

A high-output, high-quality fMRI compatible sound system.

*Alan R. Palmer, D.C. Bullock and J.D. Chambers
MRC Institute of Hearing Research
University of Nottingham
Nottingham NG7 2RD, UK.*

A HIGH-OUTPUT, HIGH-QUALITY FMRI COMPATIBLE SOUND SYSTEM

INTRODUCTION	5
THE SOUND SYSTEM.....	5
<i>Figure 1: Front and rear views of the console.....</i>	<i>6</i>
<i>Figure 2: External view of the headstage.....</i>	<i>6</i>
SWITCHING ON AND SWITCHING OFF.....	9
INTERACTIONS BETWEEN THE PC AND THE SCANNER.....	9
HOW TO USE THE PROGRAM.....	10
PLAYING MUSIC CDS.....	12
<i>Figure 9. The CD player.....</i>	<i>12</i>
SETTING THE SOUND LEVEL	12
SOUND SYSTEM PERFORMANCE.....	13
IHR FMRI SOUND SYSTEM: FULL SPECIFICATION	13
FREQUENCY RESPONSE AND EXTERNAL SOUND ATTENUATION	13
<i>Figures 10A the frequency response and 10B attenuation characteristics of the headset</i>	<i>14</i>
MAGNETIC DISTURBANCE.....	14
RESULTS USING THE SOUND SYSTEM.....	16
SPECIAL SAFETY FEATURES.....	17
INSTALLATION INFORMATION	17
SETTING UP THE HARDWARE AND ALLOCATING THE NECESSARY RESOURCES.....	18
INSTALLING THE SOFTWARE	18
DEMONSTRATION COMPACT DISK.....	19

INTRODUCTION

This document describes the sound system developed by the MRC Institute of Hearing Research for use in functional magnetic resonance (fMRI) studies. A description of the system is given and where appropriate is supplemented with technical specifications and other details.

While fMRI is increasingly used in studies of the auditory system the high sound levels generated in image acquisition (a 3T scanner can generate sounds of over 130 dB SPL) represent a considerable problem. Additionally, the close proximity of the ears to regions of interest in the temporal cortex means that any headphones used cannot contain materials that disrupt the magnetic fields. To overcome these problems most groups have adopted sound systems delivering sounds via plastic tubes combined with good levels of passive attenuation at the ear. However, existing tube-phone systems present calibration problems and make correction for frequency and phase distortions difficult, thus rendering noise-cancellation techniques less viable, and are non-ideal in terms of fitting, comfort and sound isolation. The system described in this document is based on electrostatic earphones and produces low-distortion sounds over a wide dynamic range up to high levels, minimal disruption of the magnetic fields, good passive attenuation and is easy to fit. The high output levels allow use with subjects with impaired hearing and the low-distortion allows tightly controlled auditory stimulation paradigms. Control of the sound system is via a PC computer, and purpose-built interrupt handling allows easy synchronisation of the stimulation with the scanner sequence.

THE SOUND SYSTEM

The Sound System consists of three separate units as shown diagrammatically in Figure 6. These are: (1) a PC with a Sound Card with optical encoding on-board and a purpose-built interrupt handling card; (2) a Console switch box (Figure 1 shows the front and rear views of the console with the console microphone and monitor speaker); and (3) a remote headstage (Figure 2 shows the headstage with connection to the headphones). (1) and (2) are located in the scanner control room and while (3) can be mounted on or near the scanner housing, to avoid electromagnetic interference from the headstage that could reduce the S/N ratio of the BOLD response, it is advantageous to mount the headstage outside the screened scanner room, but still as close as possible to the scanner (see recommended installation below). The headstage provides signals to a modified set of electrostatic headphones (Figure 3) via non-metallic carbon fibre cables. The headsets are constructed from commercially available electrostatic headphones (Sennheiser HE60/HEV70), which are non-metallic, combined with standard industrial ear defenders (Bilsom 2452). A subject response box linked by optical fibres is also provided. The only connections to the remote headstage are a low-voltage DC power feed, a high-voltage bias supply and twin optic fibres that transfer all status and audio data signals. Whether the headstage is mounted inside or outside the screened scanner room it is advantageous to send the audio signals in digital (optical) form over the possibly long distances involved (up to 40-50 feet) so that no transients or other electrical interference from the very large magnet power supplies can be induced in the transmission lines. The optic fibre signals are compatible with standard CD and DAT audio equipment and can be fed directly via line inputs. Microphones attached to the headphones and the console provide an intercom system. In the recommended installation only the headphones, subject microphone and response buttons enter the screened scanner room and all electrical connections passing into the scanner room are radio-frequency filtered. As a result the sound system minimally affects the baseline image noise levels (see below).

Figures 4 and 5 show the interior views of the console and headstage with the various component circuits labelled. The recommended arrangement of the sound system components is shown in Figure 6.

