USING `show_data`*

CIPIC Interface Laboratory
Center for Image Processing and Integrated Computing
University of California, Davis
http://www.interface.ucdavis.edu
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1. Introduction

The script `show_data` is a MATLAB™ program that makes it easy both to inspect and to listen to head-related transfer function data (HRTF data) in the UCD-CIPIC format. It provides a graphical user interface that supports the following functionality:

1. Load an HRTF data file
2. Simultaneously display several graphs
   - Left-ear and right-ear impulse response images
   - Left-ear and right-ear frequency response images
   - Left-ear and right-ear impulse response graphs
   - Left-ear and right-ear frequency response graphs
   - Interaural time difference versus elevation
3. Change azimuths and elevations
4. Use logarithmic or linear frequency scales
5. Apply or remove spectral smoothing
6. Listen to spatialized test sounds
   - Sounds at a particular azimuth and elevation
   - Sounds in sequence of elevations around a "cone of confusion"

The companion function `hor_show_data` provides similar but more primitive functionality for inspecting and listening to HRTF data for the horizontal plane. Its operation is described in Section 6.

2. System Requirements

The program uses three-dimensional arrays, and thus requires MATLAB 5.x or higher. It has been tested primarily on PC platforms under Linux and Windows 9x, and may have to be modified to run on other computing systems. Although we welcome reports of problems or suggestions for enhancements, no support of any kind can be provided.

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2. The Minimum You Need To Know

The impatient reader can proceed as follows:

1. Launch MATLAB.
2. Either connect to the `show_data` directory or add the `show_data` directory to MATLAB's search path.
3. At the MATLAB prompt, type "`show_data`". The empty GUI window should appear. Maximize it to make it fit the full screen.
4. Load an HRTF data file by scrolling to and clicking on a subject number in the subject listbox.

If nothing goes wrong, at this point all of the empty boxes in the window should fill with data. The initial interaural-polar coordinates are 0° azimuth and 0° elevation. You can use the buttons under the graphs on the right to step through different elevations, or the buttons in the center under the images to step through different azimuths. With luck, you can also listen to a test stimulus, preferably using headphones. The `PLAY THREE LOCATIONS` button plays sounds at the current azimuth and three adjacent elevations. The `PLAY CONE OF CONFUSION` button plays 50 sounds for all elevations around the cone of confusion for the current azimuth. If everything is now obvious and intuitive, you can stop reading and enjoy HRTF data exploration. The rest of this document systematically fills in the details.

3. The `show_data` Window

The GUI for `show_data` is shown in Fig. 1. When `show_data` is first started, the six large data windows at the top of the display are blank. When an HRTF data set is loaded, the data windows are filled and the user can control which portion of the data set to display. In this section, we describe the contents of each user-interface control and each data display window. We only describe normal operations; some suggestions for what to do if things go wrong are given in Section 5.

3.1 Specifying the HRTF data file

With a few unimportant exceptions, none of the `show_data` controls will operate until an HRTF data set has been loaded. A data set is identified by the same three-digit number that identifies the subject. To tell `show_data` which data set to use, use the subject selector listbox to scroll to and click on a desired subject number (Item 1 in Fig. 1) If the file is not found or is not in valid UCD-CIPIC format, an error message will appear in the status area at the bottom of the window. See Section 5 if you encounter this problem.

3.2 Interaural-polar coordinates

To understand the data displays, you need to understand the interaural-polar coordinate system that is used with the UCD-CIPIC HRTF data. This spherical coordinate system is shown in Fig. 2. It looks like a globe tipped over, so that the axis of rotation is not vertical but horizontal. The polar axis or axis of rotation is the line between the ears. The origin is at the midpoint of the this interaural axis, and for a human subject is typically a bit below and behind the center of the head. The vertical plane that bisects the head left and right is called the median plane. The direction of a ray from the origin to a sound source is specified by two angles, the azimuth angle θ and the elevation angle ϕ. In interaural-polar coordinates, the azimuth θ is the angle between the ray and the median plane. The elevation ϕ is the polar angle, specifying the rotation around the interaural axis.

