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ON THE SPATIAL RESOLUTION OF VIRTUAL ACOUSTIC ENVIRONMENTS FOR HEAD MOVEMENTS IN HORIZONTAL, VERTICAL AND LATERAL DIRECTION

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ABSTRACT

Dynamic binaural synthesis based on binaural room impulse responses (BRIRs) for a discrete grid of head orientations can provide an auralization naturally responding to head movements in all rotational degrees of freedom. Several experiments have been conducted in order to determine thresholds of just detectable BRIR grid resolution for all three rotational directions of head movements using an adaptive 3-AFC procedure. Different audio stimuli as well as BRIR datasets measured in different acoustic environments were used. The results obtained reveal a high sensitivity of listeners towards discretization effects not only in horizontal, but also in vertical and lateral directions. Values indicate a minimum spatial resolution necessary for a plausible binaural simulation of acoustic environments.

1. INTRODUCTION

The simulation of acoustic environments by means of dynamic binaural synthesis based on measured BRIRs can provide a very high degree of realism [1]. An integral prerequisite for perceptual quality is the realistic interaction between the listener's head movements and the synthesized sound field. It is important whether the virtual acoustic environment (VAE) is able to track all rotational head movements (see Figure 1) and how fine angular movements can be resolved with respect to the underlying BRIR data set resolution.

At the same time, higher resolutions of BRIR data sets bring about longer measurement times for acquisition, as well as higher computational cost and memory size for auralization. Therefore, measured thresholds of just noticeable BRIR grid granularity are crucial in order to optimize the effort for measuring and auralizing binaural data without introducing perceptual artefacts.

The spatial resolution of the human auditory system has been operationalised with different measures. These include the localization blur, i.e. the mean error made when identifying the spatial position of a sound source, and the minimum audible angle (MAA), i.e. the minimum detectable displacement of a sound source. In anechoic environments, MAAs of 1° – 10° have been found, depending on frequency and direction of sound incidence [2]. However, none of these measures can directly be used to derive a necessary resolution of BRIR data sets as natural sound fields contain reflections from all directions of incidence and listeners are free in orientation and velocity of their head movements.

Today, most VAEs track horizontal and sometimes also vertical head movements. The provided spatial resolution is different between implementations (Table 1). Moreover, it is common to use HRTF or BRIR datasets with lower resolution interpolated to finer grid sizes [3][4][5][6].

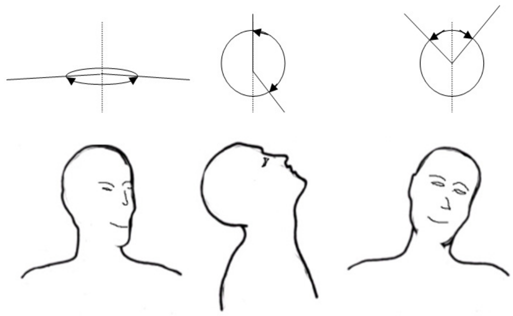

Figure 1: *Rotational degrees of freedom of head movements (from left to right): Horizontal, vertical and lateral rotation and typical movement ranges.*

Here, studies on the audibility of interpolations between HRTF data [7] showed that an original data set with 2° horizontal and vertical resolution could be inaudibly replaced by linear interpolations of a data set reduced to 2° – 36° resolution for static sources and 8° – 90° resolution for moving sound sources. Again, the values strongly depended on the direction of incidence. The (measured or interpolated) resolution required for a plausible auralization of acoustical environments has, however, never been investigated under realistic conditions, i.e. for natural source signals, for natural (non anechoic) environments, and for all rotational degrees of freedom of head movements.

