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Synthetic individual binaural audio delivery by pinna image processing

Simone Spagnol and Michele Geronazzo

*Department of Information Engineering,
University of Padova, Padova, Italy*

Davide Rocchesso

*Department of Architecture and Arts,
Iuav University of Venice, Venice, Italy, and*

Federico Avanzini

*Department of Information Engineering,
University of Padova, Padova, Italy*

Abstract

Purpose – The purpose of this paper is to present a system for customized binaural audio delivery based on the extraction of relevant features from a 2-D representation of the listener's pinna.

Design/methodology/approach – The most significant pinna contours are extracted by means of multi-flash imaging, and they provide values for the parameters of a structural head-related transfer function (HRTF) model. The HRTF model spatializes a given sound file according to the listener's head orientation, tracked by sensor-equipped headphones, with respect to the virtual sound source.

Findings – A preliminary localization test shows that the model is able to statically render the elevation of a virtual sound source better than non-individual HRTFs.

Research limitations/implications – Results encourage a deeper analysis of the psychoacoustic impact that the individualized HRTF model has on perceived elevation of virtual sound sources.

Practical implications – The model has low complexity and is suitable for implementation on mobile devices. The resulting hardware/software package will hopefully allow an easy and low-tech fruition of custom spatial audio to any user.

Originality/value – The authors show that custom binaural audio can be successfully deployed without the need of cumbersome subjective measurements.

Keywords 3D audio, Spatial sound, Binaural, HRTF, Pinna, Auditory localization, Headphones

Paper type Research paper

1. Why customize spatial audio?

In recent years, spatial sound has become increasingly important in a plethora of application domains. Spatial audio models are able to provide information about the relationship between the sound source and the surrounding environment including the

listener and his body which acts as a further filter (Pulkki *et al.*, 2011). Among the diverse possibilities offered by spatial audio technologies, binaural (i.e. headphone-based) reproduction systems – if properly designed – allow tailoring immersive and realistic auditory scenes to any user without the need for loudspeaker-based systems. These technologies go well with mobile devices in particular, as headphones are typically used on the move without the need to hold anything in hand.

Binaural audio rendering approaches are typically based on the concept of head-related transfer function (Cheng and Wakefield, 2001), or HRTF. HRTFs capture the transformations undergone by a sound wave in its path from the source to the eardrum and in particular those caused by diffraction, reflection and resonance effects onto the torso, head, shoulders and pinnae of the listener. Such characterization allows virtual positioning of a number of sound sources in the surrounding space by filtering the corresponding signals through a pair of HRTFs, thus creating left and right ear signals to be delivered by headphones. In this way, three-dimensional sound fields can be simulated.

Non-individual HRTF sets, typically recorded by using dummy heads, are known to produce evident sound localization errors (Møller *et al.*, 1996). On the other hand, obtaining personal HRTF data for a vast number of users is simply impractical because specific hardware, anechoic spaces and long collection times are strictly required. Structural HRTF modeling (Brown and Duda, 1998) represents an attractive solution to all of these shortcomings. By isolating the effects of different components (head, pinnae, ear canals, shoulders, torso) and modeling each of them with a corresponding filtering element, the global HRTF is approximated through a proper combination of all the considered effects. Moreover, by relating the temporal/spectral features of each component to corresponding anthropometric quantities, one can in principle obtain an HRTF representation that is both computationally economical and customizable.

A complete structural filter model of the HRTF is currently being studied by the authors (Spagnol *et al.*, 2013a; Geronazzo *et al.*, 2013a). In the model, special care is reserved for the contribution of the external ear to the HRTF: data and results collected to date allow in particular the development of a parametric HRTF model customizable according to individual anthropometric data, which in turn can be automatically estimated through straightforward image analysis (Spagnol *et al.*, 2010b). This means that by feeding such model with a suitable characterization of the listener's anthropometry and by rendering the resulting audio stream through motion-tracked headphones, low-tech custom binaural audio can be delivered in real time on a standard mobile device.

This paper explains in particular how custom audio streams can be derived from a set of distinctive pictures of the listener's pinnae, with a special focus on the extraction of the relevant parameters for HRTF customization (Section 2) and delivered to the listener (Section 3). Furthermore, static localization performances of the HRTF model are assessed through a preliminary subjective test (Section 4).