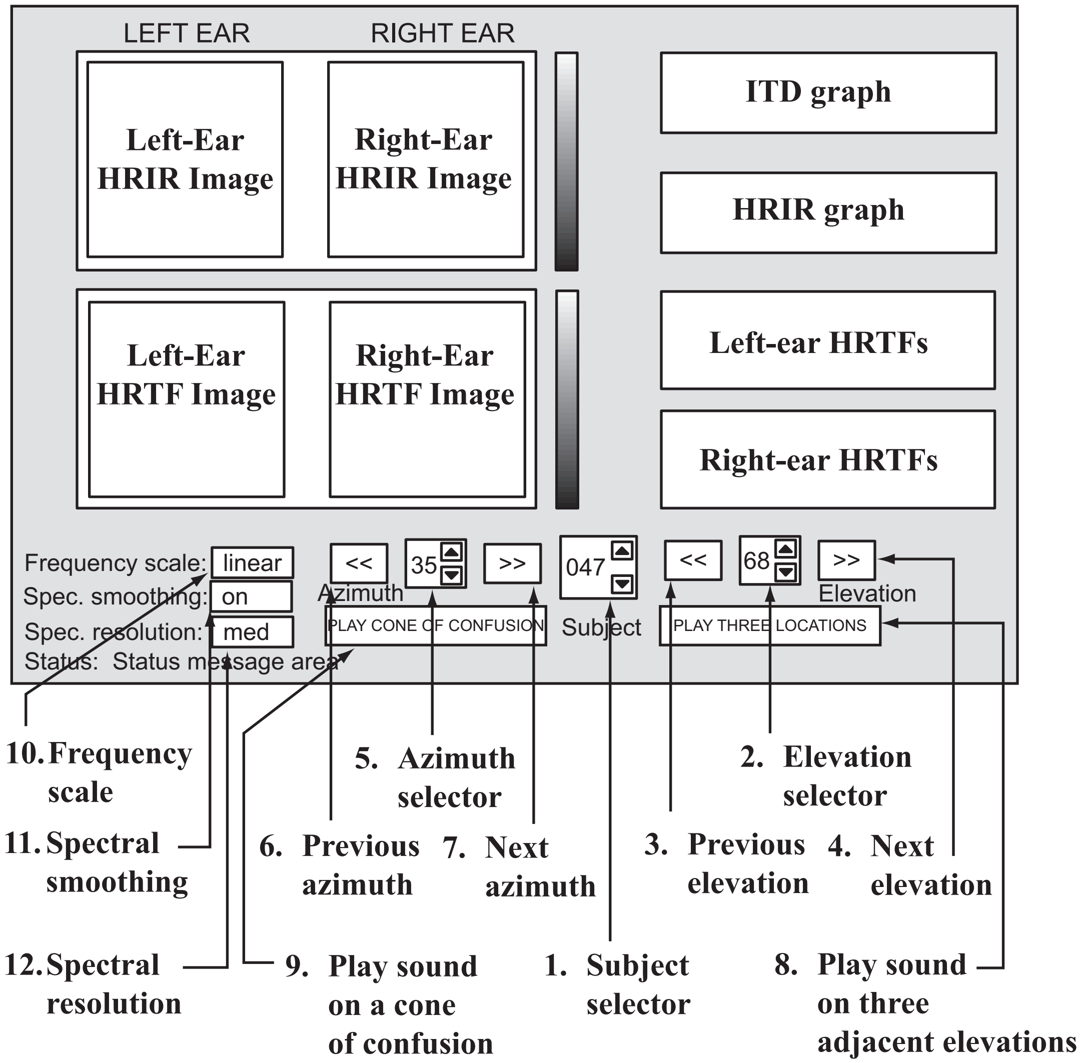

Fig. 1. Layout of the GUI for `show_data`

A number of things follow from this definition. First, the median plane is defined by $\theta = 0°$. The azimuth is always between $-90°$ and $90°$, being negative for points on the left and positive for points on the right. In general, a surface of constant azimuth is a cone. It is often called a “cone of confusion,” because the interaural time difference (ITD) is roughly constant on a cone of constant interaural azimuth, which removes one of the major cues for sound localization. A surface of constant elevation is a half plane. In particular, the surface where $\phi = 0$ is the anterior horizontal half plane, and the surface where $\phi = 180°$ is the posterior horizontal half plane.

