JASA ARTICLE

Dependence of binaural gain for infrasound on interaural phase difference

Marion U. Bug,[1,a)] Melina Strüp,[1] and Torsten Marquardt[2]
[1] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[2] *UCL Ear Institute, University College London, 332 Gray's Inn Road, London, United Kingdom*

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

(Received 17 March 2022; revised 14 June 2022; accepted 15 June 2022; published online 5 July 2022)

[Editor: Leslie R. Bernstein] Pages: 163–171

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 Møller 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 Møller 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 Møller 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

---

[a)] Electronic mail: marion.bug@ptb.de

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., Møller 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, 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 $\mathrm{SAM}_{8\mathrm{Hz}}$ 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 $\mathrm{SAM}_{8\mathrm{Hz}}$ 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 $\mathrm{SAM}_{8\mathrm{Hz}}$ 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; Møller 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, $f_c \approx 30$ 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 *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 repeated 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 Møller 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 $\text{SAM}_{8\text{Hz}}$ 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:[1] 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, $\text{SAM}_{8\text{Hz}}$, 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-ear-transfer 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 $\text{SAM}_{8\text{H}}$ 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

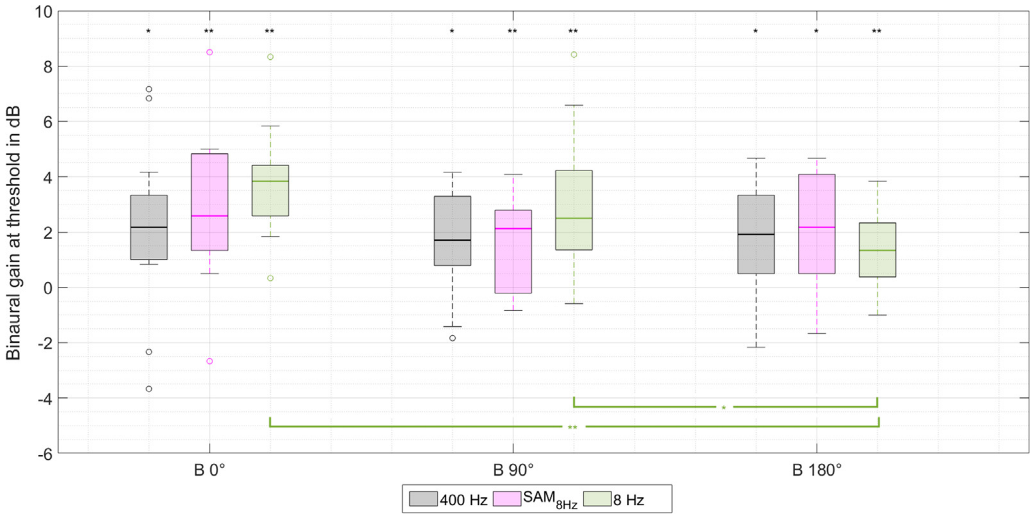

FIG. 1. (Color online) Binaural gain at threshold for the different binaural conditions with respect to the better-ear monaural thresholds. The asterisks on top of the boxes indicate that the binaural gain of the corresponding presentation condition is significant. The brackets below the boxes indicate 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).

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° yielded 2.5 dB lower binaural gain than B 0° ($p < 0.001$) 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 SAM$_{8Hz}$) and Møller and Pedersen (2004) at 8 Hz. The corresponding average levels in dB SL and dB SPL are given in Table II.

A maximum-likelihood tracking procedure (MLT) [see, e.g., Green (1990)] was used in a 2-AFC paradigm to obtain the *level difference required for equal loudness* (LDEL). In this procedure, the subject's most likely psychometric function (PMF) was updated iteratively during the measurement.

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).

