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Audibility of High Q-factor All-pass Components in Head-related Transfer Functions

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ABSTRACT

Head-related transfer functions (HRTFs) can be decomposed into minimum-phase, linear-phase and all-pass components. It is known that low Q-factor all-pass sections in HRTFs are audible as lateral shifts when the interaural group delay at low frequencies is above $30\mu s$. The goal of our investigation is to test the audibility of high Q-factor all-pass components in HRTFs and the perceptual consequences of removing them. A three-alternative forced choice experiment has been conducted. Results suggest that high Q-factor all-pass sections are audible when presented alone, but inaudible when presented with their minimum-phase HRTF counterpart. It is concluded that high Q-factor all-pass sections can be discarded in HRTFs used for binaural synthesis.

1. INTRODUCTION

Head-related transfer functions (HRTFs) contain the transformations that affect the sound in its path to the eardrum of a listener. These transformations are responsible for the human ability of localizing sound sources. HRTFs, as other electroacoustical transfer functions, can be decomposed into minimum-phase, linear-phase and all-pass components [1][2]. It has been suggested that a valid model of HRTFs is in the form of an interaural time difference (ITD) and minimum-phase components [3][4][5], where the ITD is computed from the linear-phase part of the HRTF. However, it has been shown that audible low Q-factor all-pass components have to be included in the ITD [6]. High Q-factor all-pass components are discarded in such models, even though they are audible as a ringing in general electroacoustical transfer functions [7]. Møller *et.al.* [7] suggested that all-pass sections in HRTFs would not be audible since they are centered at the same frequencies were dips occur in the magnitude response of their minimum-phase components. The goal of our investigation is to test the audibility of high Q-factor all-pass sections in HRTFs. It is hypothesized that high Q-factor all-pass sections are audible when presented alone, but they become inaudible when presented with their minimum-phase HRTF counterpart.

1.1. Theoretical Background

HRTFs are mixed-phase systems that can be decomposed into minimum-phase and excess-phase components. The latter can be further decomposed into linear-phase and all-pass components. If expressed in the z-domain:

$$HRTF(z) = HRTF(z)_{min.} \cdot HRTF(z)_{exc.} \quad (1)$$

$$HRTF(z)_{exc.} = HRTF(z)_{lin.} \cdot HRTF(z)_{all-pass} \quad (2)$$

Therefore, HRTFs can be expressed in terms of their minimum-phase, linear-phase and all-pass components as follows:

$$HRTF(z) = HRTF(z)_{min.} \cdot HRTF(z)_{lin.} \cdot HRTF(z)_{all-pass} \quad (3)$$

The minimum-phase part contains all the spectral information that aids sound localization. It has the same magnitude characteristics as the original HRTF, but the phase response is the smallest possible for that magnitude. As the energy is most concentrated at the beginning of the impulse response, the filters are the shortest for systems with that same magnitude. Minimum-phase systems and their inverses are causal and stable. In the z-plane, all poles and zeros are inside the unit circle.

A linear-phase component is a delay or shift of a signal in time. In HRTFs, it is represented by the initial time before the arrival of the sound to each ear. A linear-phase system has unity magnitude and its phase is linear with a negative slope.

The all-pass component has also unity magnitude. In the z-plane, a first-order all-pass section consists on a single pole inside the unit circle and a zero at a conjugate reciprocal location. Second order all-pass sections are complex conjugated pairs of poles inside the unit circle and zeros at mirrored positions. General all-pass sections can be expressed as the product of first and second-order all-pass sections. A thorough theoretical background on all-pass sections can be found in [2][7] and will not be repeated here. However, it is worth to mention that all-pass transfer functions can be expressed in terms of their center frequency (f_0) and quality factor (Q-factor). Considering the all-pass impulse response as an impulse followed by an exponentially decaying sinusoid, the center frequency of the all-pass section is close to the frequency of the exponential decay -i.e. ringing- and the Q-factor is associated to the peak in the phase and group delay of the all-pass. The Q-factor is related to the decay time of the impulse response: a low Q-factor implies that the all-pass impulse response dies out in a short time, while a high Q-factor implies that it remains ringing for a longer time.

1.2. Literature review

Mehrgardt and Mellert [8] investigated the decomposition of HRTFs measured on human subjects. They found that the excess-phase component was nearly linear up to 10 kHz and concluded that HRTFs were minimum-phase up to that frequency. It has to be noted that Mehrgardt and Mellert used the term all-pass instead of excess-phase.

Wightman and Kistler [9] reported that the decomposition of their measured HRTFs into all-pass and minimum-phase components supported the findings of Mehrgardt and Mellert that the HRTFs could be modeled by a minimum-phase system up to 10 kHz. On that basis, Kistler and Wightman [4] developed a principal component model of minimum-phase HRTFs. Their psychophysical results showed that localization performance with minimum-phase HRTFs was similar to that with measured HRTFs -both conditions being played back through headphones. Wightman and Kistler discussed these findings in [3]: they regarded the linear delay as being part of the all-pass sections and agreed with Mehrgardt and Mellert in that measured HRTFs were nearly minimum-phase up to 10kHz. However, Wightman and Kistler concluded that the psychophysical evidence supported the idea that modeling HRTFs as a minimum-phase transfer function plus a linear-phase component did not affect localization.