Where the range of azimuths is only $180°$, the range of elevations is a full $360°$. We find it convenient to restrict elevation to the range $-90° < \phi < 270°$. That way, a sequence of increasing elevations moves the point systematically through the following sequence of positions around the listener: below, front, above, behind, below. As we observed above, for sources in the horizontal plane, $\phi = 0°$ locates points in front, and $\phi = 180°$ specifies points in back. In general, with interaural-polar coordinates, it is elevation, not azimuth, that distinguishes front from back.

Because of physical experimental limitations, the actual range of azimuths for UCD-CIPIC HRTF data is limited to $[-80°, 80°]$, and the actual range of elevations is limited to $[-45°, 231°]$. Thus, there is always a wedge-shaped volume below the subject for which no HRTF data is available.

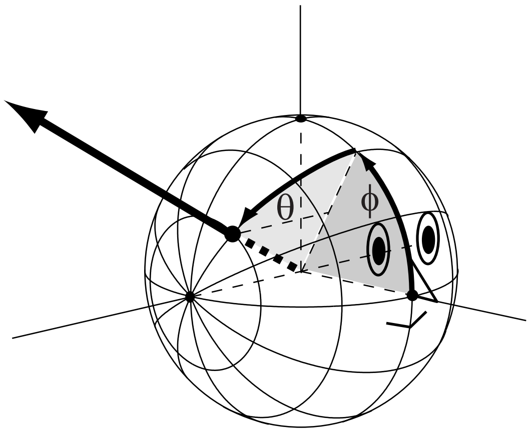

Fig. 2. The interaural-polar coordinate system, with azimuth θ and elevation ϕ

3.3 The HRTF images and graphs

Fig. 3 shows a typical display when an HRTF data file has been loaded. Every image or graph shows data for the specified azimuth angle, which is $-80°$ in this example. MATLAB's "zoom" feature is always enabled, so that you can magnify any region by left-clicking and dragging with the mouse, or by right clicking to restore the figure. The four square boxes on the left show the impulse responses and frequency responses as images. The four rectangular boxes on the right show these responses as graphs, as well as showing a graph of the ITD. We begin by describing the graphs, as identified in Fig. 3 by the circled letters.

A. ITD graph. The ITD is the difference between the time the sound arrives at the right ear and the time that it arrives at the left ear. To make better use of screen area, this graph shows only the magnitude of the ITD; if desired, the algebraic sign can be determined from the HRIR images. If the head were a perfect sphere with the ears located across a diameter, the ITD would be a function of azimuth alone. This interesting graph shows that the ITD also varies with elevation.* This variation is usually relatively small, but significant anomalies occasionally appear. Usually this is a consequence of the subject having moved while the measurements were being made. However, on occasion it indicates an error in the procedure that was used to calculate the ITD. We will see shortly how the HRIR images (E and F) can be used to determine if the ITD calculation is suspect.

B. HRIR graph. The HRIR is the head-related impulse response, which is plotted in blue for the left ear and in red for the right ear. The HRIR graphs are for the specified current azimuth and current elevation (see Fig. 3). They are scaled so that the largest magnitude is unity.

C. Left HRTF graph. The magnitude of the left-ear HRTF in dB is shown as a function of frequency. The solid red graph is for the specified azimuth and elevation, and the two dotted blue graphs are for adjacent elevations. Ordinarily, these three curves are nearly identical, but having all three makes it easier to recognize situations where the response is very sensitive to small changes in elevation. All HRTF graphs and images can be shown on either a logarithmic or a linear frequency scale, raw

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* The axis values were removed from Fig. 3 for clarity. The average ITD for the case shown was approximately -0.6 ms, ranging from -0.63 to -0.54 ms.

or smoothed, and with low, medium or high frequency resolution. The controls for changing these displays are described in Section 4.