2. Extraction of pinna features

If we fix the direction of the sound source with respect to the listener, the greatest dissimilarities among different people's HRTFs are due to the massive subject-to-subject pinna-shape variation (Cheng and Wakefield, 2001). The external

ear plays an important role by introducing peaks and notches in the high-frequency spectrum of the HRTF, whose center frequency, amplitude and bandwidth greatly depend on the elevation angle of the sound source. Unfortunately, although we know that these peaks and notches are responsible for vertical localization ability (Hebrank and Wright, 1974), their relation with anthropometry has not been fully understood yet.

However, a previous work of ours (Geronazzo et al., 2011) highlighted that while the resonant component of the pinna-related counterpart of the HRTF (known as PRTF) is similar among different subjects, the reflective component of the PRTF comes along critically subject-dependent. In the same context, and more rigorously in a following work (Spagnol et al., 2013a), we exploited a simple ray-tracing law to show that in median-plane frontal HRTFs (with elevation ranging from $\varphi = -45°$ to $\varphi = 45°$) the frequency of the spectral notches, each assumed to be caused by its own reflection path, is related to the shape of the concha, helix and antihelix on the frontal side of the median plane at least. This opens the path for a very attractive approach to the parametrization or selection of HRTFs based on individual anthropometry: extrapolating the most relevant parameters that characterize the pinna's acoustic contribution just from one or more pictures of the user's external ear.

Clearly, extracting the relevant features from a 2-D representation of the pinna implies a mandatory image-processing step. The clearest contours of the pinna as well as the ear canal entrance must be recognized to calculate distances between reflection and observation points and translate them into notch frequencies. Intensity edge detection techniques applied to a single picture of the pinna are hardly exploitable. In particular, the Canny (1986) method is known to fail in low-contrast areas, such as the pinna. This task can be instead achieved through a technique known as multi-flash imaging (Raskar et al., 2004): by using a camera with multiple flashes strategically positioned to cast shadows along depth discontinuities in the scene, the projective-geometric relationship of the camera-flash setup can be exploited to detect depth discontinuities (in our case, pinna contours) and distinguish them from intensity edges due to color discontinuities.

To investigate the potential of such technique, a multi-flash camera prototype was custom-built by the authors. The device, pictured in Plates 1 and 2, is composed of a through the lens (TTL) serial JPEG camera connected to a battery-powered Arduino UNO microcontroller board equipped with a data-logging shield. Four Super Bright White LEDs are symmetrically positioned around the camera eye and can be turned on independently. The electronic components are secured to a rigid board and enclosed in a hemi-cylindrical polyvinyl chloride (PVC) foil mimicking the pinna helix shape (see Plate 2). Finally, because a dark environment is desirable when shooting such kind of pictures, the open side of the arc can be closed by a black silk cut with Velcro fastening strips.

Acquisition of the required pinna pictures is managed as follows. As depicted in Plate 3, the subject presses the open top side of the device right around the left or right pinna trying to align the hemi-cylinder with the helix. The shape of the device affords correct orientation as referred to the outer ear. An Arduino sketch takes a set of four pictures, each synchronized with a different light flash. Because of the required storage time, this basic procedure takes approximately 30 seconds, during which the subject should try to

