A Comparison of the Performance of Classroom Amplification with Traditional and Bending Wave Speakers

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Classroom amplification (CA) is used to compensate for the poor acoustics in schools to some degree by amplifying the teacher's voice and projecting it throughout the classroom via loudspeaker(s), thereby improving the signal to noise ratio (S/N). A new loudspeaker technology based on bending wave physics is reported to preserve the speech signal with more fidelity and with less loss of power than traditional cone loudspeakers, thus providing an improved signal as well as an improved S/N. This research compared a CA system coupled with either a traditional or bending wave speaker in a classroom on two measures: (a) an octave band analysis of the frequency distribution and (b) performance by third and fourth graders on a high frequency emphasis, multiple choice speech discrimination test.

The standard classroom is a very challenging place to listen and learn, particularly for primary-aged children, who have poorer discrimination skills and more difficulty listening in noise than older children and adults (Crandell, Smaldino & Flexer, 1995; Papso & Blood, 1989). Typically, as the distance from the speaker increases, noise from various sources decreases audibility of high frequency speech information (Leavitt & Flexer, 1991). The unsatisfactory signal (teacher's voice)-to-noise ratios (S/Ns) in classrooms have been identified as an impediment to listening and learning for children with and without special needs (Crandell, 1991; Finitzo-Hieber & Tillman, 1978; Hart, 1983; Neuss, Blair & Viehweg, 1991; Rosenberg, 1998; Ross & Giolas, 1971; Sarff, 1981; Zabel &Tabor, 1993).

The use of classroom amplification (CA) to improve S/Ns has been advocated since the 1980s (Ray, 1988; Sarff, 1981). In CA, the teacher's voice is amplified and projected throughout the classroom via loudspeaker(s). Use of CA in controlled studies has resulted in improved S/Ns, enhanced speech understanding and significantly better academic achievement for children with various disabling conditions as well as for children without any special learning needs (see Rosenberg, 1998 for a review). However, installation of CA may improve S/N without improving speech acoustics. To assure a good speech signal throughout the classroom, high frequency information must be preserved uniformly, which is a challenge with traditional speaker technology (Mapp & Colloms, 1997). Each classroom presents a unique listening environment due to its dimensions, location, construction materials, and arrangement of items within. Also, options available in CA systems include number and placement of speakers, speaker type, and tone controls. Different combinations of these variables result in different acoustic properties of the speech signal at different points in the space (Flexer, Crandell & Smaldino, 1995). A good match between classroom and CA system is necessary for the best possible speech signal presentation throughout the classroom.

The use of CA in classrooms is increasingly common (Johnson, Benson & Seaton, 1997). There are an estimated 20,000 systems in use in the U.S. with the number increasing steadily (J. Ramey, personal communication, January 16, 2001). There is a need for a simple way to compare systems, judge the adequacy of a system before purchase, or determine appropriate control settings, speaker placement, and other features. Equipment designed to measure the degradation of the speech signal as it travels from the source is available, but the cost is prohibitive (Leavitt & Flexer, 1991) and results yield only an estimate of the effect on speech understanding. The best way to determine if a system provides an adequate signal for young listeners is to directly measure children's ability to understand speech delivered in a classroom using that system.

There is no consensus in the field on the number or placement of loudspeakers for best speech understanding (Crandell & Smaldino, 2000), and it is recognized that different systems or configurations yield dissimilar speech recognition or discrimination performance in children. Crandell (1993) found significant differences in speech recognition performance in 20 children with normal hearing using various commercially available CA systems. Four CA systems were compared using Phonetically-Balanced Kindergarten (PBK-50) monosyllabic word lists. Stimuli were recorded in a classroom-like setting, but were presented to the children in an audiometric test booth under earphones. Prendergast (1999) compared two systems having different configurations (one speaker mounted high in a corner and four speakers, one in front of each wall on stands) in vivo with 107 kindergarten through third grade children using the Word Intelligibility by Picture Identification Test (WIPI) (Ross & Lerman, 1971). A picture selection response format was chosen to allow children (including pre-readers) to be tested in groups. The WIPI was designed for 4 – 6 year old children with hearing loss and with smaller vocabularies than expected for their chronological ages (Ross & Lerman, 1971). Because of the need to find sets of rhyming or similar words that not only were within a restricted vocabulary but that also could be unambiguously illustrated, the required discriminations are relatively gross (e.g., king, ring, swing, spring). Although Prendergast (1999) found a statistically significant difference between the speech discrimination performance using the two CA configurations, the difference was of the magnitude of one error out of 25 responses and all scores were high (means of 98% versus 94%). Thus, a ceiling effect may have obscured the degree of difference between the conditions.