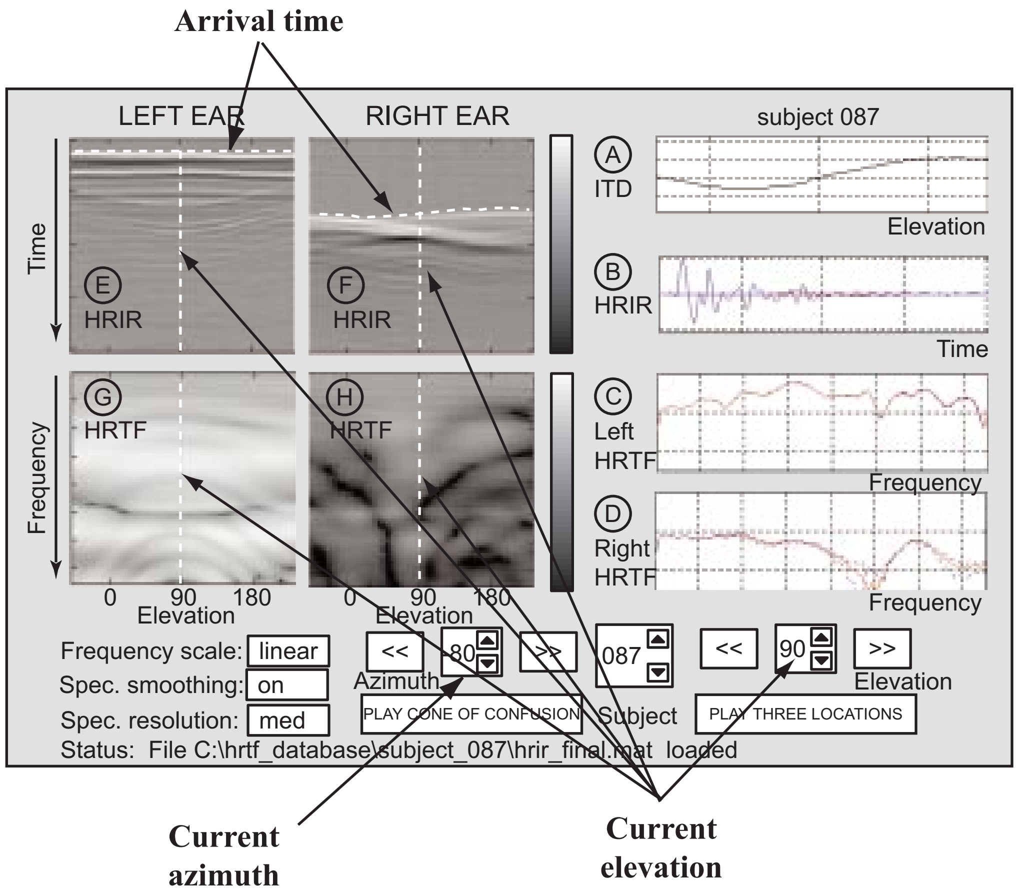

Fig. 3. Appearance of the GUI after an HRTF data set has been loaded

D. Right HRTF graph. This is the same as C, except that it is for the right ear.

E. Left HRIR image. Where the graphs show the response for one particular elevation, the images show the responses for all 50 elevations. Every vertical line through the image at E corresponds to an impulse response at a particular elevation. The dotted vertical lines correspond to the elevation used for the graphs. Thus, the left-ear HRIR shown in the graph (B) corresponds to the "slice" along the vertical dotted line running through the image (E), with bright values corresponding to +1 and dark values corresponding to -1. The more or less horizontal dotted line near the top of the image displays the computed initial arrival time of the incident pulse. Ideally, the arrival time for the ipsilateral ear (the ear nearer the sound source) should be absolutely constant. Any variation in the imagery indicates subject movement. Any variation in the dotted line indicates an error in the program that computed the arrival time. Such variations are rare, but they do occasionally occur.

F. Right HRIR image. This is the same as C, except that it is for the right ear.

G. Left HRTF image. Every vertical line through the image at G corresponds to an impulse response at a particular elevation. The dotted vertical lines correspond to the elevation used for the graphs. Thus, the left-ear HRTF shown in the graph (C) corresponds to the "slice" along the vertical dotted line running through the image (G). No scaling is done, the dB values being indicated by the colorbar to the right of the HRTF images.