Plate 1.
The multi-flash camera
prototype: electronic parts
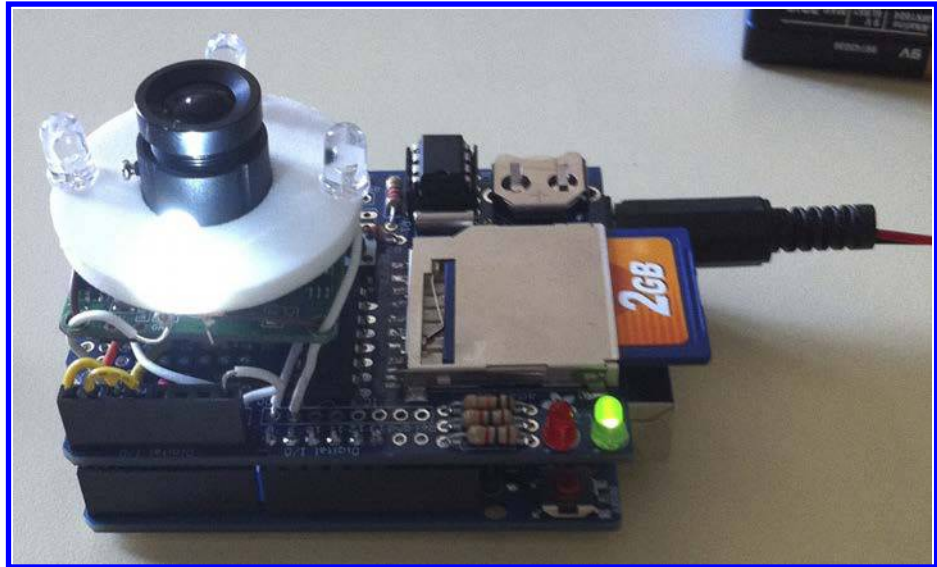
Plate 2.
The multi-flash camera
prototype: full prototype

keep the device as still as possible with respect to his/her pinna. The four pictures, stored in a wireless SD card as 320×240 pixel *jpg* files, are ready to be transmitted with low latency to a mobile device.

An image-processing algorithm is then able to recognize and separate the contours which are of interest to us and straightforwardly calculate the associated notch frequencies as functions of the elevation angle of the sound source. To do so, the four pictures (left side of Figure 1) need to be fed to a collection of scripts automatically performing the following steps:

Plate 3.
Acquisition of the four
pinna pictures
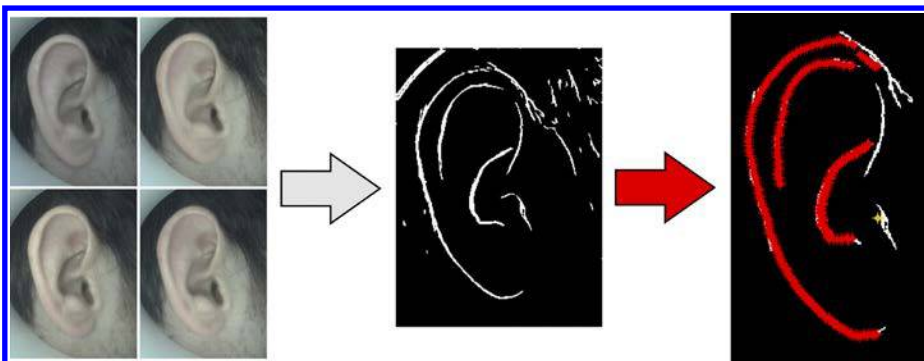
Notes: left: the four pinna pictures; middle: the depth edge map; right: the extracted contour points (red) and the ear canal point (orange)

Figure 1.
Contour extraction
procedure

- *Motion correction*: To compensate for subject motion, the four pictures are first rotated and then translated for the best possible relative alignment according to a standard 2-D correlation function;
- *Depth edge detection*: Based on the four pictures and their relative differences in shadow and lighting, a *depth edge map* is computed through the algorithm proposed by Raskar *et al.* (2004) as a binary matrix whose white pixels

represent the most prominent depth discontinuities (middle panel of Figure 1);

- *Map refinement*: Only the connected components containing at least 100 pixels are kept in the depth edge map;

- *Ear canal detection*: The connected component corresponding to the tragus edge is isolated; the ear canal entrance is taken as the darkest point of one of the initial pictures falling in the tragus edge's bounding box;

- *Contour tracking*: For each desired elevation angle φ, all the $0 \rightarrow 1$ transitions in the depth edge map along the ray originating from the ear canal point and heading toward the pinna with $-\varphi$ inclination are stored as distances in pixels. Then, a partial tracking algorithm (McAulay and Quatieri, 1986), originally used to group sinusoidal partials along consecutive temporal windows according to their spectral location, is exploited to track the three longest contours (concha wall, helix inner border and helix outer border in increasing order of distance) along elevation φ, where distance values take the role of partials (right side of Figure 1);

- *Computation of pinna-related features*: The three distance tracks $d_i, i = 1, 2, 3$, are translated into notch frequency parameters through the following linear law (Spagnol *et al.*, 2010a):