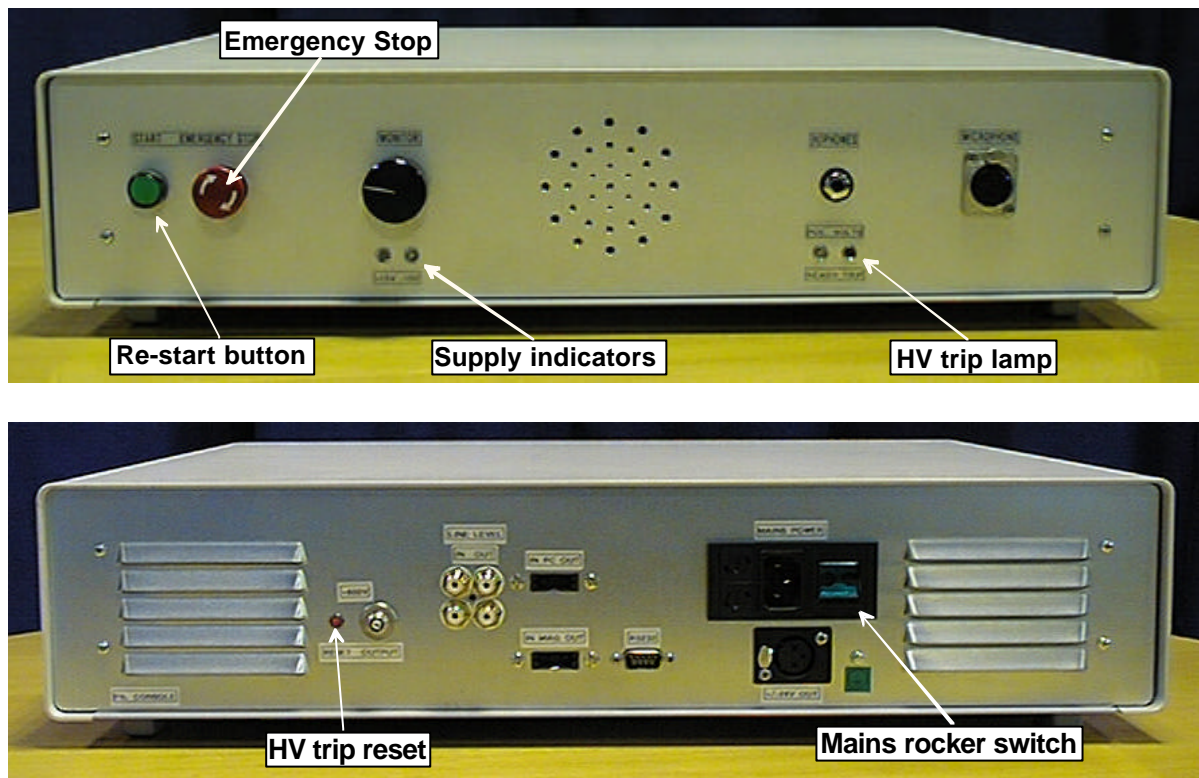


Figure 1: Front and rear views of the console



Figure 2: External view of the headstage



Figure 3: The headphones with safety grill and thick plastic cable protection.

Interior View of the Console

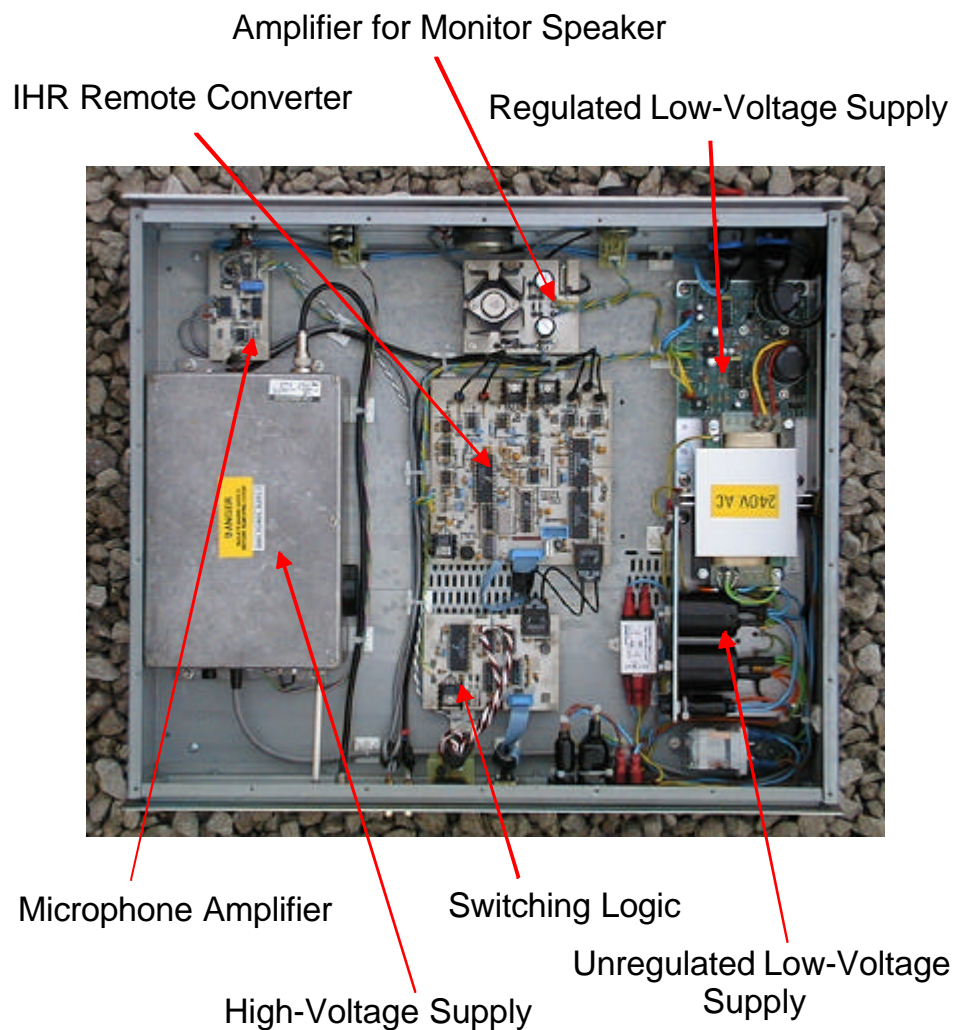
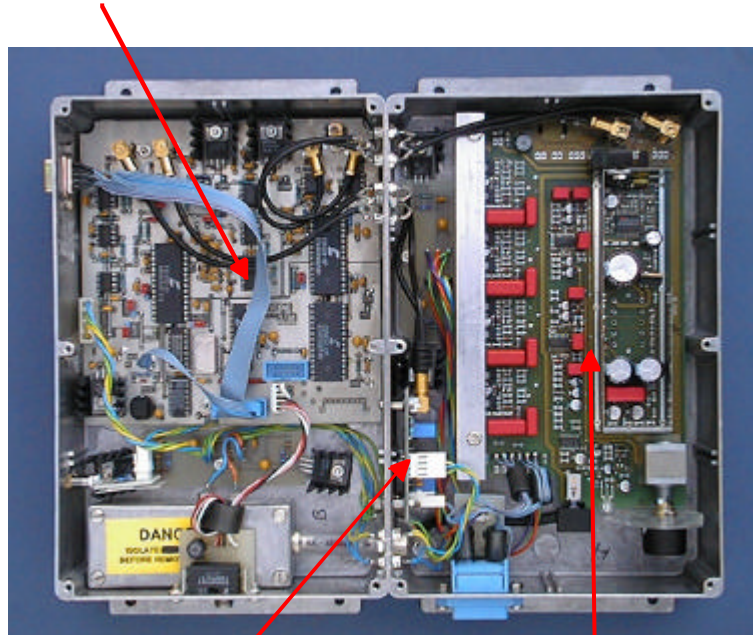


