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Initial Development of a Spatially Separated Speech-in-Noise and Localization Training Program

Richard S. Tyler^{*}, Shelley A. Witt^{*}, Camille C. Dunn^{*}, and Wenjun Wang^{*}

^{*}Department of Otolaryngology—Head and Neck Surgery, University of Iowa

Abstract

Objective—This article describes the initial development of a novel approach for training hearing-impaired listeners to improve their ability to understand speech in the presence of background noise and to also improve their ability to localize sounds.

Design—Most people with hearing loss, even those well fit with hearing devices, still experience significant problems understanding speech in noise. Prior research suggests that at least some subjects can experience improved speech understanding with training. However, all training systems that we are aware of have one basic, critical limitation. They do not provide spatial separation of the speech and noise, therefore ignoring the potential benefits of training binaural hearing. In this paper we describe our initial experience with a home-based training system that includes spatially separated speech-in-noise and localization training.

Results—Throughout the development of this system patient input, training and preliminary pilot data from individuals with bilateral cochlear implants were utilized. Positive feedback from subjective reports indicated that some individuals were engaged in the treatment, and formal testing showed benefit. Feedback and practical issues resulted from the reduction of an eight-loudspeaker to a two-loudspeaker system.

Conclusions—These preliminary findings suggest we have successfully developed a viable spatial hearing training system that can improve binaural hearing in noise and localization. Applications include, but are not limited to, hearing with hearing aids and cochlear implants.

Keywords

Aural rehabilitation; binaural hearing; cochlear implants; hearing aids; localization; spatial hearing; spatial training; speech-in-noise

Most listeners, even those well fit with hearing aids and/or cochlear implants (CIs) who hear well in quiet, often experience significant problems in noise (Tyler et al, 1983; Stickney et al, 2004; Turner et al, 2004; Fu and Nagaki, 2005; Cullington and Zeng, 2008; Won et al, 2008). To effectively listen in noise, individuals must be able to distinguish the speech and the noise, presumably based on accurate coding of each, and be able to attend to the speech and ignore the noise. Although this can be accomplished monaurally, the use of binaural hearing can facilitate hearing in noise (e.g., Middlebrooks and Green, 1991; Muller et al, 2002; Tyler et al, 2002a, 2002b; van Hoesel and Tyler, 2003; Laszig et al, 2004; Litovsky et al, 2004; Schleich et al, 2004; van Hoesel, 2004; Ramsden et al, 2005; Senn et al, 2005). The binaural contribution to spatial hearing is facilitated by the ability to localize, track, and suppress information from one source to focus on another, attend to one ear and suppress the other, and judge both

movement and distance (Gatehouse and Noble, 2004). Excellent reviews of the broader perspectives of spatial hearing are available (e.g., Cherry, 1953; Cherry and Sayers, 1959; Yost and Gourevitch, 1987; Yost and Guzman, 1996; Blauert, 1997; Gilkey and Anderson, 1997; Dubno et al, 2002; Plomp, 2002; Litovsky et al, 2004).

There are several opportunities to improve hearing in noise, including the use of hearing aids and cochlear implants, signal processing, fitting, and training. Sweetow and Palmer (2005) have appropriately cautioned that research is needed on the efficacy of training programs. It is important to distinguish that performance can improve over time as a function of experience or specific training and as would be expected, experience and training that results in an improvement in hearing also results in changes in brain plasticity (Kraus et al, 1995; Tremblay et al, 1997; Scheffler et al, 1998; Tremblay et al, 1998; Ponton et al, 2001; Tremblay et al, 2001; Tremblay and Kraus, 2002). Training can take different forms. For auditory training, this could include

- Training on real stimuli, such as speech and/or environmental sounds (Shafiro, 2008);
- Training on synthetic or modified real stimuli (Rosen et al, 1999; Fu and Galvin, 2003; Fu et al, 2005), such as using vowels with accentuated formants (e.g., Tye-Murray et al, 1988);
- Training on basic psychoacoustical stimuli, such as pure-tone discrimination; and
- Training in another modality, such as vision, with the intent that there would be some cross modality gains.

