THE ENVIRONMENT FOR AUDITORY RESEARCH

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Background

Army personnel are required to perform missions while immersed in a wide range of ambient sounds. The desired acoustic signals reaching a soldier's ears are often physically corrupted by head-worn equipment and unwanted mechanical and natural sounds. To study hearing abilities *in situ*, the reflective surfaces, sound sources, and head-mounted equipment must be emulated in a controlled setting. Acoustic recreations of rural and urban soundscapes mixed with relevant military sounds need to be presented to listeners in controlled laboratory spaces to quantify the effects of auditory environments on listening tasks. For this reason, the Environment for Auditory Research (EAR) facility was conceived and constructed at the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground, Maryland. This new facility will be used to study the ability of soldiers to detect, identify, and localize sounds in realistic operational sound fields and to develop equipment to maximize human communication performance.

"The combination of research spaces and capabilities is unmatched at any military, academic, or industrial facility world-wide."

The Environment for Auditory Research facility is operated by the Auditory Research Team (ART) of the Visual and Auditory Processes Branch (VAPB)—part of the Human Research and Engineering Directorate (HRED) of the ARL. The ART's mission is to conduct basic auditory and speech perception research applicable to ground troops, i.e., dismounted soldiers. Areas of research include the perception of simple and complex sounds, and the effects of hearing protection, head gear, and workload on performance of the human auditory system. Specific types of experiments to be conducted in the EAR facility include auditory localization and situational awareness, as well as speech, distance, and motion perception. The EAR facility is designed to be reconfigurable to simulate a wide range of indoor and outdoor acoustic environments.

ARL is committed to providing access to the space for any researchers who wish to take advantage of its unique capabilities. Mechanisms through which this can occur include test services agreements (TSAs), where individuals rent the space and/or use personnel from the ART for collection of specific data; visiting scholar programs in which researchers spend a set amount of time working in the facilities; and collaborations through joint research efforts such as a cooperative research and development agreement (CRDA). ARL welcomes inquiries about the potential for future collaborations or use of the research facility.

The EAR facility spaces are flexible to accommodate different types of experiments. The acoustic absorption characteristics can be modified from nearly anechoic to moderately reverberant. The sound sources, e.g., loudspeakers, can be repositioned around the listener and hidden from the listener's field of view to minimize visual cues for auditory source location. The ambient noise floor for all research spaces meets noise criterion fifteen (NC-15) specifications when the heating, ventilation and air conditioning (HVAC) system are operating. With the HVAC system off, the spaces are at or below hearing threshold levels. A diagram of the EAR facility is shown in Fig. 1.

The EAR facility encompasses four indoor spaces plus one outdoor space, all coordinated from a single Control Room. First, the Sphere Room was created for research in spatial perception and includes loudspeakers located as if they were connected to a sphere. Second, the Dome Room was created for research in auditory localization with a much denser array of loudspeakers and can be configured to evaluate perception of sound in a hemispherical shape. Third, the Distance Hall was created for research in distance estimation and auditory depth perception and is shaped like a rectangular box. Fourth, the Listening Lab was created for research in speech perception and enables evaluation of up to ten listeners at one time, as well as testing of various sound reproduction systems. Lastly, the OpenEAR outdoor portion of the facility was designed for auditory research in real-world outdoor environments.