Figure 4: Interior view of the console showing the positions of the components

Interior View of the Headstage

IHR Remote Converter



Subject Microphone Amplifier

Sennheiser Headphone Amplifier

Figure 5: Interior view of the headstage showing the positions of the components

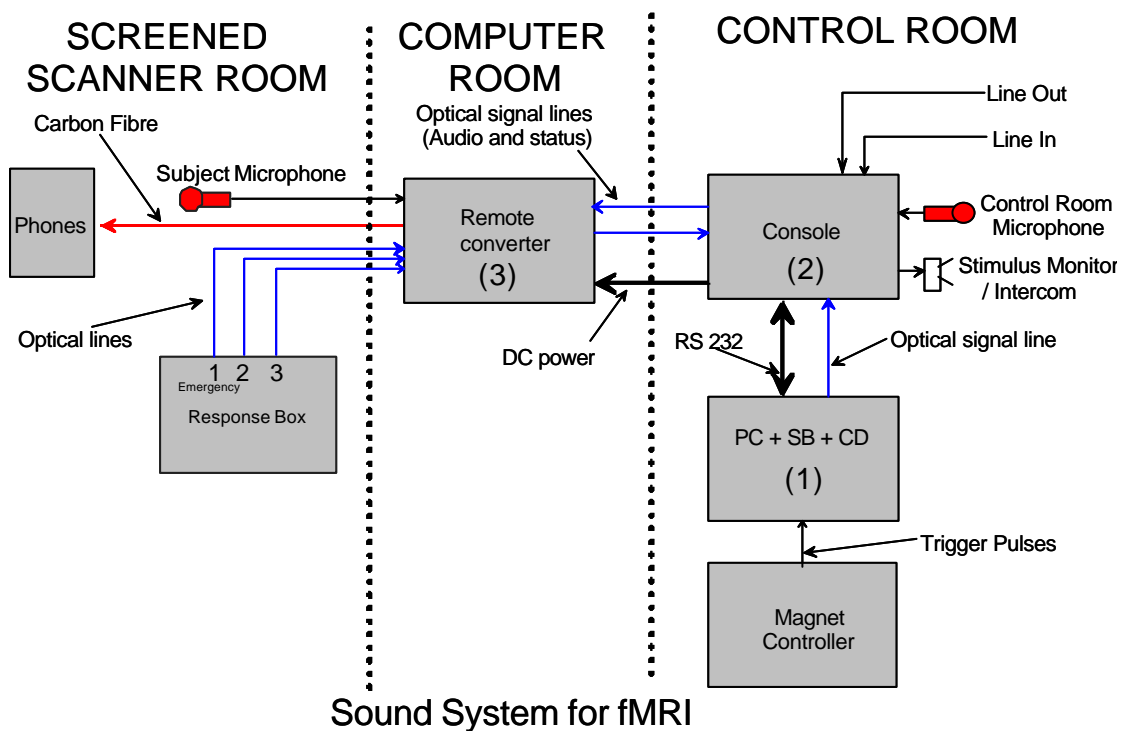


Figure 6: Recommended installation

Switching On and Switching Off

When the system is switched on the microcontroller in the console can receive spurious signals via the COM2 port, until the power supplies stabilise. The console should be switched on before the sound system program is run on the PC, as the program sends an initialising signal to the console.

Mains power is supplied via a switched IEC power inlet on the rear panel of the console. The IEC mains lead supplied is fitted with a 5A fuse which for safety **must always be replaced with a fuse of the same value**. After connecting the IEC lead to the console, plug the lead into a convenient 13A socket outlet and apply power to the console using the green rocker switch on the IEC inlet at the back of the console. The rocker will illuminate green to show that mains power is present in the console.

The sound system console is fitted with a red panic/emergency stop button. The button has a safety latching action such that when pushed it has to be rotated in the direction of the arrows (clockwise) to release it. Once the red emergency button has been released, the circular green start button (on the front panel next to the emergency stop) may be pressed to power up the system. At this point the yellow and blue $\pm 15V$ supply indicators should light. The HV ready lamp should follow almost immediately. If the HV trip lamp flashes instead, there could be damage to the HV feed cable so before resetting the HV trip make sure that all the cabling is intact. The HV trip is reset by pressing the reset button situated on the rear of the console adjacent to the HV outlet. If the remote headstage is fitted correctly, its yellow and blue supply indicators should be illuminated confirming that the $\pm 15V$ and $\pm 10V$ supplies are present.

There is provision for the console to be operated remotely and the connections for this facility are accessed via the 7 pin XLR microphone connector on the front panel of the console. A separate control panel containing an emergency stop button, a monitor loudspeaker with volume control and a microphone with push-to-talk button can be attached to this connector.

When a remote control panel is *not* being used, it is imperative that the console microphone is kept plugged into the microphone socket or the system will *not* power up. Inside the microphone plug is a link in the circuitry for the remote emergency stop which must be present to allow the system to be switched on.

The system may be switched off by pushing the emergency stop button or by using the rocker switch on the IEC mains inlet on the rear of the console.

Interactions between the PC and the Scanner

The sound system uses 16-bit digital waveforms for recording and playback of audio data either stored on the PC disk, or on CD-Rom. Stereo samples are fed at 44.1 kHz from the computer disk, CD or line-in, via sound card and console, over optical links to converters in the headstage. Synchronisation of the sound output with the scanning is achieved by a TTL pulse sent from the scanner which is detected by a purpose-built interrupt card in the PC. The PC counts the pulses and can also add an additional constant delay allowing the stimulus to be moved in time to any position relative to the imaging sequence, whilst still maintaining synchronisation with the imaging controller.