There are several different approaches to training, and several factors should be considered in the development of training materials and approaches (Tyler, 1994). For example, the use of different training “units,” from phonemes to paragraphs, has advantages and disadvantages. The speech stimuli used can be natural, altered, or edited natural speech, or synthetic speech. Tyler (1994) proposed training on specific listening situations, including one-to-one, small and large groups, television, telephone, car, public address systems, and work environments. Also to be considered is the type of background noise, whether lipreading is possible, distance to the source, reverberation, and whether localization of the source might be an advantage. With today’s computer technology, the use of a broad range of stimuli and simulations of different situations is now possible.

There are many computerized auditory training systems available (see Table 1). One recent popular program is the Listening and Auditory Communication Enhancement (Sweetow and Henderson-Sabes, 2004), which presents categorized sentences based on certain topics. Sentences are initially played acoustically and then reinforced with auditory and visual feedback.

Even less attention has been directed toward localization training. It is generally accepted that perception of interaural timing differences (ITDs) and interaural level differences (ILDs) are needed for localization. Wright and Fitzgerald (2001) studied the effects of training of ILDs and ITDs presented over headphones. Subjects trained 1 hr per day for 9 days. Although discrimination of ILDs and ITDs improved, a slower stage of improvement was shown for the ILD cue but not for the ITD cue. This indicates that there are differences in learning patterns of these two localization cues. Additional data studying differences in learning patterns between ITDs and ILDs showed that processing of high-frequency ITDs resembles that for low-frequency ITDs but differs from that for high-frequency ILDs (Zhang and Wright, 2007).

The present article describes a novel training system developed with the use of multiple loudspeakers to provide spatial separation of speech and noise. The purpose was to create a training system focused on hearing with two ears, which would allow hearing-impaired listeners the opportunity to improve their ability to understand speech in the presence of background noise and to improve their ability to localize sounds.

The development of this training program took several years starting with a laboratory system (initiated in 2004) and progressed to a two-loudspeaker home-based system.

EQUIPMENT

Eight-Loudspeaker Laboratory System

The laboratory system consisted of eight loudspeakers (Sony SS-MB115; frequency range: 60 to 20 kHz; 14.5 in in height) in a sound-treated booth placed to form a 108° arc in the horizontal plane (Byrne et al, 1998). All loudspeakers were placed on speaker stands so that sound was presented at the ear-level of the subjects. Subjects were seated facing the center of the speaker array at a distance of approximately 1.4 m with a touch screen computer monitor placed in the front and below the plane of the loudspeakers (Dunn et al, 2005).

Eight-Loudspeaker Home-Based System

After several laboratory sessions and feedback from users, we decided it was then appropriate to develop a home-based system to maximize the opportunity for training. The eight-loudspeaker home-based system consisted of a rectangular card table, laptop computer, sound card (Layla24/Type II CardBus from Echo Digital Audio Corporation), power strips, and eight miniature loudspeakers (Harman Kardon; HK195; frequency range: 90 to 20 kHz; 6.5 in in height). The loudspeakers were placed on the table in a manner representing the same ratio as the 108° laboratory system arc. The table was marked with a grid to show subjects where and in what position to place the loudspeakers when they were setting up the equipment at home. The laptop computer was placed on a box in front of the table but below the level of the loudspeakers so as not to baffle the sound coming out of the loudspeakers. Subjects took this system home and set it up in the comfort of their own home. They were instructed on the equipment setup and use of the system and were required to show proficiency in being able to set up the equipment and run the program prior to leaving the clinic. Once home, they were instructed to contact the clinic after they had the equipment set up prior to initiating training. A clinician spoke with each subject via the telephone to confirm the equipment setup and to ensure that the program was working properly.

Two-Loudspeaker Home-Based System

After additional experience and feedback it became apparent that a smaller system with equipment already available in many homes would be more practical. The two-loudspeaker home-based system consisted of a computer, two external loudspeakers (the same loudspeakers used in the eight-loudspeaker home-training version) and a CD-ROM with installation instructions (see Fig. 1).

TRAINING PROGRAM

The training program includes both localization and speech-in-noise modules. Subjects can choose to train on either localization or speech in noise. The program was created using Microsoft Visual Basic, Visual Studio 6.0. Figure 2a shows screen shots of the eight-loudspeaker system. Figures 2a–c show screen shots of introductory text. Figures 2d–f show screen shots of the localization training. Figures 2g–j show screen shots of the speech-in-noise training.