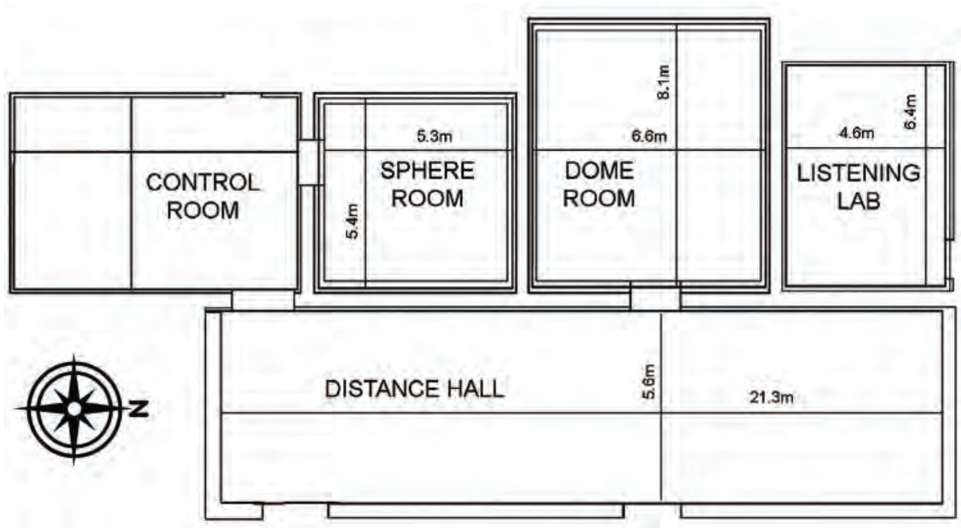

Fig. 1. Layout of the four test chambers in the EAR facility.

Research spaces—general characteristics

The four indoor research spaces have several features in common, which include low noise floors, acoustically deadened listening spaces, and flexible lighting systems. Calibration of the sound system in each room is accomplished centrally via the Control Room. Three identically instrumented listener stations are available for use in any of the research spaces. Two of these stations can be moved to any location within the research spaces. All spaces use the Peavey Media Matrix signal processing equipment and common loudspeaker models.

The EAR facility was constructed to block out as much external noise as possible. This is particularly important at Aberdeen Proving Ground where it is common to have ground vibrations from armored vehicles rumbling past the building, explosions from test range ordnance, and high intensity engine and propeller noise from low flying aircraft. The walls, doors, and ceilings were treated with Sound Transmission Class 64 (STC 64) rated construction material. The sub-floors are slab-on-grade concrete. Floors in the Sphere Room, Dome Room, and Distance Hall are floating floors constructed with fiberglass panels covered with plywood and finished with commercial carpet. To further minimize transferred acoustic energy, the floating floors in these three rooms do not contact the walls. As a result of this acoustic treatment to the spaces, most of the outside noises are inaudible inside the four research spaces.

Reflections from intentionally generated sounds inside the EAR facility are controlled with Black Sonex™ Foam S.T.O.P.™ melamine foam wedges. The wedges cover all interior surfaces and vary from four inches thick in the Distance Hall to ten inches thick in the Sphere and Dome Rooms. The walls in the Listening Lab are covered with fiberglass panels. The reverberation times for the Sphere Room, Dome Room and Listening Lab are less than 200 msec for frequencies of 250 Hz and higher.[1] The reverberation times in the Distance Hall are approximately 400 msec for 250 Hz and below and 200 msec for 500 Hz and above. The higher reverberation times in the Distance Hall are due to the geometry of the room and the use of thinner foam wedges. These carefully chosen acoustic materials provide a relatively quiet, flexible and nearly anechoic space for conducting auditory research.

The Sphere Room, Dome Room and Distance Hall are each equipped with an instrumented listener station. The listener station is based on a freely rotating and adjustable chair. The chair is instrumented with pushbuttons for recording a participant's response, a laser pointer to provide angular pointing feedback to the participant, and an optical shaft encoder to record the chair's orientation relative to the room. Additionally, a hand-held laser pointer and response device adapted from the stock of a Glock handgun can be used by a participant to indicate the perceived location of a sound source. A head tracker can be used to record the participant's head position and orientation. All reaction times and participant responses are transmitted wirelessly to the work station in the Control Room.

Calibration and validation of sound sources is automated within each of the indoor research spaces. A centrally located microphone records a specific sound emitted from each of the loudspeakers used in a particular experiment and records its spectrum. The spectra from all loudspeakers are then compared and the average response across all loudspeakers is determined. Once a degree of acceptable tolerance has been established by the user, any loudspeaker outside of the established tolerance will have a correction applied to it to bring it in line with the average. Validations are accomplished through measurements made from two microphones mounted within the space. Spectra obtained from these microphones will be compared to the spectra obtained during the calibration. The software program will alert the experimenter if anything is outside of the tolerable range. The calibration procedure is intended to be carried out at the beginning of an experimental set up, and the validation procedure is intended to be carried out as a daily check to ensure no changes have occurred across the duration of a research study.

