# The Development and Validation of an "Intelligent" Classroom Sound Field Frequency Modulation (FM) System

**Norman Lederman**
*Oval Window Audio*

**Cheryl DeConde Johnson**
*Colorado Department of Education*

**Carl C. Crandell**
*University of Florida*

**Joseph J. Smaldino**
*University of Northern Iowa*

**The adverse acoustical environments often found in classrooms have led to the proliferation of small sound reinforcement systems currently referred to as "sound field FM amplification systems". Previous studies detail how speech perception is negatively affected by variable background noise conditions created by poor acoustics, room heating/cooling systems, noisy audiovisual and computer equipment, and other noise generated both inside and outside the classroom. Available manually adjusted sound field systems do not address the fact that background noise levels and teacher microphone input levels often change throughout the day in the classroom. This article will report on the development and field validation of adaptive signal-processing technology that "listens" to the classroom's changing background noise, automatically adjusting the sound field system's output in order to maximize signal-to-noise ratio and speech intelligibility. Field test data demonstrated positive effects of this adaptive signal processing technology on speech perception.**

## Introduction

Most classrooms equipped with conventional sound field frequency modulation (FM) systems are set up for one particular room condition (i.e., one background noise level and an optimum teacher microphone placement) (Crandell, Smaldino, & Flexer, 1995). Unfortunately, this condition is not a constant. Unless the volume control is constantly adjusted throughout the day, the systems operate at one set level of output/volume everyday, and the teacher microphone may move from its optimal position. As a result, the effectiveness of these sound field systems varies widely throughout each day as the background noise, vocal effort, and microphone-to-mouth distance change. Based on these observations, a classroom sound field system was conceptualized to "listen" to the environment in which it is operating and automatically make adjustments to its output in order to maintain a favorable signal-to-noise ratio (SNR). This technique, generally referred to as "ambient noise compensation" (ANC), has been in use for several years in the professional sound reinforcement industry with applications ranging from sports arenas to train stations. This article first briefly describes the development of a sound field system that uses ANC technology. In addition, results from experimental field testing of the technology are discussed.

## Design Considerations

Several technical aspects of sound field FM systems were considered, including choice of microphone, microphone technique, amplifier and loudspeaker design, equalization, loudspeaker placement, and classroom acoustics. While the project enabled the design of a new classroom sound field system "from the ground up", the authors realized that every aspect of the system was deserving of an in-depth research and development project. In the interest of time, the focus was narrowed to creating and evaluating a classroom sound field system that would automatically self-adjust to changing microphone-input signals and varying background noise conditions. It was later decided that rather than designing a total system, it would be more expeditious to develop an "add-on" signal processor that would easily connect with, and improve, the performance of existing sound field systems, especially in settings with variable background noise conditions. This approach makes the technology economical and accessible to more people who can benefit by an improved "retrofitted" sound field system. This decision ultimately resulted in a new sound field system accessory named SmartSpeaker "Intelligence"™, a small "black box" that is simply connected between the output of the sound field system's wireless microphone receiver and the input of the amplifier.

The most sophisticated sound system will only sound as good as its input signal. SmartSpeaker's digital signal processing circuitry depends on a high quality signal in order to make the appropriate "decisions" about the SNR status of the system. It was concluded that only head-worn microphones could deliver the required level of quality consistently (Lederman & Hendricks, 2000). In SmartSpeaker, a non-distorting input compressor-peak limiter controls the dynamic range of the teacher's speech signal, while providing some correction for changes in microphone distance and vocal effort.

Ambient Noise Compensation (ANC) monitors the SNR conditions in the room through a "sense microphone" that is located 6' away from one of the system loudspeakers, and automatically makes adjustments of up to 12 dB to compensate for changes in background noise. The ANC employs digital signal processing that continuously measures the system's true SNR, comparing the loudspeakers' acoustic (output) signal with the original electrical input signal and taking into account signal level, spectrum and signal statistics. A variable adaptive response time ensures that changes to the signal level occur unobtrusively. The device being tested requires an initial calibration that may be performed with a sound level meter or by ear. Once established, calibration does not have to be repeated unless the sound field system's control settings or loudspeaker-sense microphone distances are altered.

