3; B 90° #6–#9; B 180° #4 and #5). The asterisks on top of the boxes indicate that the corresponding binaural condition required a significantly lower SPL than for the monaural condition to be perceived as equally loud \((p < 0.01)\) in the post hoc analyses. The brackets below the boxes indicate significant differences in the LDELs between binaural conditions. Data are from 16 subjects (15 subjects for the 8 Hz stimulus).
Here, the median values by which the level at B 180°/C14 was adjusted to achieve loudness equal to B 0°/C14 were 1.1, 0.4, 1.4, and 2.1 dB for the 400 Hz, SAM8Hz, 32 Hz, and 8 Hz stimuli, respectively. Based on paired-sample t-tests, these values did not differ from the binaural gains found for loudness matches #2–#5.

The increase in the median values for the 400 Hz pure tone from IPD 0°/C14 to 180°/C14 by 1.1 dB was insignificant but in line with the results of Koehl and Paquier (2015). Their LDELs differed by about 1.4 dB (significant) for a frequency of 400 Hz presented at 40 phons and with 772 μs interaural time difference (corresponding to a 90° IPD) relative to diotic presentation. Moore et al. (2018) reported statistically significant negative LDELs of up to 1.5 dB for SAM tones with envelope IPDs of 0° with respect to envelope IPDs of 90° and 180°, where both of the latter were perceived as louder than the diotic stimuli. Their results were obtained with a carrier frequency of 1 kHz, a modulation frequency of around 8 Hz, a modulation depth of 100%, and at levels of 30 and 70 dB SPL. In our study, no significant loudness increase was found with the SAM stimulus, either for matches #2–#5 with a monaural reference or in the direct comparison between B 0° and B 180° (match #10).

The loudness of the transposed stimulus was expected to depend on IPD, as the resulting neural response should be closer to that produced by an 8 Hz pure tone than that from the SAM8Hz stimulus (Dreyer and Delgutte, 2006).

1. Procedure

The supplementary experiment only included loudness matching of stimulus pairs as listed in Table III, with procedures identical to those used in experiment 2. The L/R match (#1) was used to achieve equal loudness at the two ears for the remaining nine matches. Absolute thresholds were not measured. As, to our knowledge, no equal-loudness-level contours for transposed stimuli exist, one of the authors roughly adjusted the level of the TP8Hz stimulus under the L condition to give the same loudness as for an SAM8Hz stimulus under the L condition at a level of 44.7 dB SPL (average level used for a SAM8Hz stimulus in experiment 2). This led to a level of about 57 dB SPL, which was subsequently used for all subjects, who were not identical to those who participated in experiments 1 and 2. These measurements were performed in one session of approximately 45 min.

2. Results and discussion

The binaural gains for the transposed tones are shown in Fig. 3. The IPD dependence was indeed similar to that observed for the 8 Hz pure-tone stimulus. For both stimuli, the binaural gain (median values) with 180° IPD was only about half of that with 0° IPD. The results are also listed in Table I.

A one-factor r-ANOVA (using the results of the averaged binaural conditions with L and R references) showed a significant effect of the presentation condition \(F(2.0, 104.3) = 52.3, p < 0.001\). According to post hoc Tukey tests, the difference between the binaural conditions B 0° and B 90° was not significant. B 180° was significantly different from B 0° \((p = 0.003)\) and B 90° \((p < 0.001)\).
Note that the stimulus levels here were approximately 12 dB higher than in experiment 2, and this might have contributed to the somewhat larger binaural gain compared to the other stimulus types. It is, however, unlikely that at 12 dB higher levels, the $SAM_{B180}$ stimulus would also have become IPD dependent because IPD dependence for SAM stimuli was previously shown to be similar at levels of 30 and 70 dB SPL (Moore et al., 2018) or even to reduce for 100 and 200 Hz pure tones at higher loudness levels (Berthomieu et al., 2017).

IV. GENERAL DISCUSSION

Comparison of our measurements at threshold (experiment 1) and at a loudness level of 40 phons (experiment 2) confirms previous findings that binaural gain increases with stimulus level over this range. This increase may be smaller for the 8 Hz stimulus (1.0 dB, on average) than for the 400 Hz and $SAM_{B180}$ stimuli (4.0 dB, on average). Because the level of R was adjusted to provide the same loudness as L in experiment 2, but no adjustment was done in experiment 1, we cannot support statistically this level-dependent binaural gain increase.

We reported our loudness-matching results in Sec. III as binaural gain, the difference in level at equal loudness for monaural and binaural presentation. However, such LDELs do not directly reflect loudness differences in the low-frequency range, where loudness level grows steeply as the SPL increases, especially in the IS range. This can be seen from the increasing density of equal-loudness-level contours toward low frequencies in ISO 226 (2003) and in Möller and Pedersen (2004) for IS [see also Kübler et al. (2015b) and Behler and Uppenkamp (2020) for direct measurement]. To consider loudness, we converted the binaural gains (decibel units) for pure tones from experiment 2 to binaural loudness-level gains (phon units) by linear interpolation of the equal-loudness-level contours (Table IV). An interesting finding is that the binaural loudness-level gain for an IPD of 180° was similar for all three frequencies. In contrast, for an IPD of 0°, the binaural loudness-level gain increased considerably with decreasing frequency, so that for 8 Hz tones, the binaural gain of 4.8 dB was equivalent to an astonishing binaural loudness-level gain of 17.5 phons. The fact that a doubling in loudness of a 1 kHz pure tone corresponds to a loudness-level difference of 10 phons (Stevens, 1956) implies for the 8 Hz tone that the loudness almost doubles as IPD changes from 180° to 0° (i.e., a difference of 8.8 phons).