Møller *et.al.* [1] showed examples of decomposition of HRTFs into minimum-phase and all-pass components, and reported that HRTFs, as a common trend, presented several second-order all-pass sections. In a work done in the same laboratory, Sandvad and Hammershøi [10] compared different filter representations of HRTFs. They concluded that minimum-phase HRTFs were good approximations, as the probability of perceiving differences between the minimum-phase and the reference HRTF was very low.

Kulkarni *et.al.* [5] studied the human sensitivity to phase structure in HRTFs. They stated that the all-pass part of HRTFs was a pure delay. However, they graphically showed that it was not the case: there were differences beyond a shift in time when comparing measured and minimum-phase head-related impulse responses (HRIRs). Kulkarni *et.al.* tested three models: minimum-phase-plus-linear-phase, zero-phase-plus-linear-phase and reversed-phase-plus-linear-phase. In these models, the linear-phase component was a pure delay that was implemented as a time shift. They concluded that the minimum-phase-plus-linear-phase model was perceptually valid as long as the low frequency ITD was correctly computed. It is implicit in the work of Kulkarni *et.al.* that they discarded the all-pass components from HRTFs. This would explain why their modeled HRTFs departed the most from empirical ones for lower azimuths at contralateral sides: according to our experience, these directions present more all-pass sections than other ones.

In a recent study, Møller *et.al.* [7] tested the audibility of second-order all-pass sections in electracoustical transfer functions, centered at different frequencies. They found that low Q-factor all-pass sections could be audible as a shift of the auditory image when presented in one ear only, and that high Q-factor were audible as a ringing if the Q-factor was high enough. They presented thresholds of audibility for both cases. For the high Q-factor case, they found that the thresholds related to a constant $\frac{Q-factor}{f_0}$ ratio. They also mentioned that, if the Q-factor took a very high value, the presence of the all-pass section became inaudible again. Møller *et.al.* suggested that the found thresholds for ringing did not applied for HRTFs: when HRTFs were decomposed in the z-plane, zeros were added inside the unit circle that gave rise to notches in the magnitude. At the same frequencies, the all-pass section were centered giving place to possible ringing. As the Q-factor got higher and was more likely to be audible, the more the ringing was minimized by the minimum-phase counterpart. Plogsties *et.al.* [6] studied the audibility of low Q-factor all-pass sections in HRTFs. They found that low Q-factor all-pass sections were audible as lateral shifts when their interaural group delay evaluated at 0Hz (IGD_0) was above 30μs, in the line with the findings from [7].

From the reviewed literature, it can be seen that [5] and [8] provide graphical evidence that HRTFs are not minimum-phase functions and contain a linear-phase and all-pass components. This has also been explicitly shown by others [1]. According to [6], it is important that the ITD accounts for all-pass components that become audible. Even though high Q-factor all-pass sections are also present in HRTFs, minimum-phase plus ITD models proved to be perceptually valid for binaural synthesis [3][5][10]. This would suggest that high Q-factor all-pass sections are not audible in HRTFs even though they are audible in more general electroacoustical transfer functions [7]. Therefore, we hypothesize that high Q-factor all-pass sections are audible when presented alone, but they become inaudible when presented with their minimum-phase HRTF counterpart.

2. METHODS

The goal of our investigation is to test the audibility of high Q-factor all-pass sections in HRTFs. All-pass sections that were more likely to be audible were selected from a large database of measured HRTFs. Signals with and without all-pass sections were presented to listeners in a psychoacoustical experiment.

2.1. Decomposition of HRTFs

Measured HRIRs at a sampling frequency of 48 kHz were used. In previous experiments at our laboratory [10] it has been shown that HRIRs of 72 taps of length (sampled at 48 kHz) were long enough to convey all the needed cues to sound localization. Due to computational constrains of the implemented algorithm, HRIRs of 64 samples were used in our investigation. All-pass sections were computed from the roots of the polynomial, by finding the zeros outside the unit circle in a z-plane representation of the HRTFs. Firstly, the initial linear delay was identified with the 5% leading edge criterion reported in [10]. The computed linear delay was removed from the HRTFs, yielding:

$$HRTF(z) = HRTF(z)_{min.} \cdot HRTF(z)_{all-pass} \quad (4)$$

$HRTF(z)_{min.}$ was conformed by all the zeros of $HRTF(z)$ lying inside the unit circle plus zeros added at the conjugate reciprocal positions of those outside the unit circle. $HRTF(z)_{all-pass}$ consisted on all the zeros of $HRTF(z)$ lying outside the unit circle plus poles canceling the added zeros in $HRTF(z)_{min.}$. $HRTF(z)_{all-pass}$ were implemented as IIR filters and $HRTF(z)_{min.}$ as FIR filters. Since high Q-factor all-pass components have long impulse responses, 1024 taps were used for all filters.