Control Room

The Control Room (Fig. 2) permits complete observation and operation of instrumentation and research activities in each of the five research spaces. The Control Room contains the front-end of all of the instrumentation and stimulus generation systems. All switching devices and power supplies needed to operate the loudspeakers within the research spaces are mounted in racks installed in the Control Room. Experimental design and execution is controlled by software

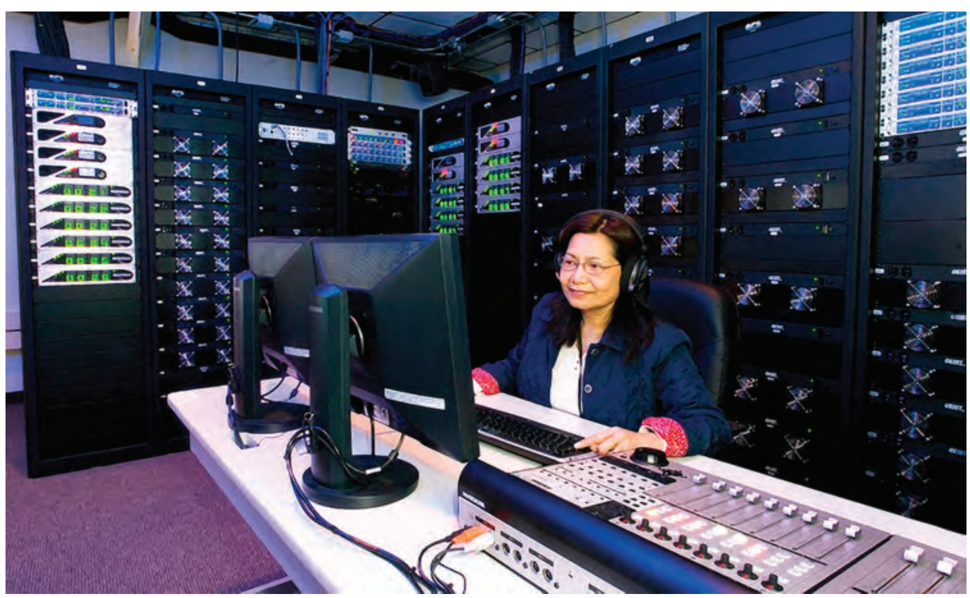

Fig. 2. A researcher configures an experiment in the Control Room. Rack mounted equipment is used to control the stimulus presentations in the research spaces.

installed on computers serving four independent work stations. Although each workstation is nominally assigned to a specific research space, complex switching systems provide the ability to reassign any workstation to any research space. This switching system can be used to reassign network connections, serial ports, digital audio signal routing, and participant response systems to any desired configuration. This flexibility allows for the reconfiguring of systems to accommodate any experimental configuration, or to continue operating in the event of a workstation failure.

Real time audio and video monitoring is accomplished through pairs of wall-mounted cameras and microphones in each of the four indoor research spaces. The outputs of the cameras and microphones are routed to an audio/video switch in the Control Room. Audio signals can be routed to the 5.1 surround sound system mounted at the ceiling of the Control Room or to the headphones connected to each workstation. Video signals are supplied from fully adjustable cameras located in each indoor research space. Selected video signals can be routed to dedicated monitors located at the individual work stations or to one of two 43 inch liquid crystal displays (LCD) mounted on the Control Room wall. The audio and video capabilities of the Control Room have been designed to provide audio-video demonstrations and instructions for new users, to monitor participants during experiments, and to enable individuals to observe the experiments without interrupting data collection. Two-way voice communications via a stand-alone professional-grade intercom system is also available between the Control Room and each of the indoor research spaces.

The wiring for all loudspeakers terminates in the Control Room and the respective research spaces. The number of connections and lengths of wires are mind boggling (see Table 1).

Table 1: By the Numbers

11 racks of equipment
4 workstations with dedicated computers
Over 25,000 meters of wire
6,443 pieces of hardware (nuts, bolts, etc.)
Over 230 linear meters of steel in the Distance Hall
118 meters of threaded rod for hanging loudspeaker poles and arms
Over 750 equipment receptacles
12,310 pins and sockets

Stimuli production

The EAR facility was designed to use as many common components as possible to minimize cost and reduce unique hardware requirements. This philosophy is best reflected in the choice of test loudspeakers. Requirements for these loudspeakers included that they be small in size (less than 4.25 inches in width), while producing a minimum of 85 dBA when excited with pink noise, at a distance of approximately 3 meters for a minimum of 2 hours. The dimensions of the Dome Room dictated the maximum width of the loudspeaker as 180 of them needed to be installed in a circular array within the given space. The output level requirements pushed the state-of-the-art beyond what was commercially available at the time. High intensity output is needed to simulate high noise military operational scenarios. SPL Integrated Solutions (now AVI-SPL) partnered with Meyer Sound Laboratory to develop a custom, self-powered loudspeaker which meets the acoustic power requirements while maintaining a frontal dimension of 4.04 inches. These loudspeakers provide the required auditory stimuli in our Sphere Room, Dome Room, and Distance Hall. The loudspeakers are closely matched in frequency response and output, and each contains an internal amplifier and a digital signal processing (DSP) module. There is a dedicated power supply located in the Control Room for each loudspeaker.