H. Right HRTF image. This is the same as G, except that it is for the right ear.

4. Controls

4.1 Changing azimuths and elevations

As was mentioned earlier, the initial display is for $\theta = 0°$ and $\phi = 0°$. There are several ways to change the elevation. You can step along incrementally by clicking the previous or next elevation buttons (Items 3 and 4 in Fig. 1). Alternatively, you can scroll until a desired elevation appears in the elevation selector (Item 2) and click on it. When the elevation is changed, the lower three graphs on the right will change accordingly, and the dotted vertical lines will move across the four images to show you where you are.

Corresponding controls can be used to change the azimuth (Items 5, 6 and 7 in Fig. 1). The main difference is that a change in azimuth will result in a change in the four images.

4.2 Frequency scale

All of the spectral plots can be shown on either a linear or a logarithmic frequency scale. To change from one to the other, simply make your selection using the frequency-scale popup (Item 10 in Fig. 1).

4.3 Spectral smoothing

All of the spectral plots can be shown either raw or smoothed. To change from one to the other, simply make your selection using the spec. smoothing popup (Item 11 in Fig. 1).*

4.4 Spectral resolution

All of the spectral plots can be seen at "low", "medium" or "high" frequency resolution. These values correspond to using 100, 200 or 400 time samples, respectively, in the FFT calculations. The default resolution is "medium." To change the value, simply make your selection using the spec. resolution popup (Item 12 in Fig. 1). Low-resolution plots are advantageous for quickly scanning through different elevations, particularly if the spectral smoothing is being used. High-resolution plots give a more faithful representation, but will take much longer to smooth. This may or may not be important, depending on the speed of your computer.

4.5 Listening to the HRTFs

Implementations of MATLAB for different platforms treat sound output differently, and the current version of `show_data` may not be able to provide sound output for your platform. If that is the case for your system, neither of the two play buttons (Items 8 and 9 in Fig. 1) will be displayed. (See ahead for a possible fix.) To try sound playback, connect the audio output of your system to headphones and click on the `PLAY THREE LOCATIONS` button (Item 8). After a brief pause, three noise bursts will be sent out the left and right audio channels. These noise bursts consist of 250-ms of windowed white Gaussian noise, 100%

* We apply a constant-Q Gaussian filter ($Q = 8$) to the power spectrum to remove perceptually insignificant high-frequency spectral fine structure. If you prefer other smoothing filters and are familiar with MATLAB, you can substitute your choice for `hsmooth.m`.

amplitude modulated at 30 Hz, convolved with the left and right impulse responses, and scaled so that the maximum amplitude is the maximum allowed sound output. The three bursts, which are separated by 150 ms, correspond to the specified elevation and the two adjacent elevations. It is particularly interesting to listen for differences in the three sounds when significant differences are seen in the HRTFs.

It is even more interesting — though computationally somewhat expensive — to listen to noise bursts for all 50 elevations. That lets you hear a sound change as it moves around a cone of confusion. It can be done by pressing the `PLAY CONE` button (Item 9 in Fig. 1). If you choose this option, however, be patient while the 100 convolutions are computed, 50 for each ear. Fortunately, once this is done the results are cached, so that you can listen to the sequence again without having to wait. Of course, if you change azimuths or subjects, the convolution process will have to be repeated.

4.6 Printing

The standard MATLAB processes can be used to print the display. However, getting the desired results requires proper print setup. Under Windows, this requires the following three selections before printing:

1. File > Print setup ... > Orientation: Landscape
2. File > Page Position ... > Paper Orientation > Landscape
3. File > Page Position ... > Match Paper Area to Figure Area

Analogous selections should be made with other operating systems.

5. Handling Startup Problems

In this section we suggest workarounds for a few common startup problems that you might encounter.

1. **MATLAB version.** When `show_data` is first started, it checks to be sure that you have version 5.x or higher of MATLAB. Because we rely heavily on three-dimensional arrays, this is a basic requirement with no workaround.