2.2. Coordinate system

As it is well known, HRTFs are direction dependent. In the following, directions will be mentioned in terms of azimuth and elevation angles. Azimuth corresponds to lateral angles and elevation to vertical angles. In the coordinate system chosen, 90° and -90° azimuth are situated at left and right sides, respectively. All directions are given in (azimuth ϕ, elevation θ). $(0^\circ, 0^\circ)$ is to the front and $(180^\circ, 0^\circ)$ is to the back of the subjects.

2.3. Selection of HRTFs

Our database of measured HRTFs [1] consists on 3880 pairs of HRTFs. As it was impossible to include all of them in the listening experiment, it was decided to analyze the database in order to select a few HRTFs with all-pass sections most likely to be audible according to their Q-factors. The conditions that we imposed to select the HRTFs for the experiment were: 1) at least one all-pass section had its Q-factor well above the high Q-factor threshold in the mid-frequency range and 2) none of the Q-factors were below the threshold of audibility for low Q-factor. The second condition was also checked by computing the IGD_0 and ensuring that it was well below 30μs. We found that the second condition was easy to fulfill. However, the first condition was mostly found in the contralateral side of the HRTFs. Fig. 1 show the six pairs of HRTFs selected. Thick lines correspond to the left side signal and thin lines to the right side signal. At the top of each box, the directions to which the HRTFs correspond are marked. Each pair of HRTFs belongs to a different subject. Fig. 2, Fig. 3 and Fig. 4 show the impulse responses of the selected HRTFs in their minimum-phase, all-pass and combined (minimum-phase plus all-pass) forms respectively -only the contralateral side is shown. Fig. 5 show the six all-pass components selected, ordered in the same fashion as in Fig. 1. The thresholds of audibility found by [7] for all-pass sections in electroacoustic transfer functions are also shown.

2.4. Conditions

Each condition compared an impulse response to the same impulse response with its all-pass sections removed. The all-pass sections from the selected HRTFs were either presented alone or with their corresponding minimum-phase HRTFs. Presentations were done in binaural and diotic (same sound at both ears) conditions. In the former, both sides of the HRTFs were used and played back. In the latter, only the most unfavorable case was reproduced at both ears, without ITD. The following conditions were determined:

A- Minimum-phase HRTFs (with corresponding ITD) with and without their associated all-pass sections.

$$HRTF(z)_{min.} \cdot HRTF(z)_{lin.}$$

$$vs.$$

$$HRTF(z)_{min.} \cdot HRTF(z)_{lin.} \cdot HRTF(z)_{all-pass}$$

B- Impulses (with ITD) with and without all-pass sections from HRTFs.

$$H(z) \cdot HRTF(z)_{lin.}$$

$$vs.$$

$$H(z) \cdot HRTF(z)_{lin.} \cdot HRTF(z)_{all-pass}$$

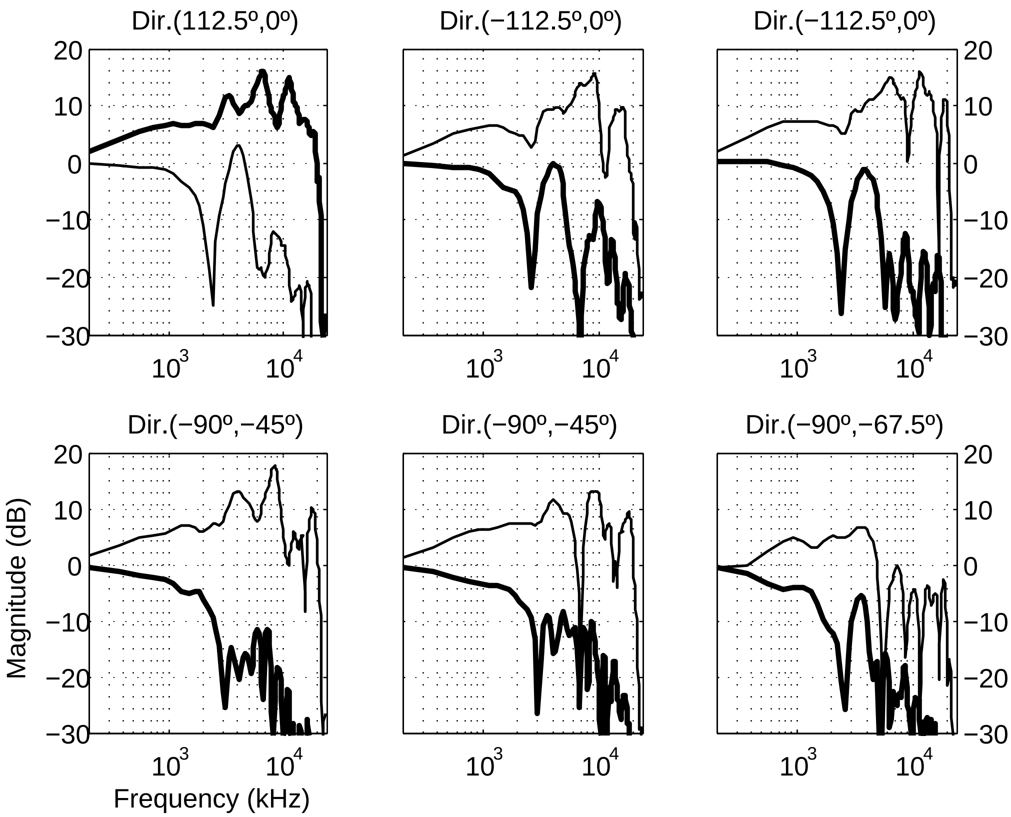

Fig. 1: Minimum-phase magnitude response of the HRTFs selected for the experiment. Thick lines correspond to the left side signal and thin line to the right side signal. HRTFs used were measured on different subjects. The direction for which the HRTFs were measured are shown at the top of each box.