Table 1 *Resolution and ranges of HRTF/BRIR data sets provided with some recent VAEs. (*missing full sphere elevation data generated by repetition, **original data range unknown, ***extrapolated from restricted original dataset)*

System	Resolution (hor./ vert.)	Range	Ref.
EASE 4	5-30° / 10°	hor. ±180°, ver: [-45°; 90°]*	[8][9]
ODEON 9	5° / 5.6°	hor. ±180°, ver: [-45°; 90°]*	[10][11]
Raven	1° / 5° (interp. to 1°/2°)	full sphere	[12][13]
IKA-SIM	15° / 10° (interp. to 5°)	full sphere	[3]
DIVA	10° / 15° (interpolated)	full sphere**	[14]
SLAB	10° / 10° (interpolated)	full sphere***	[15][16]
SSR	5° (interp. to 1°)	hor. ±180°	[4][17]
BRS	6° (interp. to 1°)	hor. ±43°	[5]

2. METHOD

2.1. BRIR data sets

At present only the Berlin HATS (head and torso simulator) FABIAN [1] provides a fast and automated measurement of binaural room impulse responses in all degrees of freedom of head movement. For the present investigation it has been used to acquire binaural impulse responses in three different acoustical environments, including

- an anechoic chamber,
- a recording studio, and
- two large lecture halls.

Therefore the HATS was seated in a specific distance from a sound source positioned for frontal sound incidence. In the anechoic chamber a distance providing acoustic far field condition was chosen. For the other measurements FABIAN was placed at around twice the critical distance, so that, taking into account the sources' directivity, a fairly balanced direct-diffuse field ratio could be expected. In all cases the same two-way active speaker (Meyersound UPL-1) was used as sound source. All datasets were measured with a spatial resolution of 1° for horizontal, vertical and lateral head movements (see Table 2). Horizontal and vertical movements were measured together, resulting in a two-dimensional BRIR grid (160° x 70°). For mechanical reasons, lateral head movements were measured separately while keeping a constant frontal viewing direction, so that here a 1-dimensional data set (120°) was retrieved.

Table 2 *Binaural datasets used in the study*

Site	**Volume**	**RT**	r_{crit}	**Dist.**	**Dataset ranges hor./ver./lat 1&2**
anechoic	1800 m³	>60Hz	-	3 m	±80°/±35°/±60°*
studio	235 m³	0.36 s	1.4 m	2.8 m	±80°/±35°/±60°*
hall 1	8600 m³	2.1 s	3.6 m	7.5 m	±80°/±35°/0°
hall 2	3000 m³	0.95 s	3.2 m	10 m	0°/0°/±60°*

* ±30° used for listening test in experiment II

The angular ranges for BRIR acquisition were chosen according to typical values observed for natural hearing [18] and physiologically motivated ‘comfort’ [19] and ‘maximum’ values [20].

Whereas a frontal sound source location was shown to be most critical for horizontal and vertical head movements (see [2]), high thresholds could be expected for lateral head movements due to the absence of ILD and ITD differences when moving the head in this direction. Hence, additional data sets were collected for lateral head movements and a sound source directly above the listener. These were measured using a different sound source (Genelec 8030) due to its reduced weight. Moreover, measurements were conducted a) with and b) without the HATS’s torso, in order to examine its influence in more detail (not shown here).

2.2. Stimuli

All thresholds were determined using two stimuli: a) pink noise of 5 seconds duration with 20 ms fade in and fade out, and b) a 5 seconds excerpt from a piece for acoustical guitar (bourrée by J. S. Bach). The latter one had proven to be particularly critical for revealing artefacts in acoustic simulations [1]. Additionally, it was meant to serve as a natural musical stimulus, containing harmonic passages as well as transient components. Pink noise, as also used in [3], [10], [12], [14], was in contrast regarded as being particularly critical for revealing spectral differences induced by a reduced HRTF/BRIR resolution. Due to a bandpass used as compensation target for the headphone's equalisation, all stimuli were bandlimited to 50 Hz – 20 kHz.