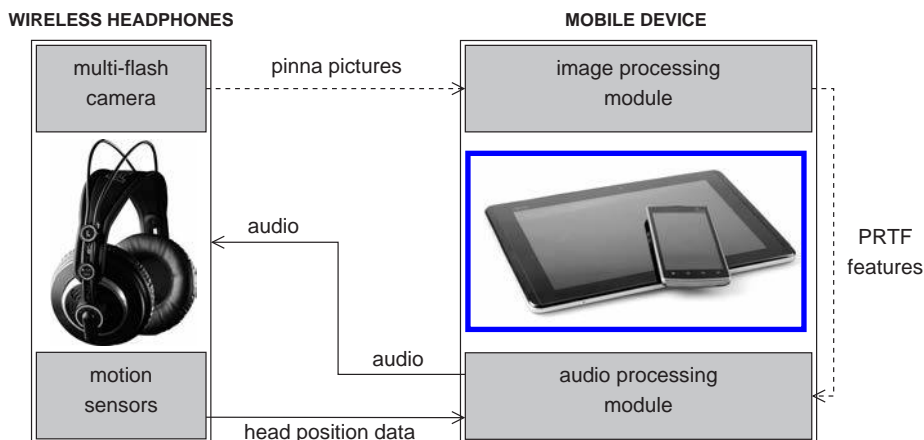$$f_n^i(\varphi) = \frac{c}{2d_i(\varphi)}$$

where c is the speed of sound and approximated as fifth-order polynomial functions of the elevation angle $F_n^i, i = 1, 2, 3$.

The effectiveness of the multi-flash device in extracting pinna contours has been investigated in a previous work (Spagnol *et al.*, 2013b). Results on 30 subjects revealed that the ear canal point is always correctly identified and that 93.3 per cent of the edge tracks are correctly extracted. The device is currently being used for anthropometry-based HRTF selection tests (Geronazzo *et al.*, 2013b); in particular, HRTF selection procedures for static acoustic scenes (Geronazzo *et al.*, 2014) have been evaluated using the same technological platform.

3. The real-time system

To exploit the above-discussed relation between anthropometry and HRTF features, we propose the modular system sketched in Figure 2. The system includes the multi-flash camera described in the previous section, proposed as a stand-alone yet wearable device. In the realization of this system, the main technical challenge lies in the exchange of the relevant data between headphones and mobile device.

If we switch from a static to a dynamic environment where the source moves with respect to the listener and/or *vice versa*, both source direction and distance perception become much eased. The tendency to point toward the sound source to minimize interaural differences, even without visual aid, is commonly seen and openly disambiguates any front/back confusion (Wightman and Kistler, 1999). Active motion helps especially in azimuth estimation and to a lesser extent in elevation estimation (Thurlow and Runge, 1967). Furthermore, thanks to the *motion parallax* effect, slight

Notes: Broken line arrows refer to offline data exchange and solid line arrows to real-time data exchange

Figure 2.
A simplified scheme of the
system's architecture and
software

translations of the listener's head on the horizontal plane can help discriminating source distance: if the source is near, its angular direction will drastically change after the translation, while for a distant source, this will not happen.

A pair of common headphonesm augmented through motion sensors, as the one pictured in Plate 4 (AKG K240 MKII), can be used to control the parameters of the structural HRTF model. The Trivisio Colibri wireless motion tracker installed on top of the headphones incorporates indeed a number of sensors (a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis digital compass) able to track the 3-D orientation of the user's head, thanks to the 6-DoF motion processing they convey.

3.1 Head tracking
Data from the motion sensors (pitch, roll, and yaw rotations of the head) are sent in real time by radio transmission to the audio processing module and translated into a couple of polar coordinates (θ, φ) of a fixed or moving sound source. These coordinates represent the input to the binaural audio engine that performs the convolution between a desired sound file and the user's customized synthetic HRTFs. This way, provided that the center of rotation of the head does not excessively translate during the rotation (distance between the user and the sound source cannot indeed be tracked in real time by the available sensors), the user will ideally perceive the position of the virtual sound source as being independent from his or her movement.