C- Minimum-phase components (without ITD) with and without their associated all-pass sections, same signal presented at both ears.

$$HRTFDiotic(z)_{min.}$$

$$vs.$$

$$HRTFDiotic(z)_{min.} \cdot HRTF(z)_{all-pass}$$

D- Impulses (without ITD) with and without all-pass sections from HRTFs, same signal presented at both ears.

$$HDiotic(z)$$

$$vs.$$

$$HDiotic(z) \cdot HRTF(z)_{all-pass}$$

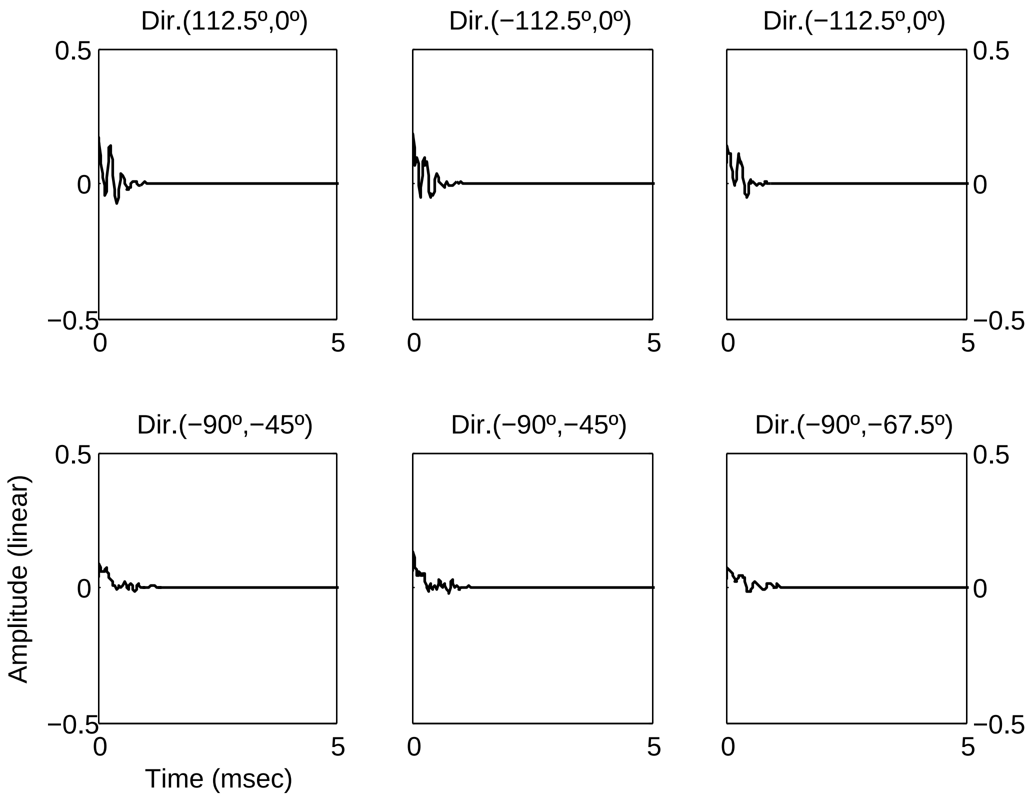

Fig. 2: Minimum-phase impulse responses of the HRTFs shown in Fig. 1. Only the contralateral side of each pair of HRTFs is shown. The direction for which the HRTFs were measured are shown at the top of each box.

Conditions C and D did not correspond to a natural situation. They were introduced to evaluate whether binaural interactions played a role in the audibility of high Q-factor all-pass sections: in the HRTFs selected there was mostly one side (contralateral) with potentially audible all-pass sections.

2.5. Procedure

A three alternative forced choice (3AFC) was conducted. In a 3AFC experiment there are six possible sequences of ordering the presentations: AAB ABA BAA BBA BAB BBA. These six sequences were presented twice per each of the six HRTF/impulse pair. This gave a total of 72 trials per condition. Trials were randomized for every listener. Stimuli was presented in four blocks of 72 trials. The two first blocks tested conditions A and B, the two last blocks tested conditions C and D. The task of the subject was to report the sample that sounded different from