The following report describes the results of two phases of research, development and field test evaluations of SmartSpeaker (herein referred to as the "prototype system"). Phase I was a 6-month feasibility study designed to develop basic technology and prove its usefulness in classroom settings. Building on the results of Phase I, Phase II was a 24-month project that resulted in improved technology, an expanded field test design and the commercialization of the final project. Following are results of field tests conducted in the last weeks of each phase.

## Field Test Validation: Phase I

### Methods

Phase I field testing of a SmartSpeaker sound field FM system was conducted in two elementary school classrooms (first and third grades) where sound field systems were already being utilized. The first grade classroom was larger than the third grade classroom to accommodate a team teaching format and larger class size. Classroom amplification had been installed in this classroom due to the larger class size and at-risk population. A background noise level of 53dBA was measured when the room was quiet and occupied.

Sound field amplification was utilized in the third grade classroom because one student was identified with an unaided unilateral hearing loss. The classroom was rectangular with student desks oriented in a traditional row design. The sound level of this room when quiet and occupied was 54 dBA.

Participants. The 1st grade class was made up of 32 students, the majority of whom were bilingual. Student desks were grouped in clusters of four facing one another. While all students participated in the listening tasks, seven students from the first grade class were eliminated from the data analysis because the teacher reported that they possessed very limited English skills, resulting in a final N of 25.

The 3rd grade class was composed of 23 students, split equally between Hispanic and Caucasian ethnicity and whose primary language was English.

Materials and equipment. Equipment included the prototype SmartSpeaker equipped sound field FM system described earlier in this article. A separate sound system (a JVC XL5252 Compact Disk player, Technics SA-EX100 stereo amplifier/receiver and a pair of Bag End TA12 JR-C loudspeakers) was used to present competing background noise. Sound levels were measured with an Extech Type II Sound Level Meter.

*The Word Intelligibility by Picture Identification Test* (WIPI) (Ross & Lerman, 1979) was used as stimuli, recorded on the left track of a compact disc. The stimulus recordings were conducted using a female voice. A 6-second interval between stimulus presentations was used for the WIPI words.

The right track of the compact disk contained a recording of a 50-50% mix of pink noise and 12 speaker babble at the varying intensity levels required for the listening tasks. This noise mix was created in order to represent industrial (e.g. heating, ventilation, air conditioning) and human-made (i.e., speech) background noise.

Procedures. Twenty-five items of the WIPI were presented twice; first, with the classroom's existing sound field FM system and then a second time, using the prototype SmartSpeaker equipped sound field FM system. The 25 word list was divided into five sets presented with each system at each of the following five SNRs: +10dB, +5dB, 0dB, -5dB, -10dB. Students marked their responses on individual worksheets (a picture and word representation of a test item and five foils in a forced -choice response format) with an X or a checkmark. Three adults were positioned throughout the class to ensure that children were on the correct page and item number. In addition to the scored listening task, the prototype system was used in each classroom for the following week. At the end of the trial period, the teachers and students completed surveys regarding the performance of the prototype system.

### Results

The results of the field testing with the prototype system are reported in Figure 1. The bar graph depicts word identification performance for each age group as a function of SNR. Scores are compared for conventional sound field amplification and the protoype system. The graphed results suggested a notable increase in word identification performance with the prototype system at the -10 dB SNR condition, e.g., 11.2% to 81.6% for 1st graders and 33.9% to 96.5% for 3rd graders.

Comments from the teacher and student evaluations were also positive. Teachers reported, "...it was easier for everyone to concentrate..." and, "I could hear my own voice more clearly". Third grade students complete a 5-item questionnaire about their observations. Results indicated that 16/20 could tell the difference between the two systems, 19/20 preferred the prototype system to the conventional system, 19/20 reported the prototype system helped them understand the teacher better, and 15/20 said it helped them pay attention better. It is readily acknowledged that the reliability of reports from young children is not always high, and that all persons involved may have been influenced by the novelty effect of new technology.