Speech Stimuli

The speech-in-noise stimuli consist of a closed set of 12 spondee words played in a background of two-talker male and female babble. Although the use of a closed-set spondee task is a relatively easy speech test, for some of the training modules the words in noise are presented in an adaptive manner. The level of the speech was held constant, and the noise was adjusted using an adaptive 50% correct rule allowing listeners to train at a level that was not too hard, but not too difficult. In addition, this training method helps avoid ceiling effects.

One list of 12 spondee words spoken by a male voice was used with both the laboratory and eight-loudspeaker home-based system. However, multiple lists and a variety of male and female voices were used in the two-loudspeaker home-based system.

Localization Stimuli

The localization stimuli for both the laboratory and eight-loudspeaker home-based system consist of the following 16 sounds: fog horn, car horn, crowd cheering, drums, door knock, ocean waves, police siren, train, applause, bugle, cat meowing, children laughing, elephant trumpeting, motorcycle engine, bell ringing, and warning siren. The two-loudspeaker home-based system included more and different everyday sounds.

Training Procedures

Training was provided in two options, which we called “active exploring” and “guided listening.”

Active Exploring

Active exploring lets the listener control the situation. They choose the type of stimuli they want to hear, the number of times they want to hear it, the level of both the stimuli and background noise, and the location of the target signal relative to the background noise. For example, if a listener is actively exploring localization using either the laboratory or the eight-loudspeaker home-based system, they might pick the sound of a “cat meowing” coming from loudspeaker 2 (off to their left). They might choose to listen to that sound 4 times in a row from that location. Then they might pick that same sound coming from loudspeaker 7 (off to their right). They might compare and contrast those two specific locations until they feel that they can tell the difference between the locations. They might also decide to keep those two locations (loudspeaker 2 versus loudspeaker 7), but vary the type of stimuli, listening to a “cat meowing” from loudspeaker 2 versus an “elephant trumpeting” from loudspeaker 7. In Figure 2e the screen options for this task are shown. The number of trials and repeats during each trial as well as sound stimuli options are all found on the bottom of the screen. The purpose is free exploration of various sounds coming from different locations.

When listeners are actively exploring speech in noise, they can select the word they want to hear, how many times they want to hear the word, and from which loudspeakers they want the noise to be played compared to where the target sound is being played. For example, when training with either the laboratory or the eight-loudspeaker home-based system they might pick the word “mousetrap” being played from loudspeaker 4 with noise being played first from loudspeaker 1 (farthest to the left), then from loudspeaker 2, and lastly from loudspeaker 3, exploring the effects of the separation of noise from the target speech signal. Again, no testing is taking place. Listeners can explore various speech sounds and the amount of spatial separation of the speech from the noise also at different degrees of difficulty (different volume levels of the speech and the noise).

Guided Listening

Guided listening tests the listener's ability to either localize or identify the sound. Either a sound (localization training) or speech stimuli (speech-in-noise training) is randomly presented. The listener selects either the location of the sound or the speech stimuli depending on which type of training he or she is completing. Feedback is provided. A correct response is acknowledged on the screen, and the sound or speech stimuli is repeated paired with a visual guide showing the correct item or location (the correct word or correct loudspeaker lights up depending on the type of training). This confirms the correct response and provides a second listening option especially if the correct answer was simply a guess. If the response was incorrect, the incorrect response is acknowledged on the screen. The incorrect response is compared and contrasted with the correct item. Listeners can choose how many correct/incorrect comparisons they want. For speech-in-noise training with either the laboratory or eight-loudspeaker home-based system, when the listener makes a correct response, positive feedback is provided, and the spatial separation between the target and noise is reduced, making the task harder. When the listener makes an incorrect response, they are told their answer is incorrect. A comparison between their response and the correct answer is then made, and the spatial separation between the target and noise is increased, making the task easier. In Figure 2j the screen options for this task are shown. The total number of trials and repeat comparisons are all found on the bottom of the screen. During guided learning for speech-in-noise training, listeners are informed that the computer will try to find the volume level at which training is not too easy, but not too hard. This is done by implementation of an adaptive procedure where the level of the speech stimuli is held constant and the noise is adjusted (Turner et al, 2004). Although the computer uses an adaptive method during training, listeners can override this by manually changing the level of either the noise or speech.