It was predicted that the California Consonant Test (Owens & Schubert, 1977), a written multiple choice speech discrimination test, would reduce the chance of a ceiling effect and, thus be a feasible instrument for assessing differences among CA systems with older primary children. The California Consonant Test (CCT) targets contrasts of high frequency consonants that are both critical to speech understanding (Leavitt & Flexer, 1991) and the sounds that are most difficult to present without degradation with traditional speaker technology (Mapp & Colloms, 1997). Although the CCT was developed for use with adults, the word attack skills necessary to discriminate among the items is a second grade skill (Illinois State Board of Education, 2000).

Recently, a new speaker technology based on bending wave physics has been incorporated into a CA product. It propagates and disseminates sound waves in a fundamentally different manner than existing speaker technology, preserving high frequency information throughout an area the size of a standard classroom (Mapp & Colloms, 1997). During the propagation of a signal by a traditional speaker, excitation of a single center point

Figure 1. Speaker activation in a traditional cone speaker (Reprinted with permission of NXT, Stonehill, Huntingdon, England).

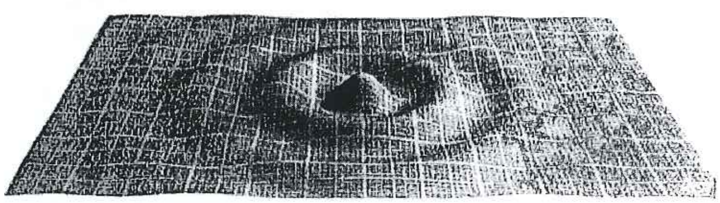
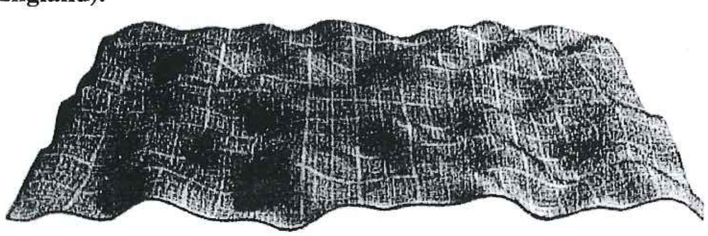
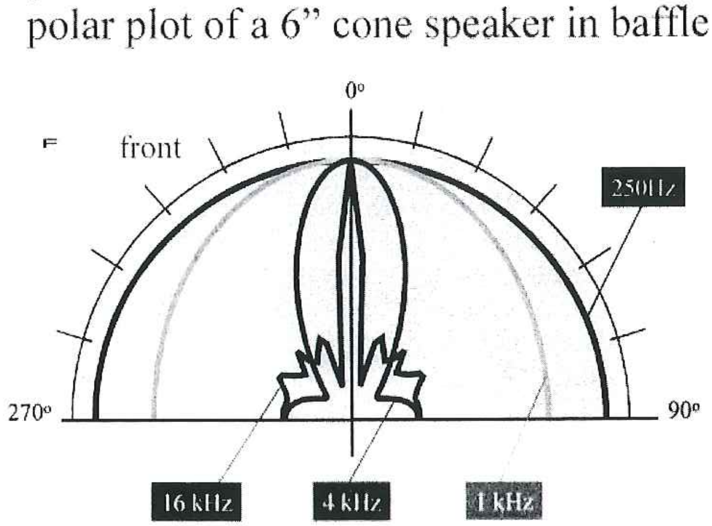


Figure 2. Speaker activation in a bending wave speaker (Reprinted with permission of NXT, Stonehill, Huntingdon, England).



occurs initially with subsequent concentric circles of decreasing excitation spreading outward (see Figure 1). In contrast, the entire surface of a bending wave speaker is involved in propagation of sound (see Figure 2.) Dissemination of the signal differs between the two technologies as well. The preservation of high frequency information is good directly in front (0 azimuth) of a traditional speaker, but becomes poorer as distance away from 0 azimuth, or the distance off axis, is increased (see Figure 3). Excitation of the entire surface in a bending wave speaker results in better preservation of high frequency information as distance