2.3. Auralization

A Linux software package for fast partitioned convolution was used to auralize the BRIR sets with a sampling rate of 44.1 kHz. The software uses two partition sizes for the block convolution algorithm: a smaller one for the initial part of the BRIRs and a larger one for the diffuse tail. When head movements of the listener are detected, the initial 2^{14} samples of the BRIR will updated accordingly. Changes in the later diffuse reverberation tail due to different head orientations or source positions were shown to be inaudible [1]. The partition size of the initial BRIR part was set to 256 samples. For the diffuse tail a block size of 8192 samples was chosen. Updating the BRIR is done via parallel spectral domain convolution and time-domain crossfading. In order to avoid switching artefacts a short linear crossfade of 5.8 ms duration (according to the smaller block size) was used. So, the first results of a filter exchange are available one audio block after recognizing a trigger event; the resulting latency of one audio block is already introduced by the underlying jack audio server architecture [www.jackaudio.org]. The time-domain cross fade results are then output blockwise and consecutively. The duration of a full crossfade is therefore as long as the dynamically interchanged early part of the BRIR. Hence, the direct sound is crossfaded with minimum latency, ensuring a minimum response time to head movements, while stretching out the fade process in time [21].

The crossfade time was chosen to avoid audible linear interpolation between adjacent BRIRs while still suppressing switching artefacts. Hence, our study is different from an evaluation of interpolation methods [6][7], as well as from recent studies on the audibility of *abrupt* changes in a) the interaural time delay [22] resp. b) the minimum phase HRTF spectra related to different directions of incidence [23][24][25]. Although these results provide valuable insight into the perception of fundamental localisation cues, the (rather artificial) separate variation of ITD and HRTF magnitude was avoided here with respect to the external validity of results for virtual acoustic environments.

The inaudibility of the crossfading between BRIRs was proven by a pre-test on crossfading white noise and sines between identical HRTFs. Since no switching was audible, it was concluded that all artefacts heard later should be due to differences in the BRIRs themselves.

A Polhemus Fastrack head tracker was used, providing an update rate of 120 Hz, i.e. new head positions every 8 – 9 ms. STAX SR202 Lambda headphones were used for reproduction. They were equalized with a linear phase inverse filter optimized by a least squares criterion [26] based on the magnitude average of 10 measurements carried out while repositioning the headphones on the dummy head after each measurement. A recent evaluation of different compensation methods for headphone equalization in binaural synthesis is given in [27].

As the 3AFC listening test design (see below) requires instantaneous switching between data sets with full and reduced resolution, the complete set of BRIRs was held in random access memory (ca. 22 GB in experiment I).

2.4. Subjects

The whole study was split into 3 successive experiments. In experiment I (horizontal and vertical head movements) 21 subjects (age 24 – 35, 19 male, 2 female) took part. 23 subjects (age 23 – 65, 20 male, 3 female) participated in experiment II (lateral head movements, frontal sound incidence), while experiment III (lateral head movements, vertical sound incidence) was conducted with 20 listeners (age 24 – 40, 18 male, 2 female). All subjects were experienced in listening tests; most had musical education.

2.5. Psychophysical Procedure

An adaptive three alternative forced choice (3AFC) test procedure was chosen [28]. Three stimuli were presented, including the reference situation with 1° resolution twice and a version with reduced grid resolution once in random order for each trial. After an initial training phase (including feedback), each run started with a test stimulus in the middle of the range of provided grid resolutions. The BRIR resolution was then adaptively changed according to the subject's responses using a maximum likelihood adaption rule ("Best-PEST" [29]). The resulting test durations ranged from 35 minutes (exp. II & III) to 1:30 hours (exp. I). Head movements were not restricted, even if no dynamical exchange of BRIRs was provided outside the indicated ranges (Table 2). During the training phase, subjects were asked to find individual movement strategies that would maximise their detection rate.

2.6. Angular Ranges

BRIR data sets were auralized using the full angular ranges measured (see Table 2). Only for lateral head movements and frontal sound incidence (exp. II) pretests showed, that for large lateral tilting angles (>35°) noticeable comb filter modulations arise when the ear approaches the shoulder (see also Figure 4 and Discussion). These modulations sometimes made even the 1° reference resolution detectable. Since this was not regarded to be a typical listening situation, auralization was limited to a range of ±30°.