When using either the laboratory or eight-loudspeaker home-based systems, the loudspeakers are set and kept in predefined locations. However, when using the two-loudspeaker home-based system, subjects are instructed to move the loudspeakers around in order to practice at a level that is not too easy, but not too difficult. They are told that, in general, the farther apart the loudspeakers are placed, the easier the task; the closer together the loudspeakers are placed, the more difficult the task; and the easiest condition will be to place one loudspeaker on their right and the other loudspeaker on their left. They are also told that the most difficult condition will be with the two loudspeakers side-by-side and placed off to either the left or right side. We encourage subjects to train themselves with the loudspeakers in different positions starting with easier locations, working toward more challenging locations. Figure 1 shows an individual using the two-loudspeaker home-based system. In the top panel the loudspeakers are placed on each side of the individual, representing a less difficult condition, while in the bottom panel the speakers are placed close together directly in front of the individual representing a more difficult condition.

SUBJECTS

The concept of the training program was to provide training for individuals with a range of hearing impairments (i.e., mild to profound) wearing a variety of hearing devices (i.e., hearing aids, cochlear implants, and/or a combination of both). However, for purposes of the initial stages of development, we chose to work with individuals who had received bilateral cochlear implants. All of the subjects in this study participated in a large multidisciplinary project at the University of Iowa and were coming in for routine research visits. None of the subjects in this paper were receiving any other type of aural rehabilitation during the time of testing and/or training for this study. They had also been using their cochlear implants for a substantial amount of time (3–8 yr of CI experience) beyond the period normally associated with experiential learning (Chang et al, 2010).

TRAINING PROCEDURES

Subjects were instructed to complete a minimum of 30 min of training each day. All subjects were given the same speech-in-noise and localization training modules. No restrictions were placed on how to train. Subjects could pick whichever training modules they wanted and could train for any length of time as long as the overall training time met the minimal requirement. The purpose was to allow each subject to determine which training modules were most intrinsically motivating for them. During the training, the computer automatically stored the dates, duration, and type of training that each subject completed.

The first set of preliminary pilot data was collected using the laboratory and eight-loudspeaker home-based system. “Pretraining” refers to performance data collected before any training took place. “Posttraining” refers to performance data collected after training was completed. The amount of training varied from subject to subject.

EIGHT-LOUDSPEAKER LABORATORY AND HOME-BASED SYSTEM

Subjects

Three postlingually deafened adult bilateral (simultaneously implanted) cochlear implant (Advanced Bionics 90K) patients served as subjects for our pilot testing. At the time of training, subject 1 (female, 61 yr old) and had three years of implant experience, subject 2 (female, 63 yr old) had 4 yr of implant experience, and subject 3 (male, 57 yr old) had a little less than 4 yr (43 mo) of implant experience. Each subject served as their own control.

Test Materials

Speech perception and localization tests were administered at pre- and posttraining. However, the specific tests varied across subjects due to time constraints. Tests included the following: consonant-nucleus-consonant monosyllabic words (CNC) (Tillman and Carhart, 1966) based on the average percent correct for two lists of words, CUNY sentences (Boothroyd et al, 1985) in noise scored by the average number of key words correct for four lists of sentences, Hearing in Noise Test (HINT) sentences (Nilsson et al, 1994) scored by the average number of key words correct for four lists of sentences, an adaptive spondee words in babble test (Turner et al, 2004), and an adaptive 12-choice spondee words in test with multiple jammers test (Tyler et al, 2006). Scoring for both adaptive tests was based on the average signal-to-noise ratio needed to recognize 50% of the spondee words based on three runs with multiple trials per run. Lastly an everyday sounds localization test (Dunn et al, 2005) was administered. Scores were reported by the average total root mean square (RMS) error based on 96 trials.

RESULTS FOR SUBJECT 1

Subject 1 trained first in the clinic with the laboratory system and then at home for 2 mo. She returned to the clinic for standard cochlear implant follow-up care at 38, 40, and 45 mo postimplantation.