3.2 The model
The output of the pinna feature extraction algorithm implemented in Sec. 2 is fed to the structural HRTF model whose global view is sketched in Figure 3. A fundamental assumption is introduced, i.e. elevation and azimuth cues are handled orthogonally, and the corresponding contributions are thus separated. Vertical control is associated to the acoustic effects of the pinna, and horizontal control is delegated to head diffraction.
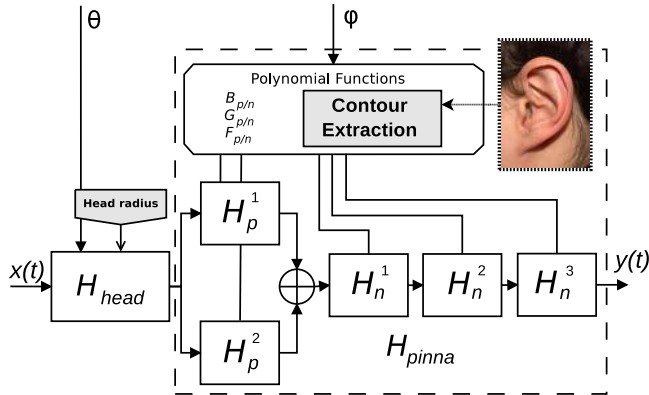
Plate 4.
Headphones augmented
with a head pose tracker

Indeed, median-plane HRTF patterns vary very slowly when azimuth increases, especially up to about 30° (Lopez-Poveda and Meddis, 1996).

As for azimuth effects, a simple spherical head model (Brown and Duda, 1998) is used for filter H_{head}, where the head radius parameter is defined by a weighted sum of the

Notes: The anthropometric extraction procedure on external ear
pictures allows an elevation-dependent parametric tuning of the
pinna filter block H_{pinna}, composed of two peak filters and three
notch filters. The subject's head radius allows instead an azimuth-
dependent tuning of filter H_{head}

Figure 3.
The structural HRTF
model

subject's head dimensions (Algazi *et al.*, 2001a). Pinna effects are instead approximated
by the more complex block $\boldsymbol{H_{pinna}}$ composed of two second-order peak filters $\boldsymbol{H_p^1}, \boldsymbol{H_p^2}$
and three second-order notch filters $\boldsymbol{H_n^1}, \boldsymbol{H_n^2}, \boldsymbol{H_n^1}$ (Dutilleux *et al.*, 2011)
approximating the two main resonances and three main notches that can be
commonly seen in typical PRTFs. The three input parameters of each filter describe,
for each peak or notch, the desired center frequency ($F_{p/n}F_p^iF_p^i$), gain ($G_{p/n}$), and 3-dB
bandwidth ($B_{p/n}$). Source elevation is the only independent parameter used by the
pinna block and drives the evaluation of a number of polynomial functions each
associated to a single filter parameter. Only the center frequency F_n of the three
notches is currently mapped from the individual pinna picture as described in the
previous section; all of the other parametric functions must be chosen a priori.

The model is designed so as to avoid expensive computational and temporal steps,
such as HRTF interpolation on different spatial locations, best fitting non-individual
HRTFs or the addition of further artificial localization cues, allowing implementation
and evaluation in a real-time audio processing environment, such as pure data. Two
appropriately synchronized instances (one per ear) of the model allow for real-time
binaural rendering.

4. A preliminary localization test
To highlight the potential of the structural HRTF model, and in particular of its pinna
block, we performed a preliminary localization test on 5 subjects (all male, age 23 to 41).
All subjects had previous experience with binaural audio and reported normal hearing
according to an adaptive maximum likelihood procedure (Green, 1993). Because our goal
was to test the performance of the HRTF model independently of the other components
of the system, in the following experiment, we neither considered automatic extraction
of pinna contours nor head tracking. The aim of the experiment was twofold:

(1) to test whether the model can render the elevation of a sound source better than a non-individual HRTF set; and

(2) to ascertain the importance of individual pinna contour extraction.