The console contains a monitor speaker and a microphone. The PC controls the status of the console allowing the following configurations:

- a) Send audio signals from the PC (stored as digital waveforms on CD-rom or hard disk) to the headphones and to the console monitor.
- b) Send signals from the console microphone to the subject.

- c) Using the subject microphone, receive speech from the subject, and reproduce through the monitor speaker (allowing subjects to talk back to the control room).
- d) Send signals from line-in sockets on the console to the subject and monitor.
- e) Play conventional CDs.

The subject or experimenter can activate the intercom at any stage.

Figure 7 shows details of the headphone construction. The Sennheiser electrostatic headphone elements are built into Bilsom ear defenders to achieve good passive attenuation of the scanner noise. Figure 7a shows an X-ray image of the headphones in which the only metallic components visible are the connections to the sound system. Since taking this image an extra plastic grill has been added as an additional safety feature (see below). Preparing the subject for the scanner is simply a case of putting on the headphones in the normal way (Figure 7b).

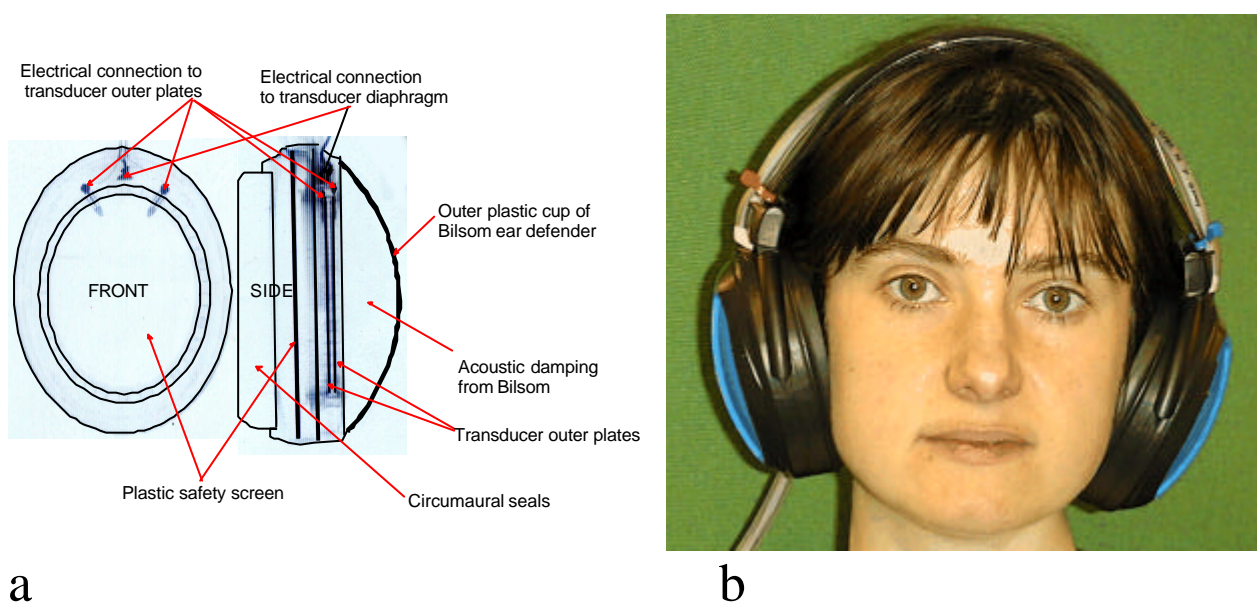


Figure 7: The headset and its construction. (a) X-ray image of the headset (b) Subject wearing the headphones.

How to use the program

The Windows 95™ user interface is shown in Figure 8. Controls (highlighted in red in the following paragraphs) should be referred to this figure.

The user sets up a **Play List** by selecting files on any of the drives connected to the PC using the usual Windows 95™ file selection techniques. A file is added to the playlist by double clicking on it or by clicking on **Add**. The playlist can be saved as a text file and re-loaded at a later date. Playlist files can also be created using any text editor to select series of stimuli.

The **PLAY CONTROL** is used to determine how the files are played. The **Play** button plays all files sequentially until the list is finished. The complete play list is repeated by setting the **Number of Repeats**. **Triggered Play** synchronises the output to the scanner. The first output is initiated when the number of **Pre. Triggers** is received, allowing for any number of dummy scans prior to collection of experimental data. Subsequent output is initiated after **Delay** whenever the number of **Triggers per Stimulus** is received. **Stop** halts the system and **Exit** returns to Windows.

The files are digitally attenuated on output by the value of **Attenuation**. This attenuator affects only stored waveform files not output from music CDs (see Playing Music CDs).

The console microphone is automatically routed to the subject when in between experiments. This allows the subject to hear the conversations in the control room, while the scanner is being set up or other conditions selected are selected, thus reducing the feeling of isolation. The Monitor Source determines whether the stimulus (**PC Audio Out**) or **Magnet Microphone** is monitored.

The headphone source can be switched between **Line Input**, **Console Microphone** or **PC Audio Out**. The **PC Audio Out** button sends .WAV files to the sound system from PC or from the CD player or will allow conventional CDs to be played.

The **Status** box indicates **IDLE** when not set for triggered play, **WAITING** when armed but not triggered and **PLAYING** when playing files. The file number in the playlist and the number of repeats is shown for monitoring progress.