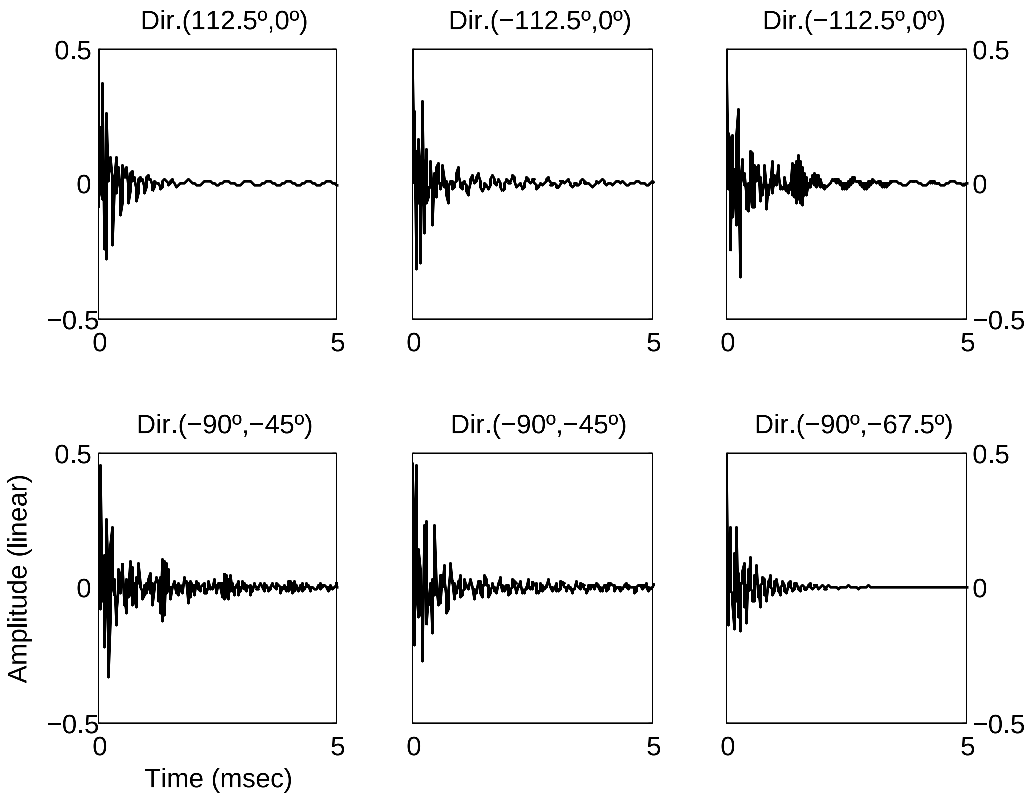

Fig. 3: Impulse responses of the all-pass sections associated to the HRTFs shown in Fig. 1. Only the contralateral HRIRs of each pair are shown. The direction for which the HRTFs were measured are shown at the top of each box.

the other two, regardless the nature of the difference.

Before the experiment, subjects were given written instructions about the task. They were taken to an anechoic chamber, where they conducted a training session consisting of 24 trials arbitrarily selected and without headphone equalization. After the training session, subjects proceeded with the experiment proper. During both training session and experiment, subjects interacted with the screen showed in Fig. 6. Each number in the screen was highlighted synchronously with a sound sample. In order to report the sample that sounded different, subjects had to touch the corresponding number in the screen. After their response to one trial, they had to press the NEXT button to hear the following trial. Subjects were given breaks between blocks, in which they were required to leave the anechoic chamber. Subjects were not given feedback during the training session nor the experiment.