	400 Hz	SAM$_{8Hz}$	32 Hz	8 Hz	TP$_{8Hz}$
Experiment	1, 2	1, 2	2	1, 2	3
No. of subjects	16	16	16	15	8
Gain at threshold (expt. 1)					
B 0°/dB	2.2	2.6	—	3.8	—
B 90°/dB	1.7	2.1	—	2.5	—
B 180°/dB	1.9	2.2	—	1.3	—
Gain at supra-threshold (expts. 2 and 3)					
B 0°/dB	5.4	6.6	6.1	4.8	7.4
B 90°/dB	5.9	6.4	6.2	3.8	6.6
B 180°/dB	6.5	5.9	5.2	2.4	4.1

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

	400 Hz	SAM$_{8Hz}$	32 Hz	8 Hz
In dB SL	39	39	29	12
Mean values in dB SPL	45.8	44.7	93.9	115.6
Standard deviation of dB SPL	3.9	3.8	7.2	4.9

TABLE III. Stimulus pairs in the loudness-matching procedure.

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°

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 −90° and B +90°. An r-ANOVA of the corresponding loudness matches (#6/#7 and #8/#9) showed no significant differences. Hence, these LDELs were also averaged for each subject and are referred to as B 90°.

The third redundancy was the direct comparison of B 0° and B 180° in loudness match #10. Corresponding results are discussed below.

Binaural gains of the individual matches, corresponding to LDEL values, were calculated by subtraction of the matched level of the given binaural stimulus from the level of the monaural reference stimulus. Median values are shown in Fig. 2 and listed in Table I. An r-ANOVA based on the LDEL values of matches #1–#9 showed highly significant effects of presentation condition $[F(3, 42) = 282.3, p < 0.001]$ and stimulus type $[F(3, 42) = 8.9, p < 0.001]$ and their interaction $[F(9,126) = 9.2, p < 0.001]$. *Post hoc* Tukey tests on matches #2–#9 showed that all binaural gains were significantly above zero ($p < 0.001$).

The binaural gains under the B 0° condition were similar across all stimulus types. An r-ANOVA of the binaural gains for B 0°, B 90°, 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, $\mathrm{SAM}_{8\mathrm{Hz}}$, and 32 Hz stimuli.

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

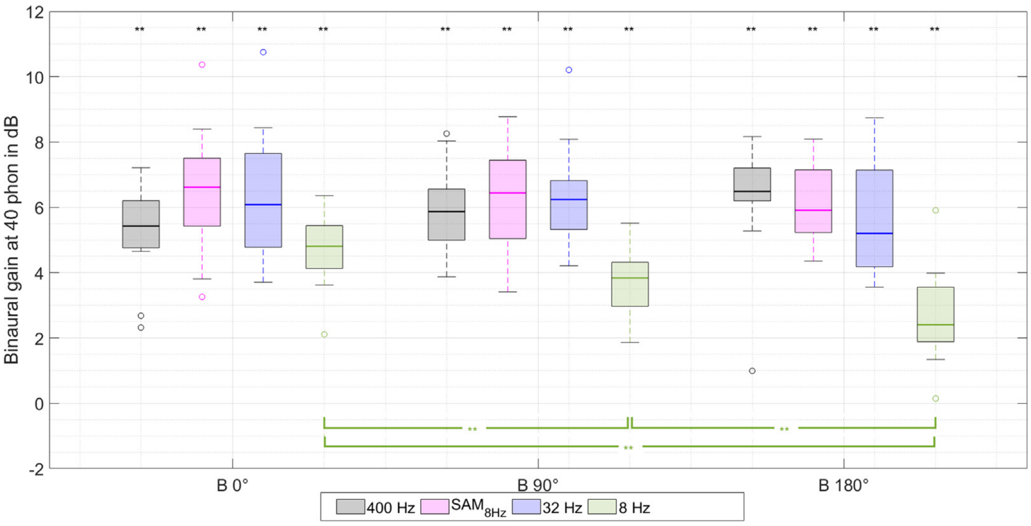

FIG. 2. (Color online) Binaural gain determined from the LDEL between monaural and binaural presentations for the various stimulus types (the following matches were combined: B 0° #2 and #3; B 90° #6–#9; B 180° #4 and #5). The asterisks on top of the boxes indicate that the corresponding binaural condition 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).