Localization

Figure 3 shows results for localization. Localization performance is represented by an RMS error in degrees based on 96 trials. The lower the number, the better the performance. At 36 mo postimplantation, this subject trained in the clinic with the laboratory version of our training system twice a day for two consecutive days. Pretraining the localization score consisted of an average RMS error of 24° while the posttraining score was 17° RMS error (significant with a paired t -test [$t(95) = 3.70, p < .001$]). The subject then took the eight-loudspeaker home-based system home and trained for an additional two months. The subject was retested at 38, 40, and

45 mo postimplantation, and while the subject did not show any more improvement in performance, the significant improvement shown after laboratory training remained.

Speech in Noise

CNC words in quiet, CUNY and HINT sentences in noise, and an adaptive spondee-in-noise test were administered pretraining at 36 mo postimplantation for subject 1. More data are available on the HINT sentences, so statistical analyses were restricted to that test. Four replications of the tests were performed at preimplantation and 40 and 45 mo postimplantation, the scores averaging 50, 90, and 82% respectively (see Figure 4). A repeated-measures analysis of variance (based on four replications per visit) revealed a significant difference among the three visits ($F(2, 6) = 25.6, p < .01$). Post hoc comparisons using Bonferroni adjustment revealed that the improvements between pretraining and both 40 and 45 mo were significant. There was no statistical difference between scores at 40 and 45 mo. As a cautionary note, the sample size is small, limiting the statistical power.

This pretraining versus posttraining comparison looked very promising on its own. However, to be conservative, subject 1's entire HINT sentence-in-noise data since implantation was graphed. A gradual improvement over time for both HINT sentences and CNC words was found, suggesting that the pre- versus posteffect might be due to continuing improvement rather than training. No significant pre- versus posttraining differences were found for CNC words and CUNY sentences in noise (using a paired t -test). The CUNY sentence score posttraining was confined, however, by a ceiling effect.

Figure 5 shows results for the adaptive spondee-in-noise test. It should be noted that this test contains the same stimuli that the subject trained on. Results show the signal-to-noise ratio required for the subject to obtain a 50% correct score based on three runs with multiple trials per run. A paired t -test revealed significant improvements for pre- versus posttraining with the right CI only, $t(23) = 4.39, p < .001$; left CI only, $t(23) = 3.57, p < .01$; and for the bilateral condition, $t(23) = 15.50, p < .001$.

RESULTS FOR SUBJECT 2

Subject 2 came in for a pretraining appointment at 48 mo postimplantation. She trained at home for 1 mo and then returned for testing.

Speech in Noise

CNC word scores in noise (+4 S/N) were 39% correct pretraining and 43% posttraining (paired t -test showed no significant difference [$t(5) = -.98, p > .05$]). HINT sentence scores (+5 S/N) were 51% (SE = 3.6) correct pretraining and 87% (SE = 2.6) correct posttraining (paired t -test showed a significant improvement [$t(11) = -8.59, p < .001$]). No additional data over time with this particular signal-to-noise ratio was available to analyze.

The results for the adaptive spondee-in-noise test with multiple jammers are represented by the signal-to-noise ratio required for the subject to obtain a 50% correct score based on three runs with multiple trials per run. The pretraining score equaled -4.8 (SE = .40) while the posttraining score equaled -7.8 (SE = .46), which was statistically significant (paired t -test [$t(89) = 5.72, p < .001$]).

Localization

No changes in localization were found between pre- and posttraining for this subject.

RESULTS FOR SUBJECT 3

Subject 3 began the training at 43 mo postimplantation, trained at home for 3 mo, and returned for testing.

Speech in Noise

CNC word scores in quiet were 85% correct pretraining and 77% posttraining (paired t -test, not significant, [$t(1) = 2.0, p > .05$]). HINT sentences in noise (+5 S/N) were 56% (SE = 2.4) pretraining and 65% (SE = 7.1) correct posttraining (paired t -test, not significant [$t(3) = -1.79, p > .05$]). As a cautionary note, the sample size is small, limiting the statistical power.

Localization

No changes in localization were found between pre- and posttraining for this subject.