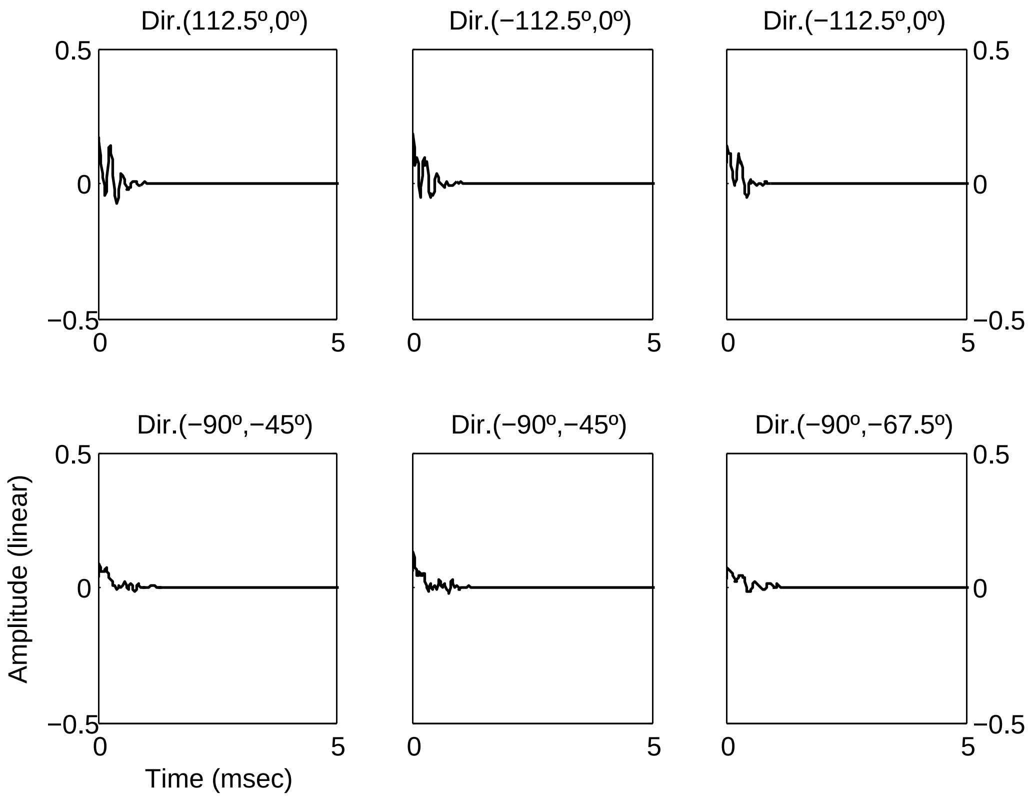

Fig. 4: Impulse responses of the combined form $HRTF(z)_{min.} \cdot HRTF(z)_{all-pass}$ -i.e. the convolution of the impulse responses shown in Fig. 2 and Fig. 3. The corresponding direction is indicated at the top of each box.

All subjects completed the experiment within two hours in a single day.

2.6. Subjects

Twelve subjects with normal hearing participated in the experiment. They were six females and six males, with ages ranging from 20 to 30 years old. Their hearing thresholds were determined by a standard pure-tone audiometry in the frequency range from 250 Hz to 8 kHz. None of the subjects had hearing thresholds above 15dB HL. Some of the listeners had participated in listening tests before, but all of them were unfamiliar with the procedure and the differences presented. Therefore, they are considered naive for the purpose of this experiment.

2.7. Stimuli

The stimulus consisted of a single impulse (perceived as a click) of 21.3 milliseconds (1024 taps sampled at 48 kHz). This impulse was filtered with the ap-

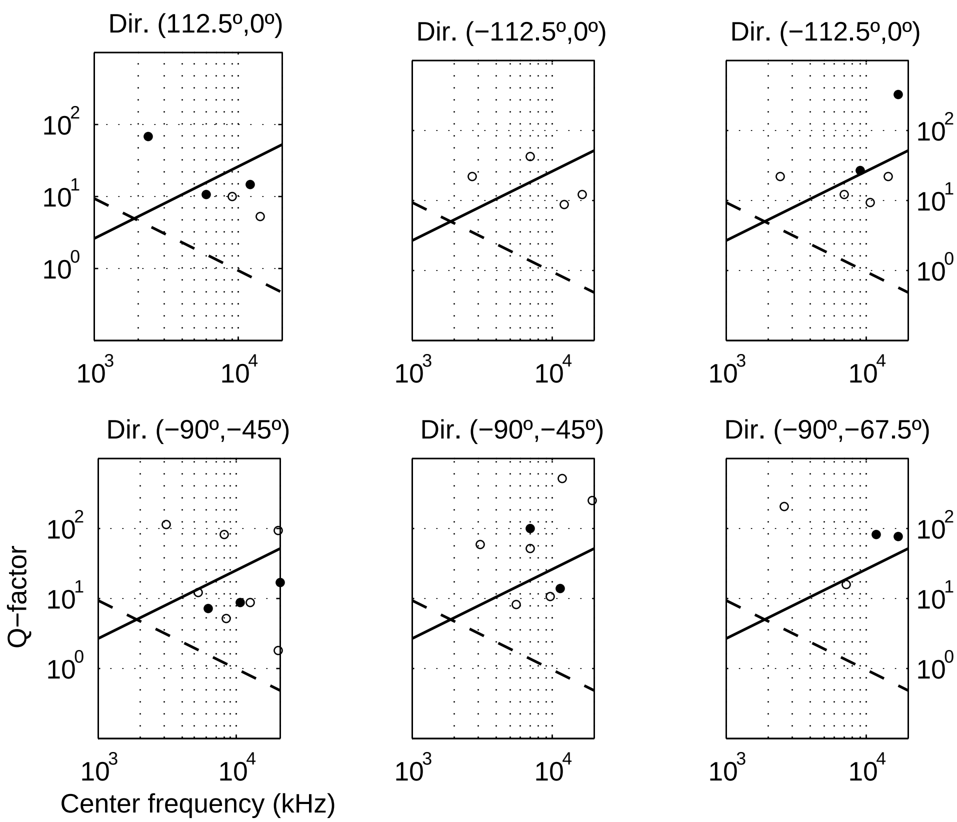

Fig. 5: Q-factors of the selected all-pass sections from the HRTFs in Fig. 1. Filled circles indicate all-pass sections from right ears, blank circles correspond to left ears. The high Q-factor and low Q-factor thresholds of audibility for all-pass sections found by [7] are indicated with the solid and dashed lines, respectively. HRTFs used were measured on different subjects. The direction for which the HRTFs were measured are shown at the top of each box.

propriate filters obtained from the decomposition in order to produce the signals required to test the conditions of interest. All processing was done with MatLab. In each trial, subjects listened to three intervals of sound. The silence between clicks was 500 milliseconds. The time between trials was controlled by the subjects.