Since in experiment I the threshold of just audible grid granularity was to be tested independently for horizontal and vertical grid resolution, the resolution was changed only for one direction. For the other direction the resolution was kept constant at maximum resolution (1°). The datasets used in experiments II & III contained only data for lateral head movements while retaining a frontal head orientation. Due to the 1° resolution of the BRIR sets, the smallest audible grid resolution threshold measurable with an adaptive forced choice procedure was 2°, a value that was reached only 3 times during the three experiments.

2.7. Experimental Design

In experiments I & II thresholds of just audible BRIR grid resolution were collected for horizontal, vertical and lateral head movements for frontal incidence of sound. Additional factors tested were stimulus (2) and rooms (3, including anechoic condition). Both experiments were conducted as full factorial, repeated measures designs, i.e. the thresholds of all subjects were measured under every possible condition. This lead to 3 x 2 x 2 x 21 = 252 threshold values in experiment I and to 2 x 3 x 23 = 138 values in experiment II.

Experiment III was conducted with sound incidence from above, since this was assumed to be most critical with respect to lateral head movements. It was also conducted according to a repeated measures design, but testing only one additional factor (stimulus = 2), thus 2 x 20 = 40 threshold values were obtained.

3. RESULTS

Figure 2 shows the results of all subjects from all tested conditions in experiments I and II for the noise (above) and the guitar stimulus (below). Since the thresholds were not always normally distributed (conservative Kolmogoroff-Smirnoff test, α error = 0.2) medians resp. percentiles were used to indicate central tendency and dispersion. Figure 3 shows the lateral threshold values from experiment III (sound incidence from above, only anechoic environment, labelled 'lateral 2') in comparison to the thresholds from experiments I & II under anechoic conditions.

Medians of just audible grid granularity ranged from 4° to 18°, depending on condition. Only three times grid resolutions <3° could be reliably detected by individual subjects: twice for anechoic environment, vertical head movement and noise stimulus (exp. I), and once for anechoic environment, lateral head movement and noise stimulus (exp. III). For the noise stimulus and all acoustical environments pooled, subjects were almost equally sensitive to a reduced grid resolution in horizontal and vertical direction (medians: 6° vs. 5°). For noise, all subjects could reliably detect grid granularities >11°, whereas these were much more difficult to detect with the guitar stimulus.

For frontal sound incidence and lateral head movements (exp. II), a reduced grid resolution was much more difficult to detect, and several subjects could not even distinguish the largest granularity from the smallest one, even in direct comparison (30° vs. 1°, see Figure 2).

A statistical analysis of the trends observable in Figure 2 was conducted by means of 3x2x2 (exp. I) resp. 3x2 (exp. II) one-way ANOVAs for repeated measures. Data assumptions (homogeneous error variances, homogeneous correlation under all conditions, [30]) were tested using Mauchly's test of sphericity. Degrees of freedom were corrected when indicated by the test. Reliability of response behaviour was very high for experiment I (horizontal and vertical head movements) with Cronbachs Alpha at 0.934. For lateral head movements (exp. II), Cronbachs Alpha was only 0.165, indicating large interindividual differences.