SUMMARY AND DISCUSSION OF EIGHT-LOUDSPEAKER SYSTEM

We interpret the following observations from these preliminary experiments with the eight-loudspeaker system as encouraging:

- Subject 1 showed improvements in localization after training with the laboratory system. These improvements remained when retested 7 mo later.
- Subject 1 showed improvements in spondee in noise testing after 2 mo of training with the home-based system.
- Subject 2 showed improvements in both HINT sentences in noise and spondee-in-noise testing after only 1 mo of training with the home-based system.

Positive comments received about the training system consisted of “easy to use,” “fun,” “creates a natural incentive to continue to train,” “kept trying to beat my own score,” “felt like a computer game that motivates you to work harder at each subsequent session.” The only negative comments received were about the hardware of the system. Subjects stated that the equipment used for the system was “cumbersome,” “had too many parts,” was “time-consuming and confusing to set up and break down,” and took up a lot of space. The combination of encouraging preliminary pilot data and positive feedback led us to streamline the hardware creating the two-loudspeaker home-based system.

The second set of preliminary pilot data were collected using the two-loudspeaker home-based system. Data were collected on both training subjects and control subjects.

TRAINING SUBJECTS

Three adult bilateral cochlear implant subjects who received simultaneous cochlear implants served as subjects. At the time of training, subject 1 (female, age 63 yr) had five years of implant experience, subject 2 (male, age 77 yr) had 8 yr of implant experience, and subject 3 (female, age 66 yr) had 7 yr of implant experience. Subject 1 received bilateral Advanced Bionics 90K cochlear implants and wore bilateral Harmony behind-the-ear speech processors. Both subjects 2 and 3 received bilateral Cochlear Corporation CI24M cochlear implants. Subject 2 wore bilateral Freedom behind-the-ear speech processors while subject 3 wore bilateral SPRINT body-worn speech processors.

CONTROL SUBJECTS

Six adult bilateral cochlear implant subjects (3 males and 3 females) who received simultaneous cochlear implants served as control subjects. All of the control subjects received bilateral

Advanced Bionics 90K internal cochlear implant devices and wore bilateral Harmony behind-the-ear speech processors. The control subjects completed the same pre- and posttest battery as the training subjects separated by 2 mo; however, they did not receive the home two-loudspeaker home-based training system, or any rehabilitation of any type. Table 2 lists the months of implantation for each subject at the time they completed the pre- and posttest battery.

TEST MATERIALS

Sweetow and Palmer (2005) suggested that the outcome measures used to assess the effects of auditory training might not be sufficiently sensitive, and this might be the cause of the lack of definitive results (see also Tyler, 1994). Because of this, two newly developed tests designed to better test real-world listening were administered. Both tests were administered using the laboratory eight-loudspeaker 108° arc equipment set-up (Tyler et al, 2006).

Localization and Recognition: Cueing the Location of Talkers

This test combines the process of localization and recognition. This reflects the point that everyday listening represents the following conjunction: determining who a person is, where they are, and what they are saying. The listener received an auditory cue (a man saying, “Hey, I’m over here”) to show them from which loudspeaker, in the laboratory eight-loudspeaker array, the target signal will be heard from. On the basis of that cue, the listener’s task is to locate the loudspeaker, reorient to it, and then report the target word. That target word will be heard against a background of competing speech babble and will come from a spatially separate loudspeaker. It is believed that listeners more accurate in localizing the source will better optimize the signal-to-noise ratio for the target speech signal.

Recognition: Multiple Jammers from Different Locations

Acoustic masking of a target speech signal by broadband modulated noise is routinely employed in assessing the performance of hearing aid and cochlear implant recipients. In everyday terms, however, listeners are often faced with competing sounds in the form of several other voices at spatially discrete locations (Hawley et al, 1999, 2004; Culling et al, 2004) rather than broadband noise. In addition, these voices can be perceived as similar to the target signal; *informational masking* (Kidd et al, 1998; Stickney et al, 2004). Informational masking benefits markedly from spatial separation but is presumably less effective when the jammer is not perceived as being speech like (Hornsby et al, 2006). This test contains two jammers and one target. The target is a female voice, and the jammers are a single male and female talker. The target is the same talker, whereas the talkers for the jammers vary from trial to trial. Subjects are instructed to report the target word heard.