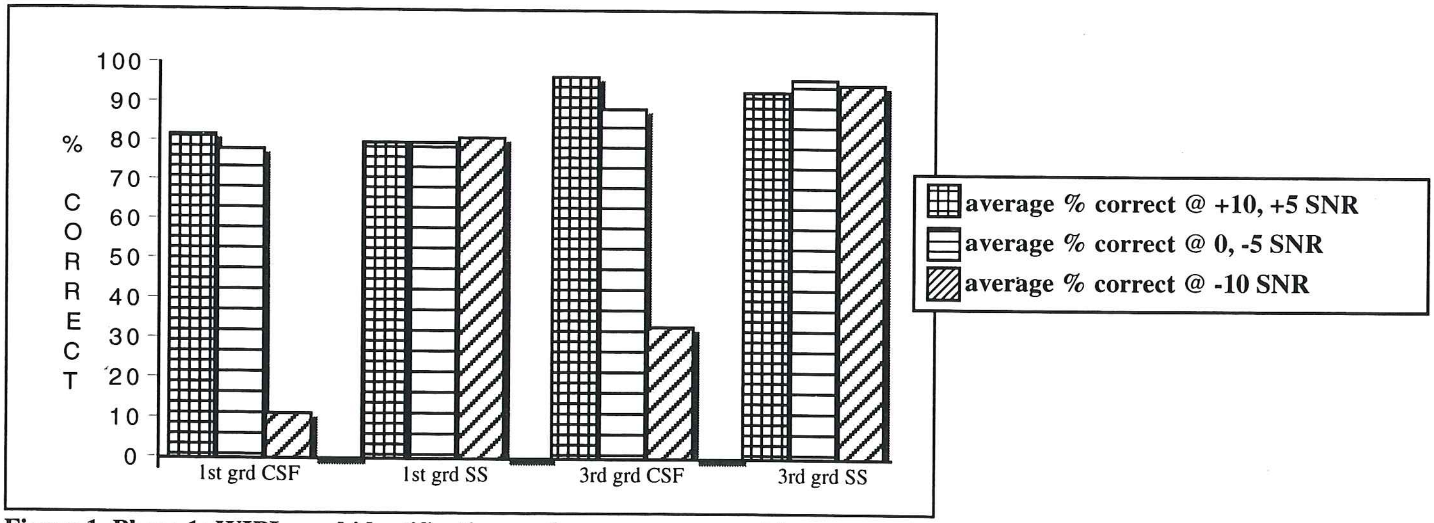

**Figure 1. Phase 1: WIPI word identification performance acress subject categories and SNR for conventional sound field (CSF) and SmartSpeaker (SS) sound field amplification**

**Field Test Validation: Phase II**

Methods

Participants. Phase II was conducted at the same elementary school and in the same rooms, although with different children. Eighty-three children served as participants, including:

- Forty 3rd grade students with normal hearing, confirmed by a hearing screening conducted before the study. These children were identified as a group at academic risk since only 21% achieved a proficient or advanced performance level on the third grade Colorado Student Assessment Program (CSAP) reading test (compared to the state average of 67%, as reported by the Colorado State Department of Education).
- Twenty-one 3rd graders identified as English Language Learners (ELL);
- Fourteen 3rd graders who received special education services (for speech-language and learning disabilities);
- Nine hard of hearing (HOH) students (two 3rd graders, three 4th graders, and four 5th graders). One HOH student was a third grader attending the elementary school; the other eight children attended a center-based deaf/hard of hearing program at another school. The mean pure tone average for the better ear for these children was 53.3dB (range = 37-75dB); the mean pure tone average for the poorer ear was 58.3dB (range = 37-75dB). These students did not have any other significant disability conditions and all were consistent hearing instrument users. To verify performance, a cursory listening check of all instruments worn by the students was conducted prior to the beginning of the testing.

In addition to these 83 children, three 3rd grade students participated in the listening tasks but were eliminated from the analysis, two because they spoke Spanish only, and one because he did not pass the hearing screening. All teachers and students had previous or current experience utilizing sound field FM and/or personal FM systems.

Materials and Equipment. In addition to the equipment described earlier for Phase I, recordings of the WIPI as well as consonant-vowel discrimination stimuli were used, again recorded on the left track of a compact disc. A 4-second stimulus interval was used for the consonant-vowel combinations.

The right track contained the same type of noise as used in Phase I. The SNR were simplified from Phase I in order to collect as much data as possible in the time available. Phase II used the following three SNRs: +6dB, 0dB, and –6dB.

The left track of the compact disc was connected to the prototype system. The right track was connected to the "background noise" sound system. A sound level meter was used to measure background noise conditions and to set the playback levels of the noise track and recorded speech materials. Trials with the ambient noise compensation on and off were conducted to evaluate the effects of ambient noise compensation. The classroom configuration for the testing of the 3rd graders is shown in Figure 2 and for the students who were hard of hearing in Figure 3. ANC corrections to the changing signal-to-noise conditions are provided with each figure.