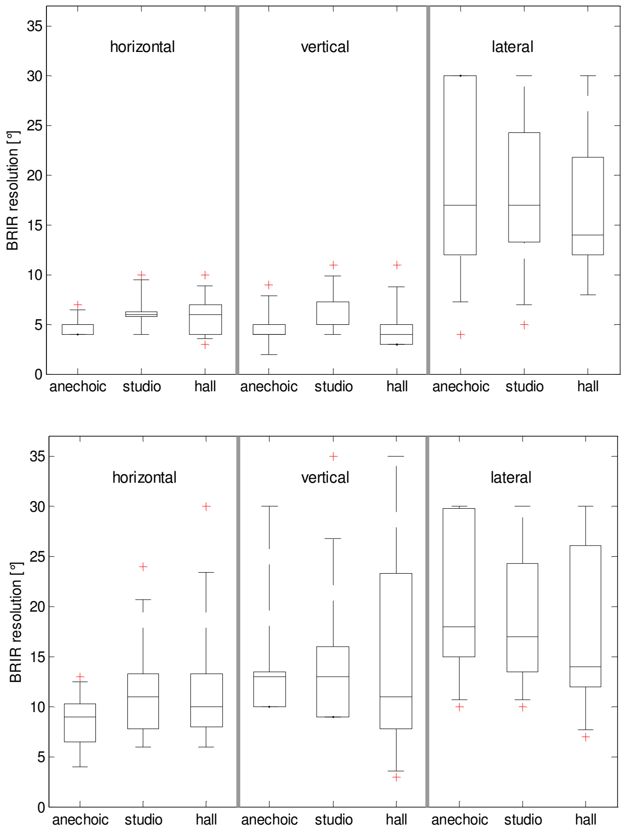

Figure 2: *Just noticeable discretization of BRIR data sets for frontal sound incidence, three rotational degrees of freedom, and three different acoustic environments. Upper plot: noise, lower plot: guitar stimulus. Boxplots indicate medians and interquartile range, whiskers 90% quantiles, crosses indicate all outliers*

For experiment I a strong interaction between the factors 'direction of movement' and 'stimulus' was observed. When listening to noise, subjects were more sensitive to a reduced grid resolution for vertical head movements (see Figure 2). The broadband noise signal obviously provided enough spectral information so that two listeners could even reliably detect a grid granularity of 2° in vertical direction. A 2 x 3 ANOVA conducted separately for each stimulus confirmed that vertical thresholds were significantly lower than horizontal thresholds (means: 5° vs. 5.6°) in the noise condition.

When listening to the guitar stimulus, however, listeners were much more sensitive to a reduced grid resolution for horizontal head movements. Here, discretization effects for modulated ITDs and ILDs obviously presented a stronger cue than spectral differences for a narrowband, musical signal.

As expected, a reduced grid resolution for lateral head movements and frontal sound incidence was detected only at very high thresholds for both noise and guitar, due to a lack of binaural cues.

When pooling over all degrees of freedom and all acoustical environments, the effect of 'stimulus' was highly significant (5° vs. 12.3°). In agreement with studies on the MAA the bandwidth of stimuli (here: noise vs. guitar) had a very strong effect in this spatial discrimination task. Only for lateral head movements the stimulus effect is negligible, since the general uncertainty of subjects was reduced only a little by the higher bandwidth of the noise stimulus.

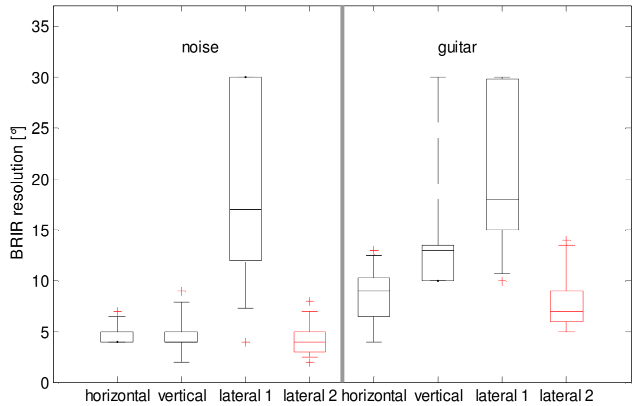

Figure 3: *Just noticeable discretization of BRIR data sets for 3 rotational degrees of freedom using 2 different stimuli in anechoic environment;, lateral 1 = frontal sound incidence, lateral 2 = vertical sound incidence.*

The factor 'room acoustics' showed no significant influence on the perceptibility of grid resolution; only a trend can be observed. For horizontal and vertical movements a slightly higher sensitivity was found for the anechoic presentations (~1°). On contrast, reduced lateral resolution with frontal sound incidence (exp. II) was easier to detect with increasing room response. Here, room reflections, particularly those from floor and ceiling, obviously provided additional cues compared to the anechoic condition, as was confirmed by the investigation for sound incidence from above (exp. III).