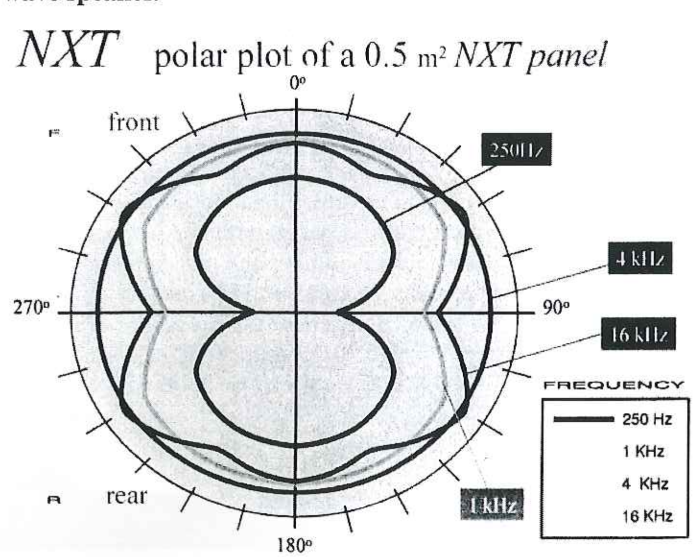
Figure 3. Acoustic radiation by frequency with a traditional speaker



increases off axis (see Figure 4). Also, because of the multiple points of excitation on the bending wave speaker, the inverse square law does not hold: the loss of power with increasing distance is less than with a traditional speaker (Mapp & Colloms, 1997). In a traditional speaker, the effect is directional propagation; in bending wave, the propagation is more omnidirectional. Improvement in the preservation of high frequency information throughout a space the size of a standard classroom with less loss of high-frequency power has been hypothesized to result in better speech understanding, particularly in "remote" areas of a classroom.

The purpose of this study was to compare both the preservation of high frequency information and the speech discrimination

Figure 4. Acoustic radiation by frequency with a bending wave speaker.



performance of primary aged children in a standard classroom with stimuli delivered through two types of speaker technology incorporated into a commercially available CA system. The following questions were asked: Does a bending wave speaker preserve acoustic information, particularly high frequency information, throughout a classroom better than a traditional speaker? Do any differences relate to speech discrimination performance between conditions or among different locations in the classroom? Is the CCT an appropriate instrument to use with children to differentiate CA systems?