4.1 Stimuli

All stimuli used as sound source signal a train of three 300 ms uniform white noise bursts with 25 ms onset and offset ramps and 250 ms of silence between consecutive bursts. The average measured amplitude of the raw stimulus at the entrance of the ear canal was 60 dB(A). The signal was filtered through a headphone compensation filter (Lindau and Brinkmann, 2012) and applied to measured responses of a knowles electronic manikin for acoustic research (KEMAR) mannequin without pinnae. It has to be highlighted that compensation was not individual; however, such kind of processing offers an effective equalization of the headphone up to 8-10 kHz on average.

Three distinct categories of experimental stimuli were then created, corresponding to the three experimental conditions of the listening test:

- Condition C_1: Stimuli filtered through the structural HRTF model with individual pinna contour parametrization.
- Condition C_2: Stimuli filtered through the structural HRTF model with non-individual pinna contour parametrization.
- Condition C_3: Stimuli filtered through a pair of HRTFs measured on a KEMAR mannequin (Burkhard and Sachs, 1975).

The HRTFs used in condition C_3 were taken from the center for image processing and integrated computing (CIPIC) HRTF database (Algazi *et al.* 2001b). As for conditions C_1 and C_2, parametric functions F_n^i, $i = 1, 2, 3$, directly derived from the manual extraction of pinna contours from an individual left pinna picture (C_1) or from a picture of a KEMAR mannequin left pinna (C_2). Constant functions $G_n^i = -30$ dB and $B_n^i = 2$ kHz, $i = 1, 2, 3$ were chosen to describe notch parameters not related to pinna anthropometry. The choice of the exact values was performed according to previous studies on the audibility and discrimination of spectral notches in the high-frequency range (Moore *et al.*, 1989; Poon and Brugge, 1993; Alves-Pinto and Lopez-Poveda, 2005). Parametric functions related to the two peaks F_p^i, G_p^i and B_p^i, $i = 1, 2$ were instead fitted to the magnitude spectrum of the pinna-resonant component averaged on all 45 CIPIC subjects' left-ear responses (Geronazzo *et al.*, 2011).

Both conditions, C_2 and C_3, were included as control conditions. As a matter of fact, the comparison between C_1 and C_3 is needed to test whether the model can render elevation better than a non-individual HRTF set, while results of the comparison between C_1 and C_2 reflect onto the psychoacoustic impact of having individual parameters.

4.2 Setup and protocol

Acquisition of pinna images was the first step. We created an *ad hoc* capture environment to acquire a left-side face picture of the experimental subject. In a second phase, the picture was first rotated to horizontally align the tragus with the nose tip, and then the maximum protuberance of the tragus was chosen as the ear canal point. The three main pinna contours were manually traced and then used to

calculate scaled distances from the ear canal point, and consequently parametric functions F_n^i, $i = 1, 2, 3$, as previously described. The subject then entered a Sound Station Pro 45 silent booth and wore a pair of Sennheiser HDA 200 headphones plugged to a Roland Edirol AudioCapture UA-101 external audio card working at 44.1 kHz sampling rate.

Nine different stimuli per condition, each repeated 6 times during the test for a total of $9 \times 3 \times 6 = 162$ trials, were presented to the experimental subject. These corresponded to 9 different elevation values from -45 to $45°$ in $11.25°$ steps in the frontal half of the median plane. We chose to consider the median plane because, as already mentioned, relative azimuthal variations up to at least $\Delta\theta = 30°$ at fixed elevation cause very slight spectral changes in the HRTF, hence we expect pinna responses in this region to be elevation-dependent only. Elevations higher than $45°$ were instead discarded because of both the high degree of uncertainty in elevation judgments (Blauert, 1983) and the general lack of spectral notches in the corresponding HRTFs (Spagnol *et al.*, 2011).

The experiment was structured in six different blocks of trials, each corresponding to one single condition and three repetitions of the nine stimuli, proposed in random order. The sequence of presentation of the blocks followed a Latin-square design. To reduce fatigue of the subject, we added a 30-second pause between blocks. Subjects were instructed to enter the elevation judgment right after each sound presentation in a graphic user interface (GUI) designed in MATLAB (see Figure 4) and inspired to the one appearing in a previous work (Begault *et al.*, 2001). Perceived elevation of the sound source was selected by placing a point in one of the two green portions of a circular ring surrounding a side view of a human-head profile. Each portion, one in front and one on the back of the profile, spanned elevations from -45 to $45°$. The back portion was added to take into account possible front/back reversals that typically occur in localization tasks with non-individual HRTF sets (Wenzel *et al.*, 1993; Møller *et al.*, 1996).