Automatic gating was incorporated by Meyer Sound into each DSP module to eliminate the typical "hiss" associated with the amplifier operating at maximum gain. Typically when loudspeakers are powered on individually, loudspeaker "hiss" can barely be perceived even at close range. However, since all of the loudspeakers in the Sphere Room and Dome Room are focused on a "sweet spot" in the center of the room, any generated hiss by one loudspeaker, although barely audible individually is multiplied by the large number of loudspeakers and is easily audible and objectionable. The incorporation of the automatic gating in the loudspeakers eliminated any perceptible "hiss." (Meyer Sound offers a version of this custom-made loudspeaker to the public as the MM-4XP miniature loudspeaker.)

Sphere Room

The Sphere Room (Fig. 3), named for its spherical loudspeaker configuration, measures 5.3 m wide by 5.4 m long and is 4.9 m high. It is designed for investigations in the integrity of auditory virtual spaces, the realism of complex auditory simulations, the effects of changes in Head-Related Transfer Functions (HRTF) on auditory perception, and the effects of helmets and other headgear on spatial orientation. The room contains 57 Meyer Sound MM-4XP test loudspeakers. The loudspeakers are positioned at five levels of elevation plus a single loudspeaker mounted directly overhead. The azimuthal separation varies with elevation such that there are equally spaced separations of 20° at the 0° elevation, 30° at the ±30° elevations and 45° degrees at the ±60° elevation, constituting a sphere surrounding the listener.

The listener station in the Sphere Room is located in the middle of the room on an elevated and adjustable platform so that the ears of the participant can be located at the center of the sphere of loudspeakers. Adjustments made with the combination of the platform and the chair cover the range of seated heights between the 5th percentile female and the 95th percentile male so that the ears of virtually any listener can be located in line with the horizontal plane. An unlimited number of sounds may be presented simultaneously to any combination of the loudspeakers. Moving sounds can be simulated among multiple loudspeakers through panning algorithms implemented in software. Four loudspeakers are located on height-adjustable stands in the corners of the

Fig. 3. A participant prepares for an experiment in the Sphere Room. The central location of the listener station and platform allow for the creation of a completely immersive auditory environment.

room to provide background noise when needed. These loudspeakers are each capable of providing background noise up to 110 dBA at the position of the listener. The combination of spherically located loudspeakers and the central position of the listener can result in a completely immersive auditory environment.

Soldiers, more than the average civilian, listen to sounds arriving from all directions; above, below, behind and beside. The ability to place a listener in an environment where sounds can arrive from any angle opens up a wide range of research possibilities. One potential line of research is the evaluation of the effects of different types of headgear on a listener's ability to identify the location of a sound arriving from any direction. Soldier headgear includes helmets, communication systems, hearing protection devices or any combination of these. The Sphere Room is intended to examine auditory localization ability in a more global sense than in the Dome Room, which is intended for more precise evaluation. Prior work at ARL suggests that wearing a helmet decreases your ability to determine the location of a sound, and further, as helmet coverage of the ear increases localization performance deteriorates.[2]

Dome Room

The Dome Room (Fig. 4) was named for its dome-like loudspeaker configuration. It measures 6.6 m long by 8.1 m wide and is 4.1 m high. It is designed for research studies investigating the human's ability to localize real or virtual, single or multiple, and stationary or moving sound sources distributed in a hemispherical space. As opposed to the Sphere Room which has widely spaced loudspeakers, the Dome Room is designed for more precise studies in auditory localization. The room contains a horizontal circular array with a diameter of 6 m that can be populated with up to 180 Meyer Sound MM-4XP loudspeakers arranged every 2 degrees of angular separation. All of the loudspeakers are connected via quick-disconnect plugs, allowing for rapid loudspeaker reconfiguration as experimental designs dictate. The dense loudspeaker configuration within this room allows research studies to be conducted examining precise identification of a sound source location.