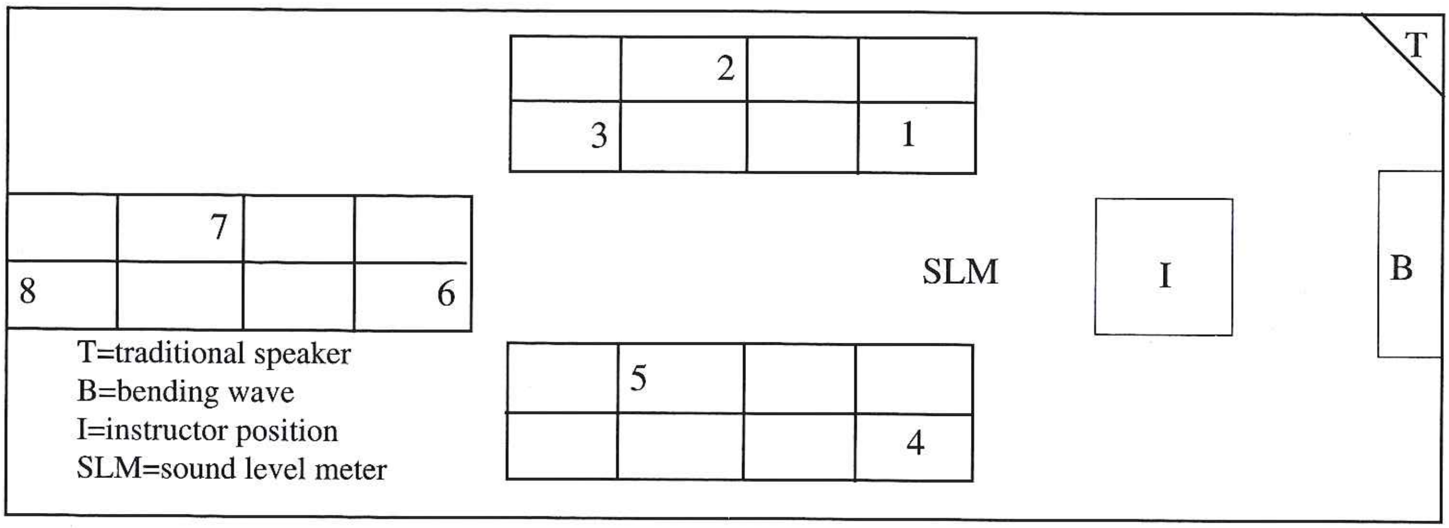
Method

Classroom Arrangement

All data were collected in a 30 X 30 foot square classroom with student desks arranged as they were for instruction. Eight sites evenly distributed throughout the student seating area were chosen as acoustic measurement locations (see Figure 5).

Because of encapsulated asbestos in the school, the use of a ceiling mounted speaker was not possible. A traditional system (LightSpeed 500C) with a single speaker (LightSpeed HI-Q) mounted high in a corner and tilted down was determined to provide the best possible signal for a classroom 30 feet by 30 feet with a 9 foot ceiling (J. Ramey, personal communication, September 27, 1999). This system had been installed in all primary classrooms in the school prior to data collection and had been used in instruction with all the participants for at least 7 months. The bending wave speaker (LightSpeed ARQ1 picture panel) was placed according to manufacturer's instructions. In this case, placement was 6 feet above the floor in the center of the north wall of the classroom, behind the typical instructional position (see Figure 5).

Figure 5. Arrangement of the data collection classroom



Acoustic measures.

The data collection classroom was square, 30 feet X 30 feet, with a 9-foot ceiling. There were a total of 4 wooden doors with glass windows and an additional 6 windows. The walls were concrete block and the floor was concrete covered with indoor-outdoor carpet. Window treatment consisted of metal blinds. An estimated reverberation time of .72 seconds was calculated according to the procedure recommended by Smaldino and Crandell (1995). This value exceeds the .4 seconds recommended by some for maximum speech recognition in a classroom (ASHA, 1995; Crandell & Smaldino, 2000; Finitzo-Hieber & Tillman, 1978) but is not atypical for classrooms for children with normal hearing (Crandell & Smaldino, 2000; Nabelek & Pickett, 1974).

Sources of classroom ambient noise included computers, fluorescent lights, and an air ventilation system (neither air conditioning nor heating were operative at the time of data collection). External sources included traffic, playground and hall noise. Classroom acoustic measures were made with a Quest (M215) portable sound level meter (SLM) equipped with an octave band filter (Quest SOB-245) on slow setting. The SLM was held as close as possible to the average ear level of seated children, perpendicular to the floor and facing the typical instructional position. Three or more samples for each data point were taken at intervals of at least 5 seconds and averaged. The value recorded for each sample was the level sustained for most of the interval (e.g., rapid transient peaks were ignored). Four types of acoustic stimuli were measured. First, the teacher's unamplified voice during instruction was measured at a point 3 feet immediately in front of the typical instructional position (reference position) and the average over 10 readings was 58 dBA (reference level). Second, the output of the CCT 1000 Hz calibration tone from each speaker was adjusted to 68 dBA at the reference position, i.e. 10 dBA above the reference level. This amount of gain is typical with CA systems (Crandell et al., 1995; Johnson, Benson & Seaton, 1997). Thus, the calibration tone from each speaker was adjusted to a single reference measure and at a single measurement point. Third, ambient occupied classroom noise (during pauses in instruction) was measured in dBA at each of the eight selected student sites (Table 1). Finally, the degree to which the two speakers preserved frequency-specific information throughout the classroom was determined by performing octave band measures with center frequencies ranging from 250 - 8000 Hz. The white noise output from each speaker was adjusted to 65 dB SPL, measured at the reference position. This level was chosen as it is the same level as average conversational speech, was quiet enough to be tolerable to those making the measurements but intense enough for stimuli from each speaker in all octave bands to exceed the threshold of the SLM. Measurements were taken of the white noise delivered via each of the two speakers at each of the eight student measurement sites in the unoccupied classroom.