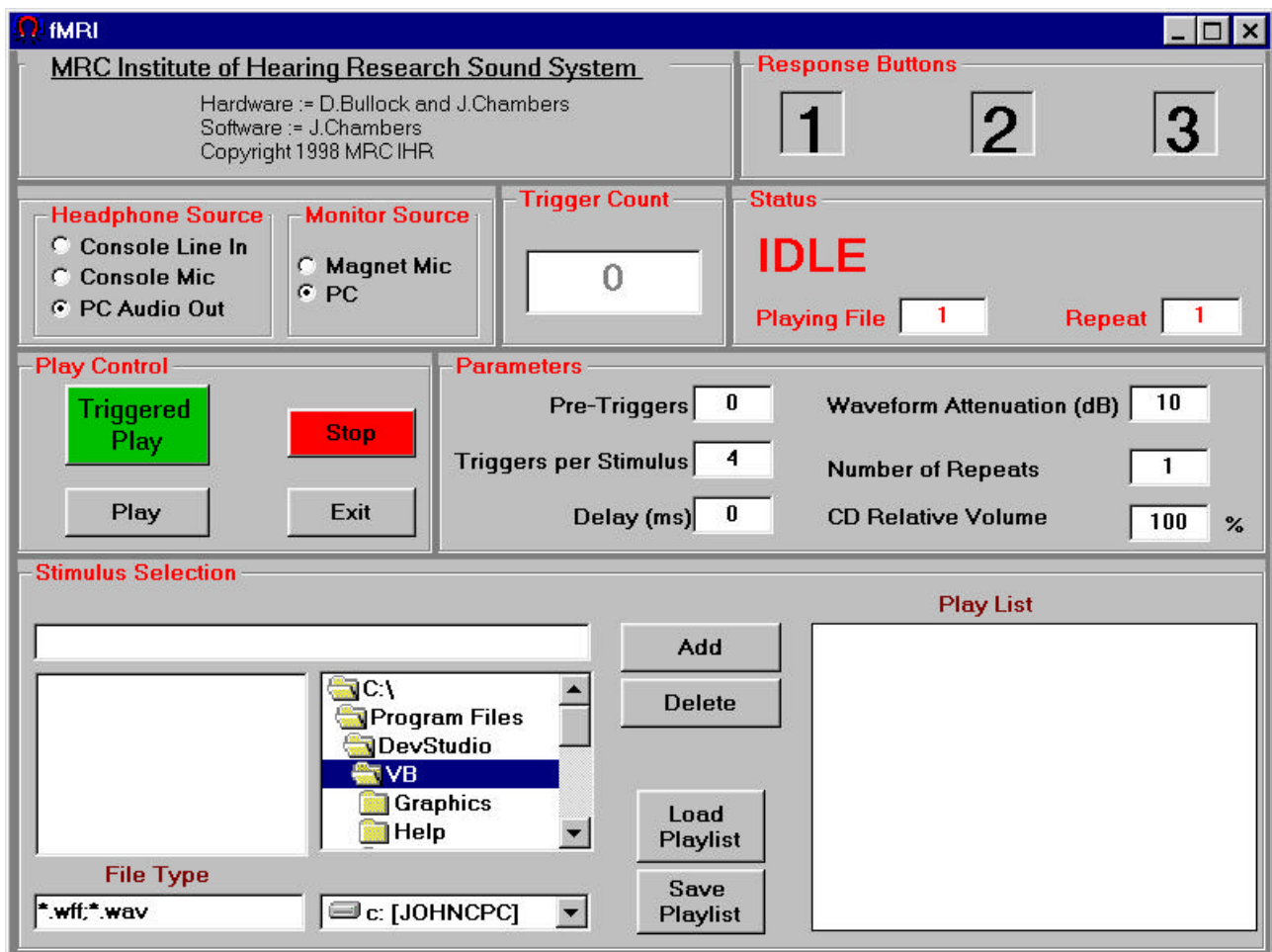


Figure 8: The Windows user interface.

A running log is kept of the subject-response-button presses (which light up when pressed). The program offers the option of saving the response log so that the responses to any individual stimulus in the playlist can be ascertained. The following lines show the format of the log:-

```
C:\SOUNDS\intense\Cb150n01.wav,15:52:07
w,C:\SOUNDS\intense\Cb150n01.wav,15:52:13
C:\SOUNDS\intense\Kb300n06.wav,15:52:17
w,C:\SOUNDS\intense\Kb300n06.wav,15:52:20
w,C:\SOUNDS\intense\Rb300n10.wav,15:52:26
C:\SOUNDS\intense\Rb300n10.wav,15:52:26
```

The first line shows the full path of the file being played and the time at which its output started. The lines beginning with “w” indicate that a button has been pressed. “w” is an arbitrary keyboard character merely used to distinguish different buttons. Following the button press indicator character is again the path of the file being played when the button was pressed and the time at which the button was pressed. Note that multiple button presses during a single sound are recorded sequentially on separate lines.

The console selects the signal source that is sent to the headphones and that is played through the monitor loudspeaker. The heart of the console is a microcontroller that is connected to the COM2 serial port of the PC, the console microphone and the subject response buttons. If either the panic button of the subject response box or the press-to-talk button on the console microphone are depressed, the system goes into full duplex communication mode i.e. the subject hears the console microphone and the monitor speaker plays the signal from the subject microphone. If neither button is depressed the routing is determined by the PC via the serial port.

Playing Music CDs

CDs are played in the usual way by starting the CD Player supplied with Windows (Fig. 9).

A comfortable listening level for the CD should be set using the **CD Relative Volume** on the interface. **The CD should be stopped on the CD Player before starting an fMRI experiment.**

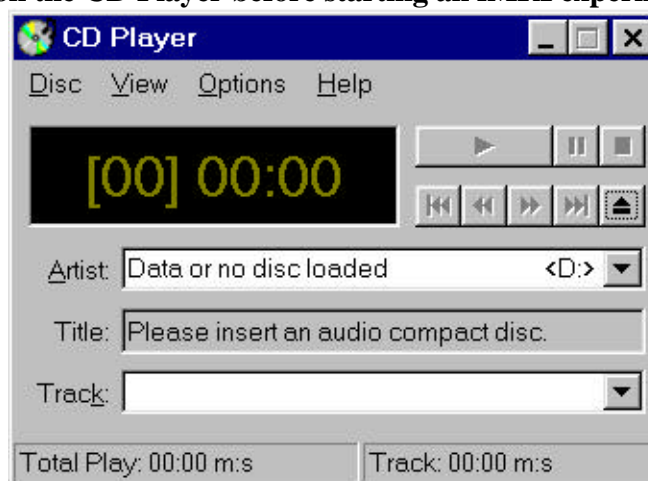


Figure 9. The CD player

Setting the Sound Level

The maximum output of the system has been set up using a 1 kHz pure tone with amplitude at full 16-bits (+- 32767) to be 100 dB SPL. Other levels below this maximum should be set on the interface digital attenuator to maintain calibration.