Training Schedule

Subject 1 completed pretraining testing at 65 mo postimplantation, took the two-loudspeaker system home, and trained for 1 mo and then returned for testing. Subjects 2 and 3 completed pretraining at a regularly scheduled cochlear implant follow-up as did Subject 1. They were instructed in the clinic on the proper equipment setup and use and received the two-loudspeaker system in the mail a few months prior to their next scheduled follow-up appointment. They called the clinic after receiving the equipment, and the procedures were reviewed. Subject 2 completed pretraining testing at 96 mo postimplantation, trained for 3 mo, and then completed posttraining testing. Subject 3 completed pretraining testing at 84 mo postimplantation, trained for 2 mo, and then completed posttraining testing.

Localization and Recognition: Cueing the Location of Talkers

Figure 6 shows results from the Localization and Recognition: Cueing the Location of Talkers test. Individual results for the three training subjects are shown in solid black lines while the average of the six control subjects is shown in a dotted black line.

A paired *t*-test between the first and second administration of the test for the control subjects showed no significant difference. A paired *t*-test between pre- and posttraining revealed that subject 1 ($t(29) = 10.9, p < .001$) and subject 2 ($t(29) = 3.2, p < .01$) showed a statistically significant improvement while Subject 3 did not.

Difference scores between pre- and posttraining were calculated for each subject and between the first and second administration for the control group. Each of the three individual subjects had larger difference scores than the average of the six subjects in the control group. An independent *t*-test on group data showed that the improvement observed in the training group ($M = -3.5, SD = 2.2$) was larger than that in the control group ($M = -1.0, SD = 1.8$), [$t(58) = 4.8, p < .001$].

Recognition: Multiple Jammers from Different Locations

Figure 7 shows results from the Recognition: Multiple Jammers from Different Locations test. Individual results for the three training subjects are shown in solid black lines while the average of the six control subjects is shown in a dotted black line. A paired *t*-test between the first and second administration of the test for the control subjects showed no significant difference. For each training subject, a pre-/postevaluation determined that subject 1 ($t(29) = 2, p < .05$) and subject 3 ($t(29) = 2.5, p < .05$) demonstrated statistically significant improvements after training while subject 2 did not. Difference scores between pre- and posttraining were calculated for each training subject and between the first and second administration for the control group. Two of the three individual subjects had larger difference scores than the average of the six subjects in the control group. An independent *t*-test on group data showed that the improvement observed in the training group ($M = -1.0, SD = 2.4$) was larger than that in the control group ($M = 0.4, SD = 1.3$), [$t(58) = 2.8, p < .01$].

SUMMARY AND DISCUSSION OF TWO-LOUDSPEAKER HOME-BASED SYSTEM

Very similar positive comments as those received with the eight-loudspeaker home-based system (e.g., “easy to use,” “fun,” “kept me motivated to keep trying to work harder”) were obtained with the two-loudspeaker home-based system. However, there were no negative comments about the hardware for the two-loudspeaker home-based system.

The following encouraging observations were made:

- Subjects had no complaints about the hardware for the two-loudspeaker home-based system.
- Subjects 1 and 2 showed improvements on a newly developed spatially separated localization and speech-in-noise recognition test after training, while a control group of individuals who did not complete the training showed no improvements.
- Subjects 1 and 3 showed improvements on a newly developed spatially separated speech-in-noise test with multiple jammers from various locations, while a control group of individuals who did not complete the training showed no improvements.
- Subject 1 showed a significant difference compared to the control group on the spatial localization and speech recognition test, while Subject 3 showed a statistically

significant difference when compared to the control group on the spatial test with multiple jammers.

CONCLUSIONS

This paper describes a novel training system developed with the use of multiple loudspeakers to provide spatial separation of speech and noise. The purpose of the project was to create a training system that would allow hearing-impaired listeners the opportunity to train with two ears to improve their ability to understand speech in the presence of background noise and to improve their ability to localize sounds. The development of the system took many years starting with a laboratory system that evolved into a two-loudspeaker system that patients can use in the comfort of their own home. The intent of this paper was to review the development of the system, to document the stages of development, and to share preliminary test results. This is important in the broader development of computer-based auditory training programs and emphasizes the potential to improve hearing in noise and localization.