4.3 Results

Figure 5 reports the elevation results of the five subjects divided by experimental condition as scatterplots. Localization errors in elevation were analyzed with front/back reversals resolved. The average localization error for the three conditions, along with front/back and up/down reversal rates (the up/down reversal rate is calculated with a tolerance of $15°$ in elevation angle around the horizontal plane and averaged over all target elevations except $\varphi = 0°$), are shown in Table I.

Results show that for all subjects, except one, condition C_1 scores the lowest elevation error. This represents an average improvement of 23.7 per cent compared to C_2 and of 15.4 per cent compared to C_3, with subjective peaks (subject SB) of 35.1 per cent and 35.7 per cent, respectively. Such a result confirms that pinna contours have high significance for elevation cues and that the proposed mapping for the structural HRTF model effectively succeeds in decreasing the elevation error with respect to non-individual HRTFs. Conversely, C_2 scores the highest elevation error in 4 cases out of 5, suggesting that the model cannot guarantee acceptable elevation performances when individual parametrization is not implemented.

The individually parameterized model also succeeds in remarkably improving the up/down reversal rates compared to the non-individual HRTF set: up/down reversals in
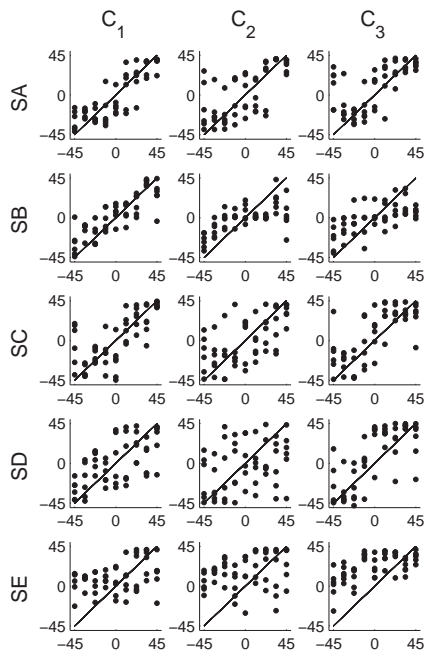
Figure 4.
The experimental GUI
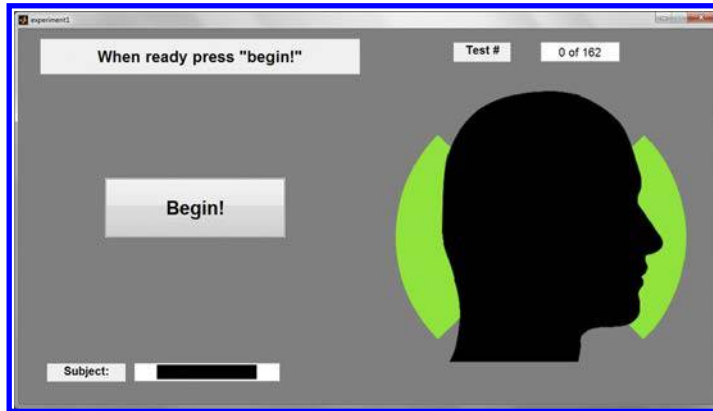
Figure 5.
Elevation scatterplots of
the five subjects, with
target and perceived
elevation on x- and y-axes,
respectively

Notes: Black lines represent ideal response
curves

C_1 are on average halved with respect to C_3. Front/back reversal rates deserve instead
a separate analysis. If we exclude the two special cases of subjects SA and SB, who
always perceive virtual sources in the front and in the back hemisphere, respectively, the
other subjects show different trends. A surprising result is that subject SD, who very
often perceives stimuli as coming from the back in both conditions C_2 and C_3, almost
eliminates front/back reversals when his individual contours are used.