Procedures. Two listening tasks were completed by each student in two listening conditions, using the prototype system with and without ambient noise compensation. The first listening task used the WIPI as a stimulus, presented by recording. As before, children marked their responses on a worksheet. Test items were divided into thirds: the first 15 stimuli were presented at +6dB SNR, the second 15 items at 0dB SNR, and the final 15 items at -6dB SNR.

The second listening task was a 54-item discrimination task of the consonant-vowel combinations of /ba/, /da/, and /ga/, recorded by a female talker speaking General American English. Students were required to identify whether the two sounds that were presented were the same or different (e.g., /ba, ba/ or /ba, ga/) by circling the word "same" or "different" on their response form. The test items were divided into three groups, this time with 18 items at each of the three SNRs. Practice items were given for each of these listening tasks.

Students were advised that as the noise level increased, it would be harder to hear the recorded words. They were told to

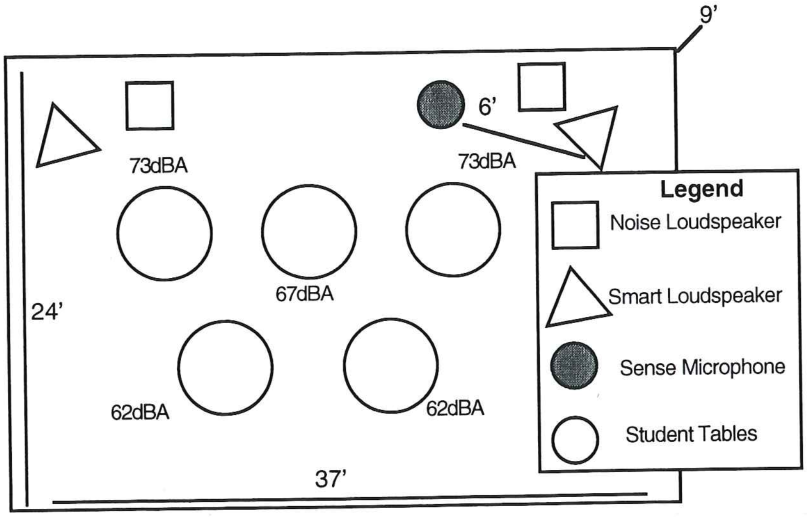

**Figure 2. Diagram of SmartSpeaker Phase II field test classroom #1.**
Ambient Background noise: unoccupied "quiet" = 46 dBA, occupied "quiet" = 52 dBA, reverberation = <.6 seconds
Normal operating level: 67 dBA (+15dB signal-to-noise level)
Listening test noise presentation and signal-to-noise:

| Noise | SFS S/N | *Smart* Correction | *Smart* S/N |
|---|---|---|---|
| 61 dBA | +6 dB | +6 dB | +12 dB |
| 67 dBA | 0 dB | +12 dB | +12 dB |
| 73 dBA | -6 dB | +12 dB | +6 dB |

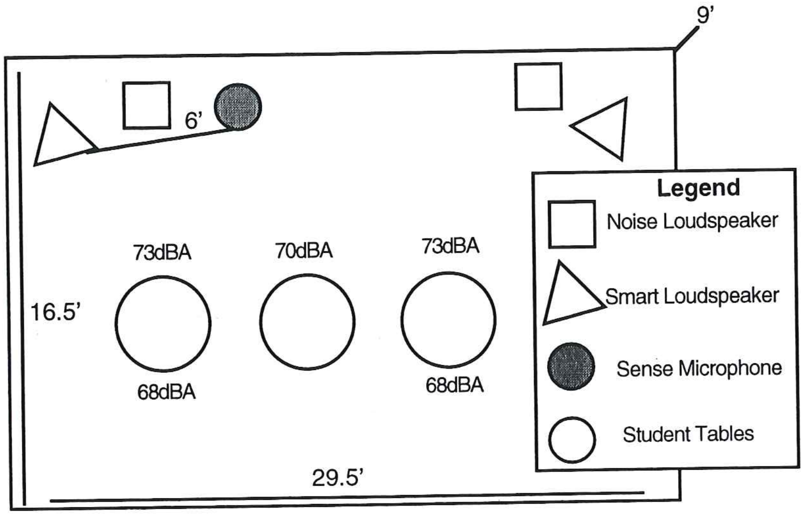

**Figure 3. Diagram of SmartSpeaker Phase II field test classroom #2.**
Ambient Background noise: unoccupied "quiet" = 48.5 dBA, occupied "quiet" = 55 dBA, reverberation = <.6 seconds
Normal operating level: 70 dBA (+15dB signal-to-noise level)
Listening test noise presentation and signal-to-noise:

| Noise | SFS S/N | *Smart* Correction | *Smart* S/N |
|---|---|---|---|
| 64 dBA | +6 dB | +5 dB | +11 dB |
| 70 dBA | 0 dB | +11 dB | +11 dB |
| 76 dBA | -6 dB | +12 dB | +6 dB |

guess if they were not sure of their answer and to mark their answers on the score sheet. It was emphasized that it was important for them to each do their own work. In addition, cards were held up prior to each item to identify the task number when the SNR was at 0dB and -6dB.

Trial order presentation was rotated based on whether the ambient noise compensation level was on or off for the consonant-vowel and WIPI tasks. The total test time including directions and practice was approximately 50 minutes.

After completing these two listening activities, students completed a magnitude of estimation of quality (MEQ) scale, in which they placed themselves on a sound quality continuum. This 100 point scale was used for the students to judge their perception of the sound quality during the listening tasks (on a continuum of 1= "very poor" to 100 = "very good").

The students were also evaluated using the Screening Instrument for Targeting Educational Risk (S.I.F.T.E.R.) (Anderson, 1989), a rating scale completed by the teachers on all students. This protocol compared each student to his/her peers in the areas of academics, attention, communication, class participation, and school behavior. The S.I.F.T.E.R. mean scores are reported by group in Table 1. The significant problem areas were academics and communication for the ELL group, and academics, communication, and attention in the special education group.

## Results

An analysis of variance (ANOVA) with an alpha level set at .05 was used for the data analysis. The mean scores for each of the listening tasks for the total population and for each of the groups is presented in Table 2. When considering the scores of the entire group of subjects, performance improved in all conditions with the prototype system "on". Statistically significant increases were evident in 5/8 conditions (WIPI word recognition at 0 SNR & -6 SNR, same/different at -6 SNR, MEQ for word and same/different tests). When considered by subgroups, the ELL students had statistically significant better performance during the WIPI test at all SNR levels as well as on both MEQs, the special education students had better performance at 7/8 tests although none were at the .05 level, regular education students demonstrated

**Table 1. Mean S.I.F.T.E.R. scores across subject categories**

| S.I.F.T.E.R. Subtest | Subjects N=83 | 3rd grade ELL N=21 | 3rd grade Spec Ed N=14 | 3rd grade Reg Ed N=40 | 3rd, 4th, 5th HI N=9 |
|---|---|---|---|---|---|
| Academic | 8.66* | 7.09** | 6.86** | 9.85* | 9.67* |
| Attention | 8.49* | 8.00* | 5.71* | 9.50 | 9.33 |
| Communication | 8.49* | 6.00** | 7.00** | 9.97* | 9.55* |
| Class Participation | 9.29 | 8.28* | 7.07* | 10.7 | 8.33* |
| School Behavior | 12.35 | 12.62 | 9.57* | 13.05 | 12.78 |

* marginal concern as defined by Anderson, 1989
** significant concern as defined by Anderson, 1989

statistically significant improvement in 5/8 areas (WIPI at each SNR, same/different at -6 SNR, and MEQ words) and the students with hearing impairment performed statistically better on the same/different test at -6 SNR.

Collectively, performance was improved in all but 2/40 conditions with 16/40 conditions reaching significance at the .05 level. These are identified in bold italicized print in Table 2.

## Discussion

In Phase I, the performance of the prototype SmartSpeaker sound field system was compared to a conventional sound field system currently utilized in the classrooms. It was found that its use of ambient noise compensation (ANC) technology resulted in better speech perception of one-syllable words in –10 dB SNR.

During Phase II, the prototype system was its own control with performance comparisons made with the system's ANC technology either on or off. The use of ANC technology resulted in better performance across test conditions in Phase II. It appears that this technology successfully identifies a change in background noise and automatically increases the volume of the signal, thereby maintaining a consistent SNR.