WARNING !! This calibration is suitable for music and speech but a full 16-bit sine wave can be presented at very high sound levels if the attenuator is set to less than 20 dB. For this reason the default attenuator setting on start up is 20 dB.

SOUND SYSTEM PERFORMANCE

The complete sound system delivers low-distortion speech and music at up to 100 dB SPL (set at this level for safety reasons) and 22.05 kHz bandwidth (limited by the digital sampling rate), with reduction of the intensity of scanner sounds by the ear defenders.

IHR fMRI Sound System: Full Specification

Headphone system.

Sennheiser HE60/HEV70 Stereo headphone/amplifier combination with Modified Bilsom ear defenders

Transducer principle	Electrostatic
Sound coupling	Circumaural
Transmission range	12 - 65,000 Hz (-10dB)*
THD	< 0.1%*
Polarisation voltage	540V max*

IHR modified headphone\eardefender specification

Attenuation of external sound	40 dB (2kHz - 10kHz) # 30 dB (500Hz - 10kHz) #
Frequency response	50 - 10,000 Hz (± 10 dB) combined eardefender/headphone # 50 - 10,000 Hz (± 10 dB) headphones before modification #
Output level capability	Up to 120 dB SPL

Stimulus delivery system

PC with internal sound card with AES and fibre-optic communication port via control console

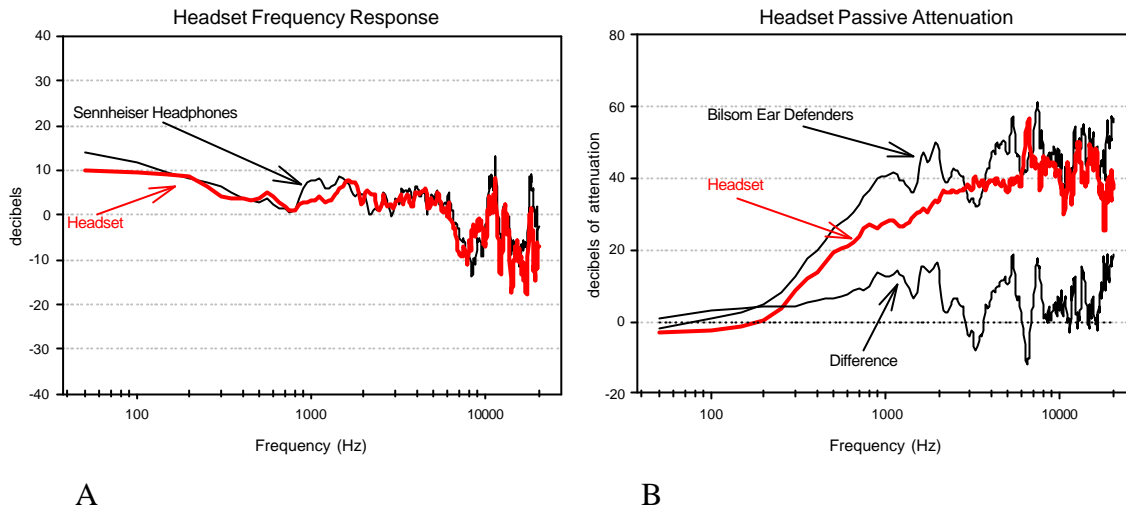
Maximum file length	Unlimited
Sample rate	44.1 kHz
Line level input for maximum output	220 mV RMS
Subject response buttons	Optical
Talk-to-subject microphone	High-quality electret microphone
Console control	RS232 (1200 baud)
Optic data format	AES, compatible with CD and DAT player outputs
Subject talkback microphone	Electret

* Sennheiser specified figures # IHR Test measurements

Frequency Response and External Sound Attenuation

Figure 10A shows the frequency response of the electrostatic headphones (thin black line) measured with a KEMAR mannikin along with the frequency response of the complete headphone/ear-defender combination (thick red line). The curves have been corrected for the frequency response of KEMAR. The incorporation of the headphones in the ear defenders does not compromise the headphone specifications, but reduces the passive attenuation of the ear defenders at low frequencies.

Figure 10B compares the attenuation of the ear defenders alone (thin black line) with that obtained with the complete system (thick red line) which provides 15 dB of attenuation at 250 Hz rising to 40 dB at 4 kHz. The second black line labelled “difference” shows the reduced passive attenuation of the complete system compared with the Bilsom ear-defenders alone.



Figures 10A the frequency response and 10B attenuation characteristics of the headset

Magnetic Disturbance

Only small distortions of the magnetic fields near the headphones were visible on tests with phantoms on a 3T scanner, as can be seen in Figure 11. The extent of these distortions was only about 1-2 cm and thus should cause no problems for imaging auditory brain areas which are located at a greater depth from the surface. These distortions appear to be absent from phantom tests using a 2T scanner.