Criterion	Subject ID	C_1	C_2	C_3
Mean elevation error	SA	12.6°	17.5°	17.5°
	SB	12.4°	19.1°	19.3°
	SC	15.4°	19.9°	17.3°
	SD	20.3°	26.4°	19.0°
	SE	24.8°	29.3°	27.9°
	Mean	17.1°	22.4°	20.2°
Up/down reversal rate	SA	6.2%	18.7%	12.5%
	SB	0.0%	2.1%	6.2%
	SC	6.2%	8.3%	6.2%
	SD	6.2%	18.7%	8.3%
	SE	10.4%	25.0%	25.0%
	Mean	5.8%	14.6%	11.6%
Front/back reversal rate	SA	0.0%	0.0%	0.0%
	SB	100%	100%	100%
	SC	77.8%	55.6%	42.6%
	SD	3.7%	90.7%	79.6%
	SE	27.8%	35.2%	48.1%
	Mean	41.9%	56.3%	54.1%

Table I.
Results of the localization test

5. Conclusions

The structural HRTF model as it currently is represents a notable extension of the only other customizable pinna model available in the literature (Satarzadeh *et al.*, 2007) as it includes a large portion of the frontal hemispace and is thus suitable for real-time control of virtual sources in a number of applications involving frontal auditory displays, such as a sonified mobile screen (Walker and Brewster, 2000). Further extensions of the model may include source projection behind, above and below the listener.

We are currently working toward a solid and reliable implementation of the structural HRTF model. The localization test described in this paper serves as the first attempt to subjectively evaluate the degree of accuracy of the presented binaural audio system. Although referring to a preliminary test, these results encourage a deeper analysis of the psychoacoustic impact that the individualized HRTF model has on perceived elevation of virtual sound sources. The reliability of the structural HRTF model and its integration in the proposed real-time system will be assessed in the next stages of the evaluation process.

Many improvements can be done at the design level. First, we will switch to a completely wireless system through the use of a pair of wireless headphones. Fast shooting is also desired to reduce the duration of the picture acquisition routine down to a few seconds and make motion correction become much less critical. We will also consider whether a smaller and more compact version of the multi-flash camera device can be slotted inside one of the two headphones' cups if space (both inside the cup and between the lens and the ear of the user wearing the headphones) permits. Ultimately, in-place sensing and processing on a mobile device having all the required motion and image sensors represents in perspective the optimal solution in terms of cost and flexibility. The resulting hardware/software package will hopefully allow an easy and low-tech fruition of custom spatial audio to any user.

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About the authors

Simone Spagnol received a BS degree in Computer Engineering in 2006 and an MS degree in Computer Engineering in 2008 from the University of Padova, Italy. He was Visiting Scholar at the Laboratory of Acoustics and Audio Signal Processing, Aalto University, Finland, in 2010. He received a PhD degree in Information Engineering (Curriculum in Information and Communication Technology) at the University of Padova in April 2012. He is currently a Postdoctoral Fellow at the University of Padova. His research interests include binaural sound localization and synthesis and sonic interaction design. Simone Spagnol is the corresponding author and can be contacted at: spagnols@dei.unipd.it

Michele Geronazzo received a BS degree in Computer Engineering in 2006 and an MS degree in Computer Engineering in 2009 from the University of Padova, Italy. He received a PhD degree in Information Engineering (Curriculum in Information and Communication Technology) at the University of Padova in April 2014. He is currently a Postdoctoral Fellow at the University of Padova. His research interests include binaural technologies and multimodal interaction in virtual environments.

Davide Rocchesso received a PhD degree from the University of Padova, Italy, in 1996. He is Associate Professor at the Iuav University of Venice, Italy. He has been the coordinator of EU project the sounding object and local coordinator of the EU project closing the loop of sound evaluation and design and of the coordination action sound-to-sense; sense-to-sound ($S2S^2$). He has been chairing the COST Action IC-0601 sonic interaction design, and he is now coordinating the EU project sketching audio technologies using vocalizations and gestures.

Federico Avanzini received a PhD degree in Information Engineering from the University of Padova, Italy, in 2001. Since 2002, he has been with the Sound and Music Computing group at the Department of Information Engineering of the University of Padova, where he is currently Assistant Professor. His main research interests are in the area of sound synthesis and processing. He has been key researcher in numerous European projects (FP5, FP6) and national projects and PI of the EU project *DREAM* (Culture 2007) and of industry-funded projects. He was the General Chair of the 2011 International Sound and Music Computing Conference.