One important issue was the evolution of the laboratory to home-based system. Initially, it was believed that a system with predetermined loudspeaker placement would be the best approach. However, it is clear from this study that the two-loudspeaker home-based system was easier to set up and use than the eight-loudspeaker home-based system. In addition, to our surprise, the two-loudspeaker system allowed for more flexibility and a greater range of loudspeaker placement allowing users more control in determining the appropriate level of difficulty for training. An advantage of a computer-based aural rehabilitation system is that it is relatively easy to change, including different gender talkers, using phrases, and the addition of contextual and audiovisual information (Tyler, 1994).

When considering the evaluation of the effectiveness of our spatial system, we were able to demonstrate improvement in performance in some patients following training. Consistent with the literature, not all subjects showed an improvement after training, and improvements were not found across all test measures. It is of particular interest that there is not a clear relationship between speech hearing in noise and localization (e.g., Hirsh, 1950; Noble et al, 1997). It might be possible to obtain benefit in one area but not the other, or alternatively, training in one might benefit the other. It should also be noted that children with cochlear implants may be able to benefit more from training than the adult listeners reported in this manuscript. This is especially true when considering auditory plasticity as being one of the reasons for improvement or training benefit.

The following are future directions currently being explored for use with the training system:

- Provide performance feedback
- Create original sounds (phrase and sentence materials)
- Create pediatric, adolescent, and geriatric versions
- Adjust the signal-to-noise ratio to accommodate moderate losses
- Create special programs for those using combinations of hearing aids and cochlear implants

Abbreviations

CI	cochlear implant
CNC	consonant-nucleus-consonant monosyllabic words
HINT	Hearing in Noise Test

ILD	interaural level difference
ITD	interaural timing difference
RMS	root mean square

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Figure 1.

An individual using the two-loudspeaker home-based system. The top panel shows the loudspeakers placed on each side of the individual representing a less difficult condition. The bottom panel shows the speakers placed close together directly in front of the individual representing a more difficult condition.

Figures 2.

Screen shots of the eight-loudspeaker system: *a.* title of the training program; *b.* text used to explain the purpose of the training program; *c.* options to get started; *d.* options for localization training; *e.* localization active exploring; *f.* localization guided learning; *g.* speech-in-noise exploring speech; *h.* speech-in-noise exploring noise direction; *i.* speech-in-noise guided learning options; *j.* speech-in-noise guided learning.

Figure 3.

Everyday sounds localization performance over time, pretraining and posttraining with first the laboratory system and then the eight-loudspeaker home-based system for Subject 1. Performance is represented by RMS error in degrees (lower the number the better the performance).

Figure 4. Speech perception scores over time for Subject 1 with pretraining data collection at 36 mo and posttraining (eight-loudspeaker system) data collection at 40 and 45 mo postimplantation. Dotted line shows improvements from pre- to posttraining.

Figure 5. Adaptive spondee-signal-to-noise ratio score for subject 1 (eight-loudspeaker system) with the right only, left only, and bilateral implants at pre- and posttraining.

Localization and Recognition: Cueing the Location of Talkers

Figure 6.

Pre- and posttraining scores for three subjects (two-loudspeaker system) and the average of six control subjects on a newly developed localization and recognition: cueing the location of talkers test.

Recognition: Multiple Jammers from Different Locations

Figure 7.

Pre- and posttraining scores for three subjects (two-loudspeaker system) and the average of six control subjects on a newly developed recognition: multiple jammers from different locations test.

Table 1**Computerized Auditory Training Systems**

Name of Product	Company
Conversation Made Easy, Speechreading and Conversation Strategies Training for Children with Hearing Loss	Central Institute for the Deaf
Computer Assisted Speech Training	Tiger Speech Technology
Hearing Your Life	Advanced Bionics
Internet Based Open-Set Speech Recognition I-Star	Tiger Speech Technology
Listening and Communication Enhancement	Neurotone
Listening Room	Advanced Bionics
Seeing and Hearing Speech	Sensimetrics
Sound and Beyond	Cochlear
Speech Perception Assessment and Training System	Communication Disorders Technology

Table 2

Number of Months Postimplantation That the Control Subjects Completed the Pre- and Posttest Battery

Subject #	Pretesting Months Postimplantation	Posttesting Months Postimplantation
Control 1	42	44
Control 2	27	29
Control 3	57	59
Control 4	28	30
Control 5	55	58
Control 6	33	36