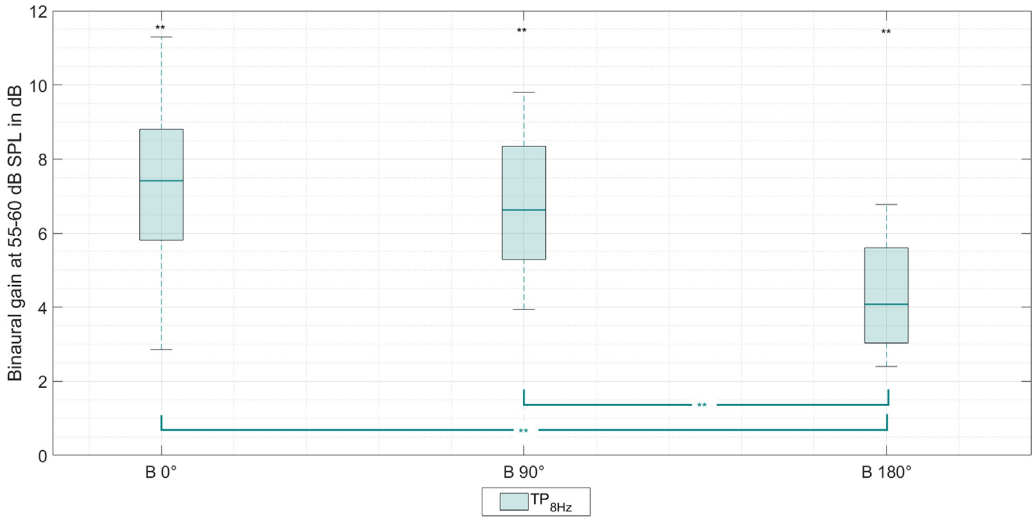

FIG. 3. (Color online) Same as Fig. 2, but with binaural gains for the TP_{8Hz} stimulus. Data are from eight subjects.

#10. Here, the median values by which the level at B 180° was adjusted to achieve loudness equal to B 0° were −1.1, −0.4, 1.4, and 2.1 dB for the 400 Hz, SAM_{8Hz}, 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° to 180° 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).

C. Experiment 3: Transposed tone

As our expectation that the effect of IPD would be similar for the 8 Hz pure tone and the SAM_{8Hz} stimulus was not met, we conducted a supplementary experiment using a transposed stimulus (referred to as TP_{8Hz} in the following), wherein a carrier tone (400 Hz) was multiplied by a half-wave-rectified modulator (8 Hz) (van de Par and Kohlrausch, 1997). Note that this stimulus has a wider spectrum than the SAM stimulus, with several sidebands around the 400 Hz carrier, spaced by the 8 Hz. As the amplitudes of the lower and upper sidebands decrease steeply (the amplitude of the fourth sidebands at 352 and 448 Hz reduced by 32 dB with respect to the amplitude of the carrier), no bandpass filtering was applied.

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 SAM_{8Hz} 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 TP_{8Hz} stimulus under the L condition to give the same loudness as for an SAM_{8Hz} stimulus under the L condition at a level of 44.7 dB SPL (average level used for a SAM_{8Hz} 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 $\mathrm{SAM}_{8\mathrm{Hz}}$ 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 $\mathrm{SAM}_{8\mathrm{Hz}}$ 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 Møller and Pedersen (2004) for IS [see also Kühler *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 $\mathrm{TP}_{8\mathrm{Hz}}$ stimulus) shows, however, that spectral location is not the determining factor.

TABLE IV. Binaural loudness-level gains in phons converted from the LDEL results from experiment 2.

	400 Hz	32 Hz	8 Hz
B 0°	5.8	11.2	17.5
B 90°	6.4	11.4	13.8
B 180°	7.0	9.5	8.7

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 $\mathrm{SAM}_{8\mathrm{Hz}}$ 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 $\mathrm{TP}_{8\mathrm{Hz}}$ 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.

ACKNOWLEDGMENTS

This study was supported by the European Metrology Programme for Innovation and Research (EMPIR, Grant No. 15HLT03 Ears II). EMPIR is jointly funded by EMPIR participating countries within EURAMET and the European Union. We thank Sven Vollbort for helping with the data collection. We are grateful to the editor, Dr. Leslie Bernstein, and the two reviewers for the many helpful comments that improved the clarity of our manuscript, especially to Dr. Brian Moore for his detailed suggestions.