For lateral head movements and vertical sound incidence (exp. III), not surprisingly, thresholds were much lower than those found for frontal sound incidence (see Figure 3). Again, the noise stimulus lead to significantly lower threshold values than the guitar stimulus (means: 4.25° vs. 7.25°, paired t-test).

The thresholds for horizontal and vertical head movements with frontal source and lateral head movements with sound source above can be regarded as the (presumably) most critical configurations of source, receiver, and direction of head movement. For pink noise as a stimulus, those values are surprisingly similar, with means of 4.8° for horizontal, 4.7° for vertical, and 4.2° for lateral head movements. Although these differences were not significant (independent-samples-ANOVA with conservative post-hoc tests), subjects were, at least by trend, more sensitive to a reduced lateral resolution than to horizontal or vertical resolutions.

4. DISCUSSION

Since we can assume that spectral differences induced by head movements and discrete BRIR data are an important cue for detecting discontinuities in VAEs, these differences have been plotted in Figure 4 for every direction of head movement investigated and for anechoic conditions. Magnitude spectra have been normalized towards their smoothed mean spectral magnitude, in order to make only direction-related differences visible.

When we look at modulations induced by vertical head movements, at first sight only minor differences are visible compared to horizontal head movements. However, most spectral variance happens in a small angular region (±10°) close to a neutral (0°) head direction. In the absence of ITD and ILD differences, this variance, caused by different orientations of the pinnae towards the sound source, is obviously high enough to let listeners detect even smaller discretization than for horizontal movements.

The magnitude spectra for lateral head movements and frontal sound source ('lateral 1') are largely independent of head orientation. Yet, with decreasing distance to the shoulder (negative angles), a comb filter characteristic is visible, which is most probably due to shoulder and torso reflections, whose path lengths decrease with the head inclined towards the shoulder. This explains why discontinuities due to a reduced BRIR resolution are easier to detect in this area, and indeed many subjects used large lateral tilts in the stipulated discrimination task.

The same comb filter can be observed for horizontal movements and for lateral movements with vertical sound incidence ('lateral 2'). While the modulations of ITDs can be assumed to be very similar for both conditions, the plots indicate a stronger acoustical shadowing for frequencies above 1 kHz (and thus: larger ILDs) and a stronger direction dependent comb filtering in lateral direction, starting already close to the neutral (0°) head direction. This might explain why slightly lower threshold values have been found for lateral than for horizontal head movements.

Since comb filter modulations shown in Fig. 4 are much less pronounced in measurements without shoulder and torso (not shown here), it can be expected that torso reflections play an important role in spatial discrimination tasks as well as for the authenticity of virtual acoustic environments in general. For a closer examination of this aspect it will be interesting to compare BRIR data measured with and without out FABIAN's torso.