Speech discrimination measures

Stimuli. The CCT consists of two equivalent forms of 100 items each. Each item includes a target word and three foils. There are 36 items in which the contrast is in the initial position and 64 items in which the contrast is in the final position. The test was constructed to focus on errors made most frequently by adults with hearing loss (Owens & Schubert, 1977). Thus, most of the test items target high frequency consonant contrasts in the final position. The first and last 50 items of list 1 were found to be equivalent for adults by Owens and Schubert. These half lists were used rather than 100 item lists because of the typical attention span of the young participants.

The traditional and bending wave speakers were each connected to the same receiver/amplifier unit (LightSpeed Model 500C). Before each administration of a CCT half list, the appropriate speaker was connected, the intensity of the 1000 Hz calibration tone was measured with the SLM at the reference position and the volume control was adjusted as needed. Changing only the speaker served as a control for possible variance introduced by another receiver/amplifier or by another teacher transmitter. A Compact Disc (CD) player (Sony CFD-S38) was placed to simulate typical teacher instructional position. The CD player was on top of a 4 foot 8 inch cart placed where the teacher generally lectured and the center of the CD speaker was 5 feet above the floor, approximately the height of the teacher's mouth. The teacher microphone from the CA system (LightSpeed Model LS4/TMP) was affixed two inches in front of the CD player speaker to simulate placement relative to the teacher's mouth (see Figure 5 for classroom arrangement). The volume control of the cassette player was adjusted to equal the 58 dBA level of the teacher's unamplified voice, at the reference position. Commercially available audiotape recordings (Auditec of St. Louis) of the two halves of CCT list 1 were transferred to CD format to facilitate counterbalancing conditions and test halves. The equipment used included a TEAC v-377 Stereo Cassette Deck connected via RCA connectors to an Apple Power Macintosh G3 Computer with an ATI Audio/Video Encoding Card and Adobe Premiere 4, Toast 4 software.

Participants. Participants were 31 third and 33 fourth grade students (32 girls and 32 boys in four classes) with hearing within normal limits. All potential participants were screened with tympanometry (Madsen Electromedics Model RCT) and otoacoustic emissions (Madsen ERO.SCAN DPOAE) during the week of data collection. Distortion product otoacoustic emissions (DPOAEs) were elicited at six frequencies (1500, 2000, 3000, 4000, 5000, and 6000 Hz) with +5 dB S/N at three or more frequencies as the criteria for passing. Most of the participants' hearing had been established as within normal limits in two previous investigations where threshold testing or screening was done monaurally in audiometric test booths by either licensed audiologists or by supervised graduate students in audiology. The criterion for passing the behavioral measures was no threshold greater than 15 dB HL at 500, 1000, 2000, 4000, and 6000 Hz. The potential participants who had not had behavioral testing in the previous 12 months, were screened monaurally in a test booth (15 dB HL, 500 Hz through 6k Hz) by a licensed audiologist within two weeks of data collection. Only CCT scores from children with behavioral hearing measures within normal limits, bilateral Type A tympanograms and a pass in each ear for DPOAEs were included in data analysis.

Procedure. Immediately preceding data collection, each class received the same scripted instruction on taking the CCT. The children were shown the multiple-choice lists and were familiarized with them (part of test protocol). Each of the students in the four classes completed the recorded sample items. Testing proceeded when all subjects had demonstrated proper response selection technique (making an X or checking the item they heard) and indicated understanding of the task after completing the six practice items. Copying another participant's response was discouraged by: (a) emphasizing that the equipment, not any child, was being evaluated; (b) setting up visual shields for each child's test area; and (c) using four to six adult proctors. Each class was tested separately at the same approximate time of day during the same week. The children whose classroom was the data collection room sat in their currently assigned seats. Teachers of all four classes changed student-seating monthly and reported that the reasons for seat assignments were related to academic group projects. Seats in the data collection room were numbered and the children from the other classrooms were assigned alphabetically by surname. Conditions and test lists were counterbalanced for the four sessions. The position of each child was associated with the sound measurement location closest to his/her seating during data collection.

The participant's CCT answer sheets were scored (percent correct) independently by two graduate students. Interscorer reliability was 97.4% after simple scoring errors were corrected by the principal investigator. The remaining differences were due to ambiguous responses. The participants had been asked to make an X on the line next to their choice, but the recording instructed the participants to "check the word." Some participants made large checks that made their intent difficult to determine. Half the ambiguous responses were scored as correct and half incorrect on an alternative basis (e.g., first, third and fifth scored as the correct response, second, fourth and sixth as the alternative incorrect response). The data were analyzed using an analysis of variance (ANOVA) with repeated measures (SPSS statistical software v. 9.0, General Linear Measures). Effects of condition, grade, sex, and seating position were examined.