The horizontal array is comprised of 12 removable segments, each corresponding to 30° of arc. The array is supplemented by two vertical arcs that can be manually moved along two wheeled tracks: one track mounted to the ceiling and the other track attached to the outside of the top of the horizontal array. The two vertical arcs can be populated with 30 loudspeakers each in rows of 5 loudspeakers each at -20 to +40° (10° increments) in the vertical plane. The two arcs can be positioned on opposite sides of the horizontal array to form a nearly 180° arc above the listener, side-by-side to form a nearly 40° span in horizontal and vertical space or in any other location for maximum flexibility in loudspeaker placement. Moving sound sources can be simulated by panning sounds across the loudspeaker arrays through software. As in the Sphere Room, four loudspeakers are located on height-adjustable stands in each of the corners of the room to provide background noise when needed.

The structural components of the horizontal array are offset from the walls so that acoustically reflective panels

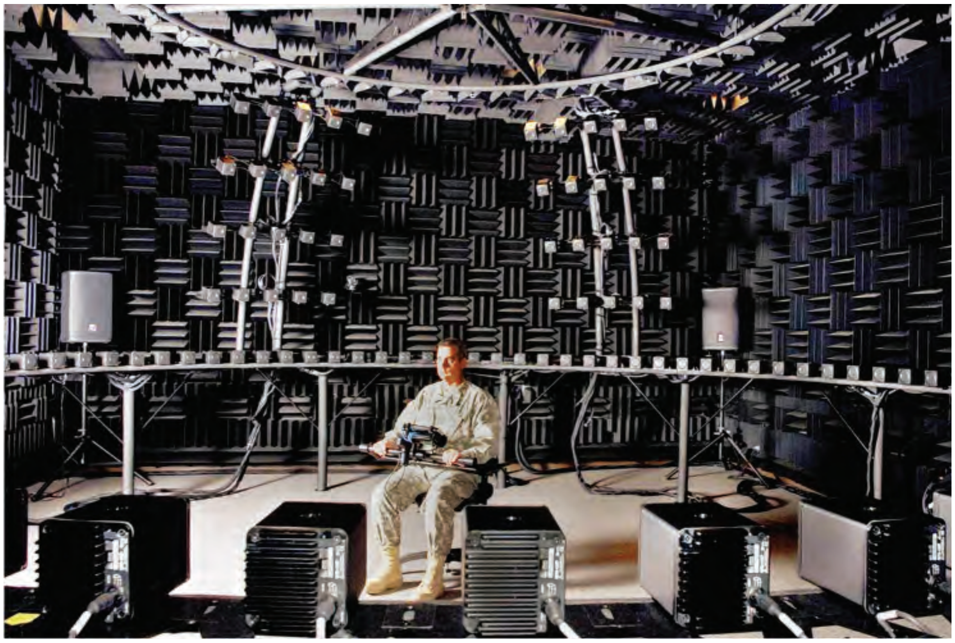

Fig. 4. A participant seated in the listener station of the Dome Room. The dense population of the loudspeakers in this room allows for precise measurement of auditory localization.

can be positioned in the space between the foam wedges and the array to increase reflectivity and reverberation time. This will enable research studies examining the effects of systematic increases in the number of reflective surfaces and a room's overall reverberation time on auditory localization performance.

The ART has previously conducted research in auditory localization as it applies to military personnel. Investigations have included evaluations of the effects of hearing protection on the ability to accurately identify the location of a sound[3–5] and localization of sounds in the presence of background noise.[6,7] The Dome Room will allow for further evaluations of auditory perception of both stationary and moving sounds.

Distance Hall

The Distance Hall (Fig. 5) was named for its rectangular shape and intended research purpose. It measures 21.3 m long by 5.6 m wide and is 3.7 m high. The acoustic configuration and audio capabilities permit investigation of auditory localization and tracking of sound sources moving in a predetermined manner toward and away from the listener, auditory distance and depth estimation, tracking of sound sources moving above the listener, and detection and recognition of sound sources appearing at moderate distances from the listener. The Distance Hall can contain up to 180 loudspeakers. These loudspeakers can be mounted to bars with the capacity to hold five loudspeakers each, suspended from the ceiling by brackets every 1.6 m from 4.5 to 21 m in front of the listener. Three tracks create parallel lanes that run the length of the hall. Each track can be populated with up to 12 rows of up to 5 loudspeakers each along the length of the hall. The mounting bars are adjustable in height from 1.2 to 3 m above the floor so that sounds can be presented at the level with the listener's ear, as well as at levels either above or below. Loudspeaker mounting bars can be positioned in horizontal, vertical or diagonal orientations relative to the listener and the mounting bars are interchangeable with those installed on the vertical arcs in the Dome Room.