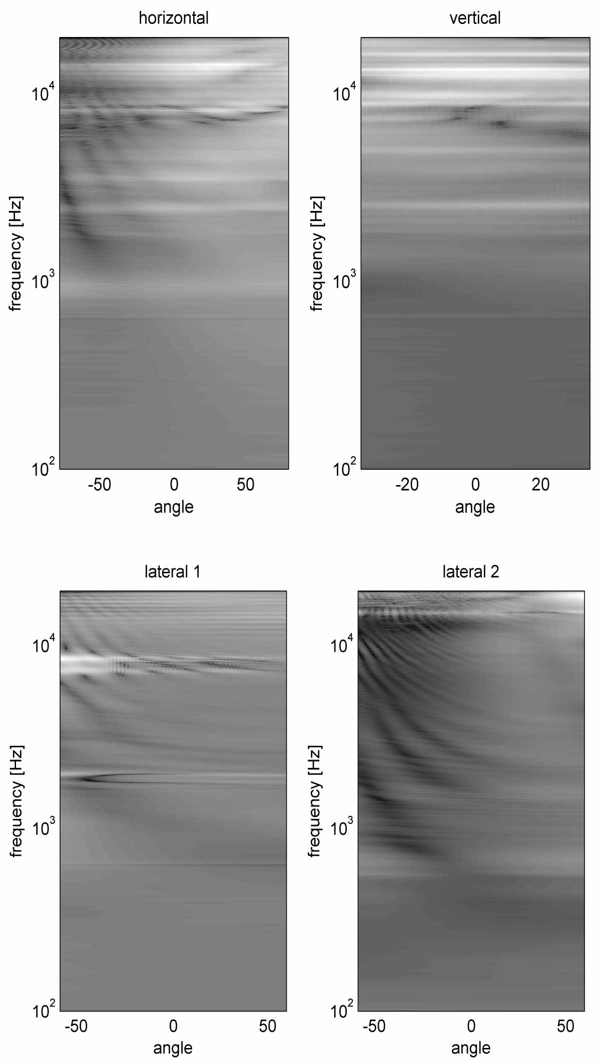

Figure 4: *Direction dependent magnitude spectra for HRTF data sets acquired in anechoic condition. Each plot has been normalized for its average magnitude spectrum. Above: horizontal and vertical head orientation for a frontal sound source, below: lateral head orientations for a frontal sound source (left) and a sound source above (right). Left ear is shown, negative angles indicate left ward movement, i.e.: downward inclination of the ear.*

5. CONCLUSION

Thresholds for the minimum audible grid granularity in virtual acoustic environments based on dynamic binaural synthesis have been determined for the three rotational degrees of freedom of head movements. Listening tests revealed thresholds for different acoustic environments and for different audio contents using an adaptive 3-AFC psychoacoustic procedure. It could be shown, that, depending on source position, the ability to detect a reduced spatial resolution in discretely measured BRIR data is very similar for all directions of head movements. When listening to a broadband noise stimulus, a reduced grid granularity in vertical and lateral direction was even more critical than for horizontal head movements, a result also supported by [25]. The results of listening tests are consistent with observations on the magnitude spectra of the HRTFs used, which exhibit higher spectral variance in lateral than in horizontal direction. For musical content with limited and non-stationary bandwidth a reduced spatial resolution of BRIRs was less critical.

The thresholds showed only very little variation with the size and reverberation time of the measured acoustic environments. Hence, even natural, partly diffuse spatial environments cannot be synthesized with binaural data of lower resolution than in the anechoic condition.

Since the conditions for a parametric analysis were not always complied with (see 3.), Table 3 gives percentiles with respect to the distribution of thresholds within our sample of 20-23 subjects for each of the three experiments.

Table 3 *Grid resolutions just audible for different percentiles of the sample of subjects for horizontal, vertical and lateral (source in front/source above) head movements.*

…was audible for	**noise** hor/ver/lat1/lat2	**guitar** hor/ver/lat1/lat2
50%	6° x 5° x 16° x 4°	9° x 12° x 16° x 7°
25%	4° x 4° x 12° x 3°	7° x 9° x 12° x 6°
5%	4° x 3° x 8° x 2°	5° x 4° x 8 x 5°
0%	2° x 1° x 3° x 1°	3° x 2° x 3° x 4°

Given the values in Table 3, a BRIR grid granularity of 2° for horizontal, 1° for vertical and 1° for lateral head movements should provide a spatial resolution for virtual acoustic environments that is sufficient even for critical listeners, critical audio content, and all possible sound source locations. Further studies on the application of different interpolation algorithms for binaural synthesis can use these granularities as a target for interpolated data sets. For musical content presented in spaces with some reverberation a resolution of 5° for horizontal, 4° for vertical and 5° for lateral head movements will be sufficient to create a plausible simulation for 95% of the listeners.

6. ACKNOLEDGEMENTS

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