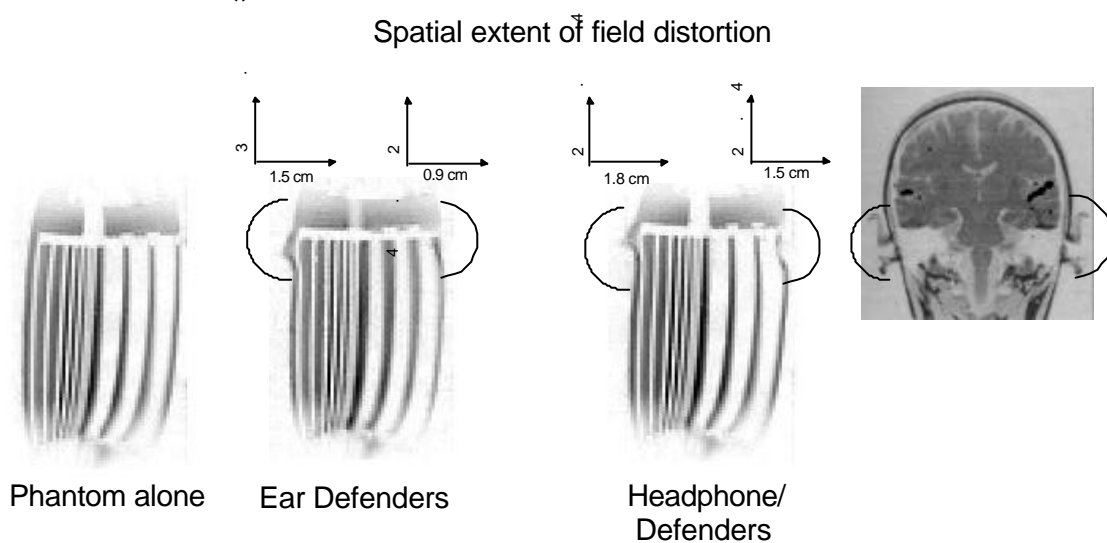
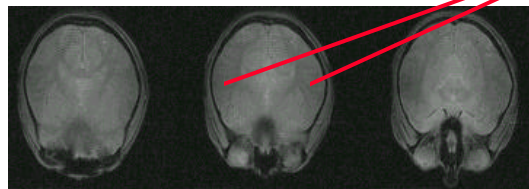
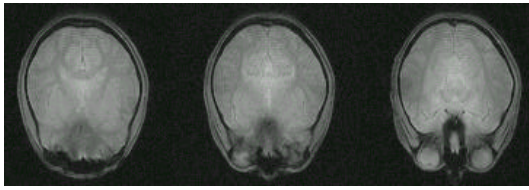


Figure 11: Distortion using EPI. The arrows indicate the vertical and horizontal extent of the field distortion measured directly from the corresponding phantom images.

Radio-frequency isolation was necessary to minimise effects of the headphones and its connections on the signal-to-noise ratio in the MR scanner, which operates at radio frequencies.

Cortical Images without Headset



Darker areas
indicating
possible
susceptibility
artifact

Cortical Images with Headset

Figure 12: Susceptibility shown in FLASH

At 3T using a FLASH sequence (at the Oxford University Centre for Functional Magnetic Resonance Imaging of the Brain) a small susceptibility problem was discovered as indicated by the darkening of the image in the region of interest shown in Figure 12. This probably stemmed from the copper wire connections to the transducers. The problem has now been overcome by using resistive (carbon fibre) cabling.

The most recent tests in the Oxford scanner allowed the generation of the field maps shown in Figure 13, showing distortion to the magnetic field at 3T when a phantom with headphones is placed in the scanner. Distortions from the static magnetic field (which is shown in grey) are represented by changes in pixel intensity (either white or black).

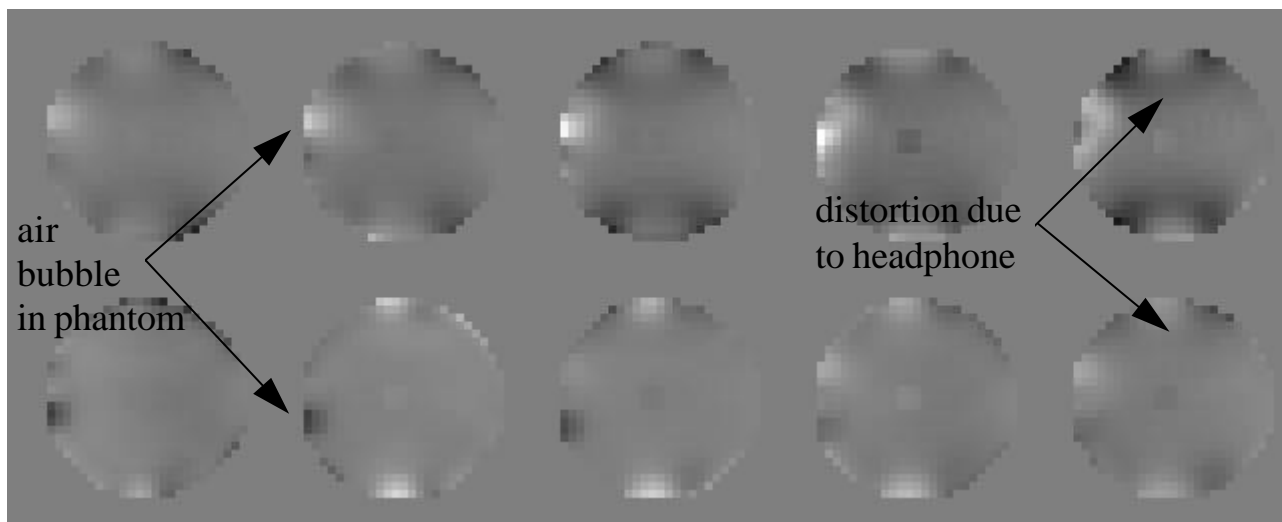


Figure 13: Magnetic field maps at 3T using a phantom with headphones attached.

Mean shift from the static magnetic field is 8.78 Hz (where 42.575 MHz = 1 Tesla). When calculated, the mean intensity change was not significantly different from a field map generated using the Bilsom ear-defenders, suggesting that any minor perturbations in the magnetic field are probably induced by the components of the ear-defenders.

Results using the sound system

Activation of the Auditory Cortex by Speech Sounds

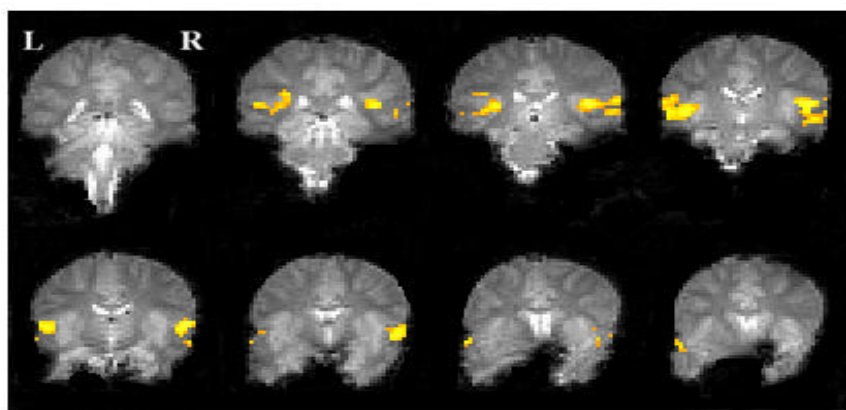


Figure 14: Activation of the auditory cortex by continuous speech presented through the IHR fMRI sound system.