2.8. Signal generation and reproduction

The equipment was placed in a control room next to the anechoic chamber where the subject sat. Signals were played back through a PC with a digital sound card RME HDSP 9632 connected to an external AD/DA converter RME ADI-8 DS. The signals fed a power amplifier Pioneer A-616. The level of the amplifier was raised and a passive at-

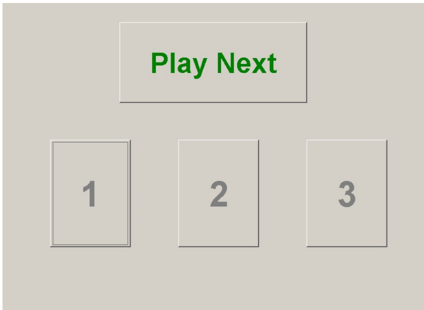

Fig. 6: Interface presented to the subjects in a touch screen for judgments report.

tenuator used to reduce the overall noise. The output of the attenuator was delivered to the subjects through headphones Beyerdynamic DT990, individually equalized. Typical transfer functions for these headphones are shown in [11].

2.9. Headphone equalization

Headphones were equalized individually for each subject. A dual channel MLS system developed at our laboratory [12] was used to measure the headphones transfer functions (PTFs) in each subject. The signals were collected by two Sennheiser KE 4-211-2 miniature microphones placed at the blocked entrance of the ear canals of the subjects. Microphones were calibrated and connected to a power supply that provided a gain of 20dB. Two measuring amplifier Bruel & Kjær 2607 were used before feeding the signals to the AD/DA converter and back to the PC. All measurements were done at a sampling frequency of 48kHz. Appropriate post-processing to construct the inverse filters was implemented with MATLAB. Equalization filters only accounted for the minimum-phase response of the PTFs.

3. RESULTS

Fig. 7 shows results for conditions A (white bars) and B (black bars). Fig. 8 shows results for conditions C (white bars) and D (black bars). The bars indicate the percentage of correct answers (ordinate) for each subject (arbitrarily numbered in the abscissa). Results from all the HRTFs in a given condition were pooled. In a 3AFC experiment, the number of correct answers is binomially distributed. The probability of guessing is 1/3 and the null hypothesis can be rejected at the 1% of significance level if the percentage of correct answers is greater than 46%. In Fig. 7 and Fig. 8, the 1% significance level boundary is shown by the solid line and the chance level is shown by the dashed line.

4. DISCUSSION

The null hypothesis -i.e. the subjects are guessing- can be rejected if the percentage of correct answers is above 46%, represented by the solid line in Fig. 7 and Fig. 8. Our results show that the null hypothesis is rejected for all subjects in conditions B and D, and for none in conditions A and C.

The results of condition A (Fig. 7) indicate that removing the all-pass component to HRTFs is inaudible for all subjects. If the same all-pass components are presented alone, the differences become audible as it is seen in the results of condition B in the same figure. Our hypothesis is confirmed by these results. Therefore, it is concluded that high Q-factor all-pass sections from HRTFs can be discarded without audible consequences.

The results of condition C (Fig. 8) show that if the same all-pass section is added at both ears with a minimum-phase counterpart, the differences are inaudible to all subjects. On the other hand, the differences become audible to all subjects if the all-pass sections are presented alone (condition D). These results would suggest that binaural interaction does not play a role in the lack of audibility of high Q-all-pass sections, as the same trend seen in Fig. 7 is followed.

Analysis of HRTFs from our database has shown that most HRTFs contain all-pass sections. Furthermore, the center frequency of high Q-factor all-pass sections correspond to deep notches in the magnitude response (compare Fig. 1 and Fig. 5). These all-pass sections would not be expected to produce the perception of ringing: if a deep notch is present in the magnitude, the amplitude of the ringing becomes smaller. This can also be understood from the impulse responses: the all-pass impulse responses are long (Fig. 3), but minimum-phase impulse responses convolved with all-pass impulse responses are rather short (Fig. 4). It would seem plausible to hypothesize that it is the particular high-frequency magnitude response associated to each all-pass section which is responsible for the inaudibility of the latter. This was also suggested in [7] in terms of the z-domain representations: in the reported process to decompose the HRTFs, we add zeros inside the unit circle that give rise to notches in the magnitude. At the same frequency, the all-pass section is centered giving place to possible ringing. As the Q-factor gets higher and is more likely to be audible, the more the ringing is minimized by the minimum-phase counterpart.

5. CONCLUSIONS

A listening experiment to assess the audibility of high Q-factor all-pass sections has been conducted. The results show that high Q-factor all-pass sections from HRTFs are audible if tested alone, but are inaudible if they are combined with their associated minimum-phase HRTFs. Therefore, it is concluded that high Q-factor all-pass sections from HRTFs can be discarded without audible consequences in binaural synthesis. In other words, HRTFs can be represented by a minimum-phase function and a linear delay as ITD.