Results

Acoustic measures

Occupied classroom noise averaged 49 dBA across the eight measurement sites. When measured at each of the eight sites, the 1000 Hz calibration tone for the CCT averaged 67.38 dB SPL and 66.75 dB SPL for the bending wave and the traditional speakers, respectively. The average S/N for the traditional speaker was +17.63 dB; for the bending wave speaker, +18.25 dB. S/N did not vary greatly by either site or by speaker type. Data at each measurement site are included in Table 1.

Table 1. S/Ns (in dBA) for the CCT Calibration Tone Delivered by a Traditional and a Bending Wave Loudspeaker Coupled to a Classroom Amplification System

Measure	Calibration tone		Classroom Noise	Signal to Noise	
Speaker	Bending	Traditional		Bending	Traditional
Site Reference	68*	68*			
1	68	68	48	+20	+20
2	67	69	50	+17	+19
3	67	66	49	+18	+17
4	68	66	49	+19	+17
5	68	66	50	+18	+16
6	68	68	50	+18	+18
7	67	66	48	+19	+18
8	66	65	49	+17	+16
Range	66-68	65-69	48-50	17-20	16-20
M	67.38	66.75	49.13	+18.25	+17.63

*Output adjusted to 10 dBA above teacher's average unamplified voice (58 dBA) measured at the reference position

Octave band measures of white noise delivered via the two different speakers and taken at the eight measurement sites are reported in Table 2. In all but 4 of the 48 comparisons, the output from the bending wave speaker was equal to or greater than the output from the traditional speaker. In the low and mid frequencies, the differences averaged less than 1 dBA across the eight sites. As frequency increased from 2000 Hz through 8000 Hz, the average differences also increased; from 3.4 dBA at 2000Hz to 14.6 dBA at 8000 Hz. Thus, the bending wave speaker did preserve high frequency energy better than the traditional speaker. The bending wave speaker white noise output varied slightly more among the eight sites, averaging 4.83 dBA across all octave bands versus 3.67 dB for the traditional speaker. Thus, variability was not large for either speaker type across the eight sites.

Table 2. Octave Band Measures of White Noise (in dB SPL) Delivered by a Traditional and a Bending Wave Loudspeaker Coupled to a Classroom Amplification System.

Octave band Center Hz	250		500		1000		2000		4000		8000	
System	B*	T+	B	T	B	T	B	T	B	T	B	T
1	56	54	58	56	57	56	67	62	68	63	66	51
2	53	54	56	56	58	57	66	61	67	58	66	50
3	52	52	56	55	56	57	65	60	65	58	66	50
4	53	52	56	56	57	58	64	62	64	58	62	50
5	54	50	59	54	58	55	65	63	65	60	66	48
6	52	52	56	54	55	54	63	61	64	59	62	50
7	50	50	53	54	55	55	64	60	64	58	64	48
8	54	52	55	54	56	55	64	62	64	58	60	48
Range	6	4	6	3	3	4	4	3	4	5	6	3
M	53.0	52.0	56.1	54.8	56.5	55.9	64.8	61.4	65.1	59.0	64.0	49.4

*B = Bending wave speaker
+T=Traditional speaker

Range for B: 3-6dB M - 4.83 dB
T: 3-5dB M - 3.67 dB

Speech discrimination performance

The means, standard deviations, ranges and median scores on the CCT for the two speaker conditions are reported in Table 3. The children averaged 58.06% for stimuli delivered via the traditional speaker, 65.68% for the bending wave speaker. The standard deviations and ranges for the two conditions were similar and the medians were .06 and .40 points different from the means, suggesting that the distribution of scores for each condition were similar. An analysis of variance (ANOVA) with repeated measures indicated that the difference in CCT scores between the two conditions was statistically significant. The effects of age, sex, grade level and location in the classroom were not found to be significant (see Table 4).