The configuration of the lighting in the Distance Hall differs from that available in the other indoor research spaces. In the Distance Hall, there are 6 independent lighting controls in rows beginning at the position of the listener. It is possible to extinguish all lighting except for a dim light above the listener location such that the listener is not able to perceive the size of the research space. This lighting scenario would allow for exploration of the perception of sound source distances that are farther away than the physically present loudspeakers through modifications of the spectral components of the sounds presented to the listener.

The Distance Hall will enable the ART to perform research in the areas of distance estimation and distance perception, as well as the effects of loudspeaker-to-listener distance on a person's ability to accurately identify the location of a sound source. There is a clear distinction between the

Fig. 5. A soldier sits in the listener position in the Distance Hall. The lighting in this room can be configured to hide the true size of the room.

importance of identifying the location of a sound at a distance for the average civilian and a soldier. For a civilian, listening to sounds at a distance is not a common occurrence in daily life and the inability to identify the location is considered at most a nuisance. In the life of a soldier, the failure to identify the location a sound at a distance can be fatal. Previous work in the area of auditory localization of distant sounds has shown that increases in the distance between the listener and the sound source create uncertainties in the listener's perception of its location.[8] The Distance Hall will enable expansion of this research under additional conditions.

Listening Laboratory

The Listening Laboratory (Fig. 6) is a multipurpose room measuring 4.6 m wide by 6.4 m long and is 3.5 m high. It is designed for studying speech perception, as well as the effects of room acoustics and sound source configurations on sound perception. Acoustic features and instrumentation of this space were designed to facilitate comparative studies of various sound reproduction systems, comparison of loudspeaker, headphone, and bone conduction sound systems, and the effects of room acoustics, noise level, and reverberation time on speech perception.

The Listening Laboratory is equipped with 14 wideband Genelec 8030A self-amplified loudspeakers and two subwoofers. The loudspeakers can be arranged to represent various sound reproduction systems (up to 10.2) or to simulate multiple talkers. The loudspeakers can be raised or lowered from floor to ceiling height through the use of chains mounted to the ceiling of the room and the use of loudspeaker stands. Sound absorptive panels cover the wooden walls and can be removed in any desired combination. Reverberation times can be changed through the removal of panels to a maximum of 400-450 msec when the majority of panels are removed.[1] This provides the means to study both the global effects of room reverberation and the effects of discrete sound reflections on auditory perception.

In addition to the loudspeakers, the room contains five headphone stations with two headphone jacks on each for a total capacity of 10 pairs of headphones. Each headphone jack is wired with an independent volume control. The combination of the self-powered loudspeakers and headphone boxes can allow for the evaluation of speech recognition through different communication systems in quiet or in noise, with or without various amounts of reverberation in up to 10 listeners at a time. This will save both cost and time in studies examining speech intelligibility, and ensure that environmental variables are the same for all participants.

OpenEAR

OpenEAR is a 4,500 square meter outdoor research facility designed for studies of auditory perception in natural field environments. It consists of an open field between two warehouse buildings. Access to this facility is through two doorways on the outside wall of the Distance Hall. Use of this area will allow studies of distance perception conducted in a laboratory environment to be replicated in a natural field environment. The proximity of OpenEAR to the Distance Hall will allow comparisons to be made in evaluations conducted with the same listeners at almost the same time that will reduce data uncertainty resulting from laboratory and field studies conducted at different times and with different listeners.

OpenEAR includes outdoor loudspeakers and microphones as well as the cabling and power needed to operate them. The loudspeakers enable generation of sounds at varying loudspeaker-to-listener distances to replicate outdoor environments encountered in military operations. The microphones enable a researcher to record sounds in the outdoor environment or to directly route the sounds taken from the outdoors through loudspeakers in the indoor research spaces.

Fig. 6. A soldier listens to speech presented through headphones in the Listening Laboratory. The foam panels within this space can be removed to increase the reverberation time of the space.