The results of this study raise a number of discussion points. First, the use of sound field amplification with children who have diagnosed hearing losses and who wear hearing aids is not well documented. The nine hard of hearing listeners in Phase II of this project exhibited statistically significant improvement in only one experimental condition out of eight (see Table 2). Why might this high-risk group not show benefit with sound field amplification? First, based on their favorable performance on the listening tasks, it was evident that they were hearing quite well with their personal hearing aids. While the addition of sound field amplifi-

**Table 2. Mean performance for word recognition, same/different, and MEQ tasks across subject categories. For Trial 1 (T-1), ANC is off; for Trial 2 (T-2), ANC is on**

| | All subjects N=83 | | 3rd grade ELL N=21 | | 3rd grade Spec Ed N=14 | | 3rd grade Reg Ed N=40 | | 3rd, 4th, 5th HI N=9 | |
|---|---|---|---|---|---|---|---|---|---|---|
| TASK | T-1 | T-2 | T-1 | T-2 | T-1 | T-2 | T-1 | T-2 | T-1 | T-2 |
| Word 1: +6 SNR | 13.60 | 14.18 | ***13.23*** | ***14.42*** | 12.50 | 12.64 | ***14.02*** | ***14.80*** | 14.22 | 13.33 |
| Word 2: 0 SNR | ***12.82*** | ***14.07*** | ***12.52*** | ***13.90*** | 11.35 | 12.71 | ***13.40*** | ***14.62*** | 13.33 | 14.22 |
| Word 3: -6 SNR | ***11.65*** | ***13.95*** | ***11.14*** | ***14.04*** | 10.07 | 12.14 | ***12.35*** | ***14.65*** | 12.00 | 13.33 |
| S/D 1: +6 SNR | 15.80 | 16.51 | 14.57 | 16.00 | 13.71 | 15.00 | 17.02 | 17.32 | 16.66 | 16.66 |
| S/D 2: 0 SNR | 15.83 | 16.07 | 15.04 | 16.19 | 14.35 | 13.78 | 16.65 | 16.80 | 16.44 | 16.33 |
| S/D 3: -6 SNR | ***14.69*** | ***16.22*** | 13.81 | 15.43 | 12.92 | 14.78 | ***15.85*** | ***17.07*** | ***14.33*** | ***16.55*** |
| MEQ Word | ***60.37*** | ***85.30*** | ***45.24*** | ***91.90*** | 62.85 | 82.85 | ***63.58*** | ***84.00*** | 78.75 | 81.11 |
| MEQ S/D | ***68.91*** | ***79.28*** | ***52.38*** | ***79.05*** | 62.14 | 80.71 | 79.25 | 79.00 | 68.88 | 81.11 |

*p* <.05 level is noted in ***bold italics*** cation did improve their relative performance in 5/8 conditions, their performance was poorer in 2/8 conditions and unchanged in 1/8 conditions. Perhaps the "mix" of personal hearing instrumentation and sound field amplification produces an effect that may not always be advantageous. Further, it is possible that the materials used were not adequately sensitive to detect the changes in performance when the ANC was on. While the results of this group of 9 students is too small to make any generalizations, it does support the need for further study of the interaction between hearing aids and sound field FM amplification.

The results of other special education and at-risk populations of students shown in Table 2 were also somewhat inconsistent. The ELL group demonstrated relatively better performance in all conditions with ambient noise compensation technology. The improvement at three of the conditions was statistically significant. While the special education group's performance improved in 7/8 conditions, none were statistically significant. In spite of this, there is a definite trend in the data to suggest that these populations benefited from the ANC. The small numbers of subjects and heterogeneity typical of these populations may have conspired to prevent statistically significant differences in performance in this study.

This field test did not include a comparison of speech perception with and without sound field amplification, since improvement in speech perception in amplified sound fields has been well-documented elsewhere (see Rosenberg et al., 1999). Future research is needed to determine whether the WIPI and/or the consonant-vowel discrimination tasks used in this study are sufficiently sensitive to identify speech perception difficulties under the adverse listening conditions utilized.

In summary, this study suggests that the introduction of advanced signal processing strategies such as ambient noise compensation increases the performance of the available soundfield FM amplification technology. Since the success of sound field FM amplification depends on a number of technical variables (system integrity, sound quality, room set-up) as well as management concerns (acoustical environment, instructional style, teacher, student), it is important to have a variety of options from which audiologists can choose when designing a sound field amplification plan for a classroom. Accordingly, ambient noise compensation may provide an option for classrooms that suffer from HVAC noise or other signal-to-noise ratio problems that are intermittent or variable in nature.

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