2. **Sound output.** Next `show_data` checks to see if it knows how to output sound with your system, printing a warning message if it does not know what to do. If you are a MATLAB hacker and know how to output two-channel sound at 44.1 kHz, it should be clear how to edit the functions `check_sound.m` and `play_sound_array.m` to get sound output working. If you don't care about sound but just want to stop the warning message from appearing each time, you can set the `show_warning` flag at the start of `show_data` to zero.

3. **Screen resolution.** The final check is for screen resolution. The program can cope with 800-by-600, 1024-by-768 and 1280-by-1024 resolutions, and will try a compromise if your screen is none of these. If this works, you can turn off the warning message by setting `show_warning` to zero. If it does not work, the only recourse is to use the property editor to edit and save the initial blank startup screen to get it to look like Fig. 1 — which is not hard, but is not recommended if you have no experience in creating GUIs for MATLAB.

4. **Data files.** All HRTF data files are named "`hrir_final.mat`." To make it easy for `show_data` to find the data files, we assume that each HRTF file is in its own directory. Specifically, the directory for Subject `nnn` must be named "`subject_nnn`". We also assume that the directory for `show_data` and its supporting files and all of the data directories are under a common parent node, which is the way that the files are organized on the CD-ROM. On many systems, it is possible to run `show_data` directly from your CD-ROM. If you prefer to copy the files to a hard drive, please maintain this directory structure, or else `show_data` will not be able to find the data files.

5. **Subject numbers.** It is not necessary to copy all of the data directories to your hard drive, but the numbers for all of the subjects will still appear in the subject listbox. If you are experienced with programming MATLAB GUIs and want to change these numbers, the file "`subject_numbers.m`" contains the cell array that specifies the subjects, and you can use it when editing the file "`hrtf_display`".

6. **Global variables.** Finally, we should note that `show_data` uses a number of scripts, and thus has a large number of global variables in the workspace. If you perform other MATLAB computations that accidentally change their values, problems can be expected. To allow you to run other functions, `show_data` does not clear the workspace, but if you encounter strange problems, we recommend (a) running connected to the directory that contains `show_data`, and (b) typing "`clear all`" to clear all variables before starting `show_data`.

6. Using `hor_show_data` to study horizontal-plane behavior

Probably the most challenging problem for spatial sound synthesis is controlling the elevation of the virtual source, and the interaural-polar coordinate system used with the UCD-CIPIC HRTF data was chosen because it is particularly convenient for examining HRTF behavior on a cone of confusion. However, it is also very interesting to examine the behavior of the HRTF on a cone with a vertical axis, or on circles of constant height. Here a conventional vertical-polar coordinate system is more appropriate. Although it is straightforward to transform vertical-polar coordinates to interaural-polar coordinates, uniform spatial sampling requires interpolation of the measured HRTFs, which is difficult to do accurately.

The function `hor_show_data` performs this interpolation for points in the horizontal plane. It does not provide all of the functionality of `show_data`, but it allows the user to inspect and listen to the data for 72 uniformly spaced vertical-polar azimuth angles. To use `hor_show_data`, proceed as follows:

1. Launch MATLAB.

2. Either connect to the `show_data` directory or add the `show_data` directory to MATLAB's search path.

3. At the MATLAB prompt, type "`hor_show_data`". The empty GUI window should appear. Maximize it to make it fit the full screen.

4. Load an HRTF data file by scrolling to and clicking on a subject number in the subject listbox. (The subject list box will disappear while the interpolated HRIRs are being computed.)

If nothing goes wrong, the empty HRIR and HRTF boxes in the window will eventually fill with data. Because the interpolation procedure is imperfect, the images will be more erratic than those displayed by `show_data`. If your system supports sound, you can also listen to a test stimulus, preferably using headphones. The `PLAY` button plays a sequence of 73 test sounds, starting in front and proceeding clockwise around the head as viewed from above. It is worth noting that, although the sounds seem to stay nicely in the horizontal plane for some HRTFs, they frequently seem to move out of the horizontal plane for other HRTFs. Thus, the person-to-person variation in HRTFs that complicates the control of elevation is important even if one only wants to render sources confined to the horizontal plane.

7. Copyright Provisions

CIPIC — Center for Image Processing and Integrated Computing
University of California
1 Shields Avenue
Davis, CA 95616-8553