The creation of OpenEAR will allow additional research to be conducted (in combination with the Distance Hall) in the area of auditory distance estimation. Previous studies conducted within ARL have taken place in an open field located approximately 5 km from the ART labs. OpenEAR will provide an outdoor research area that will be more accessible by the ART. Previous work by the ART in distance estimation at loudspeaker to listener distances of up to 800 m has demonstrated that individuals grossly underestimate the distance to sound sources and that errors increase non-linearly with distance.[9] At distances of less than 20 m, listeners are fairly accurate but estimates drop off at distances as short as 100 m. Further work in this area is needed to evaluate the reasons for this and to determine if the effects are similar between indoor and outdoor environments.

Combined use

As can be seen in Fig. 1, the Dome Room, Distance Hall, and OpenEAR are contiguous spaces. The Distance Hall includes two sets of double exterior doors which open to OpenEAR. There is one set of double doors between the Distance Hall and the Dome Room, which are aligned with a set of double doors between the Distance Hall and OpenEAR. This permits the use of two or three of the research spaces simultaneously with line-of-sight between the spaces via the open doors. This flexibility creates a synergy among the spaces. For example, the combination of OpenEAR and the Distance Hall will enable evaluation of distance estimation and distance perception studies in indoor and outdoor spaces on the same day with the same listeners under the same conditions. The combination of all three indoor research spaces plus the outdoor research space will allow for simulations of complex listening environments to be conducted within the facility. Researchers can take advantage of this novel configuration flexibility to design more realistic, but still controlled, experiments.

Summary

The EAR is a unique and flexible research facility. The combination of the research spaces and capabilities is unmatched at any military, academic, or industrial facility world-wide. The EAR complements existing research spaces available to the ART (which include three sound treated booths, a Tucker-Davis Technologies RoboArm™ for the measurement of the Head-Related Transfer Functions, a small anechoic chamber, and a reverberant chamber) for research in auditory perception and speech communication.

Infrastructure and instrument design and installation

The EAR facility was constructed under two contracts: infrastructure; and the selection, design and installation of hardware and software. A joint venture of Martinez International Corporation and Cadence, Inc. completed the infrastructure for the facility that was based on architectural and structural designs by Whitney, Bailey, Cox, and Magnani, LLC. The mechanical and electrical systems were designed by Gipe Associates, Inc., both of Towson, Maryland; and the acoustical design of the HVAC systems was accomplished by Miller, Beam & Pagnelli, Inc., of McLean, Virginia.

The contract for the instrumentation design and installation was awarded to SPL Integrated Solutions (now AVI-SPL) of Columbia, Maryland. AVI-SPL, together with AuSIM, Inc. of Mountain View and Santa Clara, California developed the hardware and software solutions for the facility based on ARL's technical specifications. Each of the research spaces has unique features typical of high quality auditory research facilities.

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Bruce Amrein attended the Baltimore Polytechnic Institute, and graduated from Loyola College of Baltimore with a B.S. degree in Engineering/Physics. He also holds MBA and Masters in Engineering Science degrees. After serving as a commissioned officer in the U.S. Army's Signal Corps, he has been with the U.S. Army Research Laboratory (ARL) since its inception in 1992. He currently serves as the Chief of ARL's Visual & Auditory Processes Branch. He holds 9 patents in technology areas ranging from the control of military vehicle drive trains to medical devices. In his free time Bruce enjoys amateur radio and woodworking. As technical director of his church, he is responsible for web design, computer networking, and design and operation of all sound systems.

Mark Ericson is a researcher and facilities manager at the Visual and Auditory Processes branch of the Army Research Laboratory (ARL). His current interests include studying how auditory motion cues are used for different tasks and improving speech communications in degraded conditions. Prior to joining ARL, Mark worked for 23 years as an engineer and scientist at the Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio. Mark received a B.S. in Electrical Engineering from Worcester Polytechnic Institute (1985) and an M.S. in Electrical Engineering from the University of Dayton (1993). Mark began at AFRL as a bench level engineer on speech recognition, active noise reduction, and auditory localization projects. He helped develop several unique facilities for auditory localization, speech communication, and hearing protection research. After earning a Ph.D. in speech and hearing science from Ohio State University (2001), he led research projects in auditory motion, multiple speech communications, radio voice communications, hearing loss, hearing protection, and warning sound displays.