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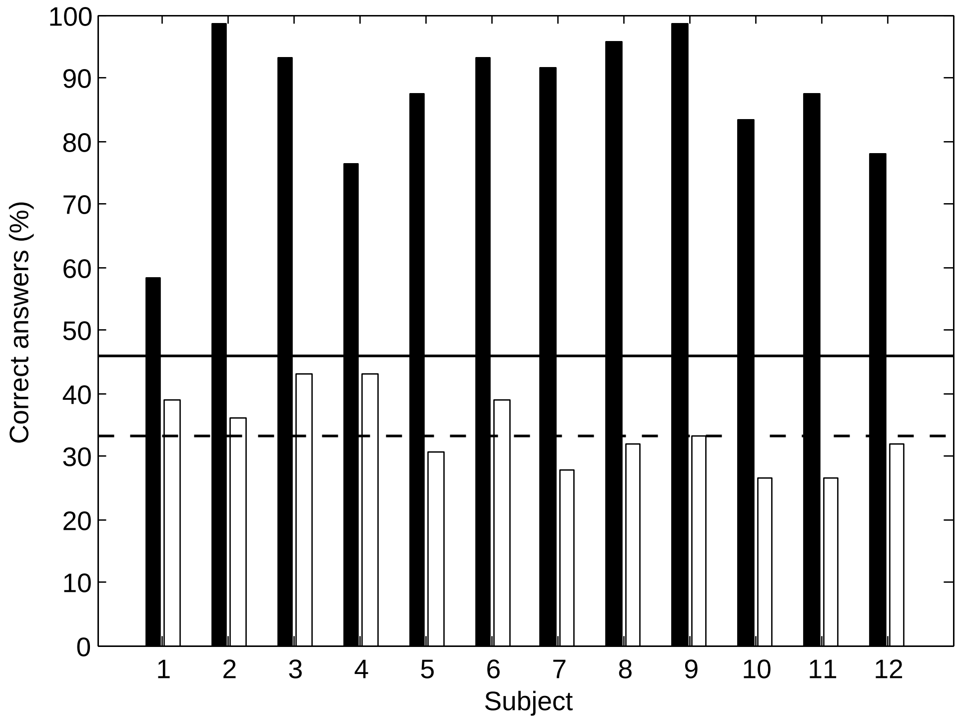

Fig. 7: Results for conditions A (white bars) and B (black bars). The bars indicate the percentage of correct answers (ordinate) for each subject (arbitrarily numbered in the abscissa). Results from all the HRTFs in a given condition were pooled. The probability of guessing is 1/3 (dashed line) and the null hypothesis can be rejected at the 1% of significance level if the percentage of correct answers is greater than 46% (solid line).

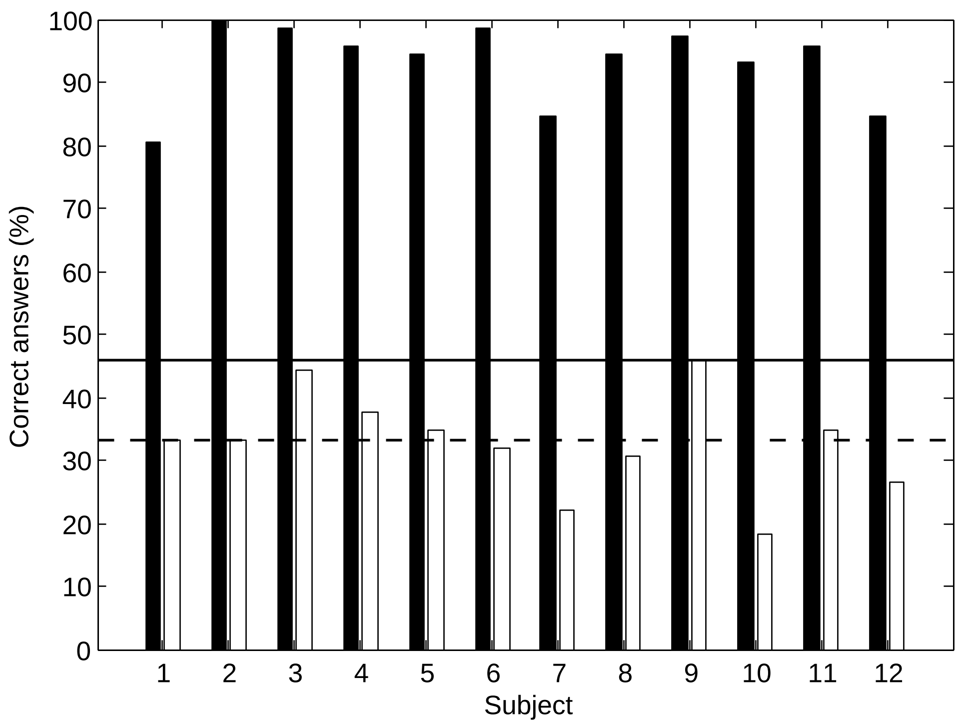

Fig. 8: Results for conditions C (white bars) and D (black bars). The bars indicate the percentage of correct answers (ordinate) for each subject (arbitrarily numbered in the abscissa). Results from all the HRTFs in a given condition were pooled. The probability of guessing is 1/3 (dashed line) and the null hypothesis can be rejected at the 1% of significance level if the percentage of correct answers is greater than 46% (solid line).