SPECIAL SAFETY FEATURES

Users of any system employing a high-voltage DC polarisation need to have complete confidence in its safety features. The headphones, as supplied, are approved for domestic use and carry the appropriate CE mark. The following is a list of the additional safety measures that we have implemented over and above the BS5724 standard for clinical equipment.

- **HV Power supply.** The headphone/amplifier combination requires 8 mA for operation at peak audio output. Fast-acting safety circuits in the power supply monitor the output current and if demand exceeds 10 mA will clamp the high-voltage output to zero and trip a resettable contact breaker cutting off the power to the HV unit and flashing the HV trip lamp on the front panel.
- **Amplifier.** The audio amplifier supplies both audio and polarisation voltages to the headphone elements. The polarisation voltage is fed through 10M Ohm resistors limiting the single fault current to 60 μ A. The driven audio lines are fed through high voltage capacitors to provide isolation from the 600V dc supply.
- **Headphones.** To enable the headphones to be used in the MR environment all ferro-magnetic parts have had to be removed, including the safety grilles. Incorporation of the headphone elements into the industrial ear defenders has meant that the rear of the element is now fully protected by a solid plastic cover. Two layers of insulating material protect the front of the element. A coarse nylon grille with holes large enough to allow good sound transmission without compromising the electrical safety, and a fine nylon gauze to prevent ingress of dust or other contamination. The carbon fibre cables to the headphones are double insulated, the outer layer being thick walled pvc piping to prevent damage to the cables by abrasion.

The first version of the sound system was built in December 1996. It, and its successors, have been used reliably and routinely for more than two years in conjunction with a 3T fMRI research scanner housed in the Physics Department at the University of Nottingham. We have obtained reliable activation of the auditory cortex using both simple and complex sounds as shown in Figure 14. We have also used the system to investigate optimal scanner sequences for use in auditory research (Hall, D.A., Akeroyd, M.A., Palmer, A.R., Summerfield, A.Q., Haggard, M.P., Elliott, M.R., Gurney, E. and Bowtell, R.W. (1998) Optimal sampling of the haemodynamic changes in auditory cortex for functional magnetic resonance imaging (fMRI). *Neuroimage*, 7, S576). Over the last 15 months, the system has been improved incrementally as experience in its use has accumulated, both in Nottingham, and as a result of tests carried out in scanners in Sheffield, Oxford and London. The preceding sections describe the current version of the system, whose design and implementation are now stable.

INSTALLATION INFORMATION

The sound system will work with a PC of relatively modest performance, but it is recommended that it be run on **at least** a 100 MHz Pentium PC with a minimum of one ISA slot. A high speed CD-ROM with digital output is required to ensure accurate synchronization of the sound output with the scanner. The system for the Oxford University Centre for Functional Magnetic Resonance Imaging of the Brain is supplied complete and fully tested.

Setting up the hardware and allocating the necessary resources

The system requires one IO port and one interrupt to be allocated to it. The hardware board inside the PC has been set up using jumpers for the required resources. Four jumpers select one of the following 16 possible IO port addresses: 210, 230, 250, 270, 290, 2B0, 2D0, 2F0, 310, 330, 350, 370, 390, 3B0, 3D0, 3F0.

The jumpers have been set to use address 230. **These should not be changed.**

The interrupt used by the card is selected using a jumper to be one of the following interrupts: 3, 4, 5, 6, 7, 10, 11, 12, 14 or 15.

The jumper has been set to use interrupt 5. **This should not be changed.**

The software is not “PLUG AND PLAY” and therefore needs to be informed of the system resources used. To allow flexibility and to accommodate the vagaries of some PC clones, the resources are defined in an initialisation file called NMRPLAY.INI, which is located in the C:\WINDOWS directory. For the system for Cambridge University Wolfson Brain Imaging Centre the initialisation file consists of the following lines:

```
[Hardware]
Interrupt=5
Control_Port=230
```

The system is set up to operate through port 0x230 using interrupt 5.

Do not change these settings without consulting IHR – incorrect values will stop the sound system from working. They could also cause many other unpredictable malfunctions!

The connections for the 7 pin XLR plug used for attaching remotely are as follows:

- 1) Emergency stop button (24Volt operated)
- 2) Emergency stop button return.
- 3) Speaker Ground
- 4) Push-to-talk
- 5) Microphone Ground
- 6) Microphone feed
- 7) Speaker feed

Installing the software

The software installation is a two-stage procedure. First insert DISK1 and run A:\SETUP.EXE. Follow the instructions on the screen. When SETUP.EXE finishes insert DISK2 and run A:\INSTALL.BAT. You should get a message ‘**DllRegisterServer in tvichw32.ocx Succeeded**’. Rebooting the machine completes the installation. The executable file is called NMRPLAY.EXE and is found in the C:\NMR\MARK5 directory.

DEMONSTRATION COMPACT DISK

To demonstrate the use of the IHR sound system for fMRI, the CD contains 25 waveform files of continuous spoken speech (speech1.wav, speech2.wav, etc).

The duration of each file is exactly 20 seconds. They span a continuous reading of a complete prose text. The text was read by a male reader, at a natural pace and with a natural prosody. The files overlap slightly with the preceeding file in order to remind the listener of the sense of the text.

An example playlist ("*playlist.lst*") is also provided. This lists all 25 speech files, in numerical order, and is intended to be used as a demonstration of a simple "on-off-on-off" fMRI experiment.

To run the demonstration:

- (i) Load playlist from the CD.
- (ii) Calculate the number of slices (and hence triggers) that will occur during each 20 second stimulus ("on").
- (iii) Set the "Number of Triggers" to **twice** the number of trigger in 20 seconds in order to provide 20 seconds of intervening silence ("off").
- (iv) Set the "Pre-triggers" to be the number of slices (and hence triggers) in a full scan (or volume)
- (v) Set the "Delay" to zero.
- (vi) Select triggered play.

The stimulus sequence will start on receiving the first trigger from the scanner.