Discussion

This study found differences in high-frequency energy preservation in a classroom setting, as well as differences in speech discrimination performance by children in grades 3 and 4. All differences, as predicted, reflected better performance with the bending wave speaker. The anticipated superiority of the bending wave speaker across distance was not seen, possibly due to the relative placement of the speakers. The bending wave speaker was close to the instructional position, and thus close to the listening space. The traditional speaker was placed as high as possible in a corner in order to create the greatest distance from the listening space and, thus, the most uniform signal in the student area. This placement produces the most rapid energy loss before the signal enters the listening space, with more gradual loss within the listening space (inverse square law). Had it been possible to position the two speakers identically, the theoretical advantage of the bending wave speaker may have been observed. However, the recommended placement of each speaker for best acoustics was not compatible with identical placement (e.g., high in a corner versus in the center of a long wall). Placement of the speakers at equal distances from the listening space may appear to provide a fairer comparison of the system. Unfortunately, only one wall and one corner were possible placements because of the composition of the classroom (e.g., intercom system and conduits in other corners, only one flat wall).

Although a significant difference in speech discrimination performance in favor of the bending wave speaker was found, the children's performance was poor under both conditions. Poor S/Ns could account for such a result; however, the S/Ns of +17 to +18 dB in the data collection classroom were better than the typically recommended +10 to + 15 dB (American Speech-Language-Hearing Association, 1995; Crandell & Smaldino, 1995; 2000; Educational Audiology Association, 2001). Difficulty with the reading task may also have contributed, but a number of factors suggest that was not the case. First, English was the first language for all the students participating. Second, while some participants were from low socioeconomic status (SES) families, those families had to initiate and complete a complicated application process to have their child attend the school. Choosing to participate in a very competitive process to provide a better educational experience for their child may be more typical of families of higher SES. Also, data from any child whose teacher questioned their ability to successfully do the task were not included in the analysis. Although the CCT was designed to be a challenging listening task (Owens & Schubert, 1977), the most probable reason for the low scores is that the recording was somewhat distorted. Support for this contention is found in preliminary results from subsequent data collection with the same aged children, a similar protocol and a new CD version of the CCT: average scores were 85 to 89% (Prendergast, 2001). However, for purposes of comparing speaker types in this study, all the participants listened to the same stimuli and thus, all were at an equal disadvantage with each technology.

Table 3. California Consonant Test Results with Stimuli Delivered by a Traditional and a Bending Wave Loudspeaker Coupled to a Classroom Amplification System (N=63)

Variable	M	SD	Mdn	Range
Traditional Speaker	58.06%	10.40%	58%	32 - 80%
Bending Wave Speaker	65.68%	9.42%	66%	36 - 84%

Table 4. Analysis of Variance with Repeated Measures for Speech Discrimination Performance (Wilks' Lambda)

Source	df	F	Significance
System	1	16.772	.000*
Sex	1	0.382	.540
Grade	1	2.372	.132
Location	7	1.137	.361

*p=.05

The difference in average performance between conditions was of the order of 8% or 4 of 50 items. Because the scores were above chance level and there was no ceiling effect, the difference in scores may be a fair reflection of differences in the performance of the two speakers. There was also informal support of a perceived difference. The participants were asked to indicate their preference by a show of hands after data collection. With few exceptions, the participants indicated the bending wave speaker as superior. While they may have preferred the appearance of the bending wave speaker (a picture of an astronaut floating above Earth), their spontaneous remarks were all related to ease of listening. When the preliminary findings were presented to the participants a month after data collection, several asked when they were getting the bending wave speaker in their classroom. Thus, the children's judgment of the bending wave speaker's superiority lends face validity to the statistically significant difference between the speech discrimination performances with the two speakers. The CCT may be a reasonable tool to use to compare systems, especially in light of the performance with the better recording.

There is clearly a need to repeat this research with third and fourth graders to see if the findings can be replicated. It would be interesting to include younger children since better preservation of high frequency information may be more critical for them than for third and fourth grade students. With more preparation for the task, second graders may be able to meet the challenges of taking the CCT.

Use of this technology with children with hearing loss is another application worth investigating. With increasing numbers of children with hearing loss in mainstream classrooms (US Department of Education as cited by Johnson & Murphy, 2001), and with the expected acceleration of that trend due to universal newborn hearing screening, it is critical that access to auditory information be optimized. The relative benefit of the two technologies for unaided children having minimal hearing loss should be determined. The possible utility of bending wave speaker technology in conjunction with hearing aids with advanced technology (e.g., digital speech processing, directional microphones, frequency transposition) or as an alternative to other assistive listening technology also needs to be explored.

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