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

Alves, J. A., Paiva, F. N., Silva, L. T., and Remoaldo, P. (**2020**). "Low-frequency noise and its main effect on human health—A review of the literature between 2016 and 2019," Appl. Sci. **10**, 5205.

Anderson, C. M. B., and Whittle, L. S. (**1971**). "Physiological noise and the missing 6 dB," Acoustica **24**, 261–272.

Behler, O., and Uppenkamp, S. (**2020**). "Activation in human auditory cortex in relation to the loudness and unpleasantness of low-frequency and infrasound stimuli," PLoS ONE **15**, e0229088.

Bernstein, L. R., and Trahiotis, C. (**2002**). "Enhancing sensitivity to interaural delays at high frequencies by using 'transposed stimuli,'" J. Acoust. Soc. Am. **112**, 1026–1036.

Bernstein, L. R., and Trahiotis, C. (**2008**). "Binaural signal detection, overall masking level, and masker interaural correlation: Revisiting the internal noise hypothesis," J. Acoust. Soc. Am. **124**, 3850–3860.

Berthomieu, G., Koehl, V., and Paquier, M. (**2017**). "Influence of interaural time differences on loudness for low-frequency pure tones at varying signal and noise levels," Proc. Mtgs. Acoust. **30**, 050004.

Clark, C., and Paunovic, K. (**2018**). "WHO environmental noise guidelines for the European region: A systematic review on environmental noise and quality of life, wellbeing and mental health," Int. J. Environ. Res. Public Health **15**, 2400.

Diercks, K. J., and Jeffress, L. A. (**1962**). "Interaural phase and the absolute threshold for tone," J. Acoust. Soc. Am. **34**, 981–984.

Dreyer, A., and Delgutte, B. (**2006**). "Phase locking of auditory-nerve fibers to the envelopes of high-frequency sounds: Implications for sound localization," J. Neurophysiol. **96**, 2327–2341.

Florentine, M. (**2011**). "Loudness," in *Loudness*, edited by M. Florentine, R. Fay, and A. Popper (Springer, New York), pp. 1–15.

Green, D. M. (**1990**). "Stimulus selection in adaptive psychophysical procedures," J. Acoust. Soc. Am. **87**, 2662–2674.

Griffin, S. J., Bernstein, L. R., Ingham, N. J., and McAlpine, D. (**2005**). "Neural sensitivity to interaural envelope delays in the inferior colliculus of the guinea pig," J. Neurophysiol. **93**, 3463–3478.

ISO 226 (**2003**). "Acoustics—Normal equal-loudness-level contours" (International Organization for Standardization, Geneva, Switzerland).

ISO 389-2 (**1994**). "Acoustics—Reference Zero for the calibration of audiometric equipment—Part 2: Reference equivalent threshold sound pressure levels for pure tones and insert earphones" (International Organization for Standardization, Geneva, Switzerland).

Joost, H., Friedrich, B., Verhey, J. L., and Fedtke, T. (**2021**). "Is infrasound perceived by the auditory system through distortions?," Acta Acust. **5**, 4.

Jurado, C., Chow, M. Y., Leung, K. M. L., Larrea, M., Vizuete, J., de Cheveigné, A., and Marquardt, T. (**2022**). "The spectral extent of phasic suppression of loudness and distortion-product otoacoustic emissions by infrasound and low-frequency tones," J. Assoc. Res. Otolaryngol. **23**, 167–181.

Jurado, C., Larrea, M., and Moore, B. C. J. (**2021a**). "The lower limit of pitch perception for pure tones and low-frequency complex sounds," Arch. Acoust. **46**, 459–469.

Jurado, C., Larrea, M., Patel, H., and Marquardt, T. (**2020**). "Dependency of threshold and loudness on sound duration at low and infrasonic frequencies," J. Acoust. Soc. Am. **148**, 1030–1038.