The first two experiments confirmed previous data showing that binaural gain is almost unaffected by IPD with the exception of the 8 Hz pure tone. However, a significant effect of IPD on binaural gain was found for IS at threshold as well as at 40 phons. The finding of experiment 3 (i.e., that IPD affects the loudness of the $TP_{B180}$ stimulus) shows, however, that spectral location is not the determining factor.

Because the detection of sounds in quiet is limited by internal noise (Diercks and Jeffress, 1962), the IPD dependence of absolute thresholds of pure tones is linked to the masking level difference (MLD) that is observed when the IPD of the stimulus changes from 0° to 180°. The results of previous studies, however, conflict with respect to the IPD dependence: Diercks and Jeffress (1962) found a lower absolute threshold with 180° IPD than with 0° IPD for 250 Hz tones. In contrast, Lakey (1976) and Bernstein and Trahiotis (2008), found the opposite for 500 Hz tones. Lakey (1976) argued that the results of Diercks and Jeffress (1962) can be explained by interaurally correlated internal noise sources like heartbeat and breathing that give, together with internal noise arising from interaurally independent sources (e.g., neural noise in the auditory nerve), a slightly positive correlation between the ears. Their own conflicting results from Bernstein and Trahiotis (2008) were explained by a frequency dependence of the interaural correlation, which might be even negative at 500 Hz (Bernstein and Trahiotis, 2008). The frequency-dependent IPD effects are based on the fact that physiological noise decreases by about 20 dB between 250 and 500 Hz (Watson et al., 1972) so that the internal noise is completely interaurally uncorrelated at 500 Hz [or even slightly negatively interaurally correlated as suggested by Bernstein and Trahiotis (2008)]. Our observation of no IPD dependence at 400 Hz is in agreement with this hypothesis. However, it does not hold for our results at 8 Hz because, due to the large wavelength, any internal noise (and non-intended external noise) would surely arrive with near zero IPD at both ears. For supra-threshold presentation of stimuli above 100 Hz, the MLD seems to become smaller: Zwicker and Henning (1991) compared the loudness of tones with 0° and 180° IPD in masking noise at various signal-to-noise ratios (SNRs) and showed that IPD effects disappeared above 30–40 dB SNR. Berthomieu et al. (2017) later confirmed their results, and we, also, did not observe a significant IPD dependence at 32 and 400 Hz. Since the IPD dependence at 8 Hz did not get weaker with increasing level, we believe that internal noise does not explain our findings. Instead, we propose an explanation in terms of binaural loudness summation.

The fact that we observed IPD dependence only with very long stimulus periodicity leads us to conclude that binaurally summed peak activity after convolution with the temporal loudness integration window is a simplified but useful predictor of loudness. Loudness integration is a complex process (Moore et al., 2018), but for a descriptive explanation of our results, it may be sufficient to consider a simple rectangular loudness integration window with an effective duration of about 100 ms (Florentine, 2011; Jurado et al., 2020), providing a low-pass filter with a corner frequency of about 10 Hz. This would mean that the still tightly
phase-locked neural activity in the brainstem to the 32 and 400 Hz tones became temporally “smeared,” and no pronounced activity maxima exist at the level of the cortex for any IPD.

Although the SAM_{8Hz} stimulus had the same period as the 8 Hz pure tone, we believe that, in contrast to the 8 Hz pure tone and the transposed stimulus, the modulation in neural activation in response to the SAM stimulus was too weak for the IPD to have an effect (van de Par and Kohlrausch, 1997; Bernstein and Trahiotis, 2002; Griffin et al., 2005; Dreyer and Delgutte, 2006).

The highly synchronized activity across the entire auditory nerve arises from the in-phase motion of the entire basilar membrane, since such low-frequency tones do not have a characteristic place on the basilar membrane (Zwicker, 1977; Jurado et al., 2022). For our conjecture, this synchrony is a precondition for the binaural gain increase at 0° IPD. We also propose that it facilitates detectability and increases loudness of IS under monaural listening conditions.

V. CONCLUSIONS

Binaural gains, expressed as sound pressure level difference, are similar across all stimulus types but were larger at 40 phons than at threshold. When expressed in phons, however, the binaural loudness-level gain was substantially larger at 8 Hz than for higher frequency tones. This must be considered when evaluating the impact of noise containing IS components.

Due to the long wavelength of IS, real-world listening conditions are very close to diotic. To shed light on the role of synchrony in neural activity on loudness, we investigated the IPD dependence of binaural gains. IPD dependence was observed only for 8 Hz tones and TP_{8Hz} stimuli, indicating that, for such long stimulus periodicities, the synchronous arrival of the strong onset activity with each stimulus cycle from the two auditory nerves can increase the loudness by almost 10 phons. Thus, loudness of IS is presumably based on synchronized neural activity peaks that still persist at the cortical level for stimulation below 20 Hz. Since the strongly synchronized neural activity in the gross-potential of each auditory nerve itself is a requirement for the observed binaural loudness level increase, it likely contributes to the loudness of monaural IS stimulation as well.

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1It was discovered only after the completion of the entire data set that the randomization option in the software had been switched off by accident.

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If you have any questions or need further assistance, feel free to ask! 😊
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