Jurado, C., Larrea, M., Rosero, D., Vizuete, J., and Marquardt, T. (**2021b**). "Critical repetition rates for perceptual segregation of time-varying auditory, visual and vibrotactile stimulation," Timing Time Percept. **10**, 122–141.

Jurado, C., and Marquardt, T. (**2016**). "The effect of the helicotrema on low-frequency loudness perception," J. Acoust. Soc. Am. **140**, 3799–3809.

Jurado, C., and Moore, B. C. J. (**2010**). "Frequency selectivity for frequencies below 100 Hz: Comparisons with mid-frequencies," J. Acoust. Soc. Am. **128**, 3585–3596.

Kaernbach, C. (**2001**). "Adaptive threshold estimation with unforced-choice tasks," Percept. Psychophys. **63**, 1377–1388.

Koch, C. (**2017**). "Hearing beyond the limit: Measurement, perception and impact of infrasound and ultrasonic noise," in *Proceedings of the 12th ICBEN Congress on Noise as a Public Health Problem*, June 18–22, Zurich, Switzerland.

Koehl, V., and Paquier, M. (**2015**). "Loudness of low-frequency pure tones lateralized by interaural time differences," J. Acoust. Soc. Am. **137**, 1040–1043.

Kühler, R., Fedtke, T., and Hensel, J. (**2015a**). "Infrasonic and low-frequency insert earphone hearing threshold," J. Acoust. Soc. Am. **137**, EL347–EL353.

Kühler, R., Hensel, J., Koch, C., Bauer, M., and Sander-Thömmes, T. (**2015b**). "Auditory cortex activation by infrasonic and low-frequency sound of equalized individual loudness," in *Proceedings of Euro Noise 2015*, May 31–June 3, Maastricht, Netherlands, pp. 2577–2582.

Lakey, J. R. (**1976**). "Temporal masking-level differences: The effect of mask duration," J. Acoust. Soc. Am. **59**, 1434–1442.

Møller, H., and Pedersen, C. S. (**2004**). "Hearing at low and infrasonic frequencies," Noise Health **6**, 37–57.

Moore, B. C. J., and Glasberg, B. R. (**2007**). "Modeling binaural loudness," J. Acoust. Soc. Am. **121**, 1604–1612.

Moore, B. C. J., Jervis, M., Harries, L., and Schlittenlacher, J. (**2018**). "Testing and refining a loudness model for time-varying sounds incorporating binaural inhibition," J. Acoust. Soc. Am. **143**, 1504–1513.

Salt, A. N., and Lichtenhan, J. T. (**2014**). "How does wind turbine noise affect people?," Acoust. Today **10**, 20–28.

Stevens, S. S. (**1956**). "The direct estimation of sensory magnitude: Loudness," Am. J. Psychol. **69**, 1–25.

Suzuki, Y., and Takeshima, H. (**2004**). "Equal-loudness-level contours for pure tones," J. Acoust. Soc. Am. **116**, 918–933.

van de Par, S., and Kohlrausch, A. (**1997**). "A new approach to comparing binaural masking level differences at low and high frequencies," J. Acoust. Soc. Am. **101**, 1671–1680.

Watson, C. S., Franks, J. R., and Hood, D. C. (**1972**). "Detection of tones in the absence of masking noise. I. Effects of signal intensity and signal frequency," J. Acoust. Soc. Am. **52**, 633–643.

Whilby, S., Florentine, M., Wagner, E., and Marozeau, J. (**2006**). "Monaural and binaural loudness of 5- and 200-ms tones in normal and impaired hearing," J. Acoust. Soc. Am. **119**, 3931–3939.

Yeowart, N. S., and Evans, M. J. (**1974**). "Thresholds of audibility for very low-frequency pure tones," J. Acoust. Soc. Am. **55**, 814–818.

Zwicker, E. (**1977**). "Masking-period patterns produced by very-low-frequency maskers and their possible relation to basilar-membrane displacement," J. Acoust. Soc. Am. **61**, 1031–1040.

Zwicker, E., and Henning, G. B. (**1991**). "On the effect of interaural phase differences on loudness," Hear. Res. **53**, 141–152.