The Effects of Speech Production and Vocabulary Training on Different Components of Spoken Language Performance

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A group of 21 hard-of-hearing and deaf children attending primary school were trained by their teachers on the production of selected consonants and on the meanings of selected words. Speech production, vocabulary knowledge, reading aloud, and speech perception measures were obtained before and after each type of training. The speech production training produced a small but significant improvement in the percentage of consonants correctly produced in words. The vocabulary training improved knowledge of word meanings substantially. Performance on speech perception and reading aloud were significantly improved by both types of training. These results were in accord with the predictions of a mathematical model put forward to describe the relationships between speech perception, speech production, and language measures in children (Paatsch, Blamey, Sarant, Martin, & Bow, 2004). These training data demonstrate that the relationships between the measures are causal. In other words, improvements in speech production and vocabulary performance produced by training will carry over into predictable improvements in speech perception and reading scores. Furthermore, the model will help educators identify the most effective methods of improving receptive and expressive spoken language for individual children who are deaf or hard of hearing.

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One of the greatest challenges facing educators of children who are deaf and hard of hearing is the provision of educational programs that develop age-appropriate language skills. For children who use spoken language as their main mode of communication, the goals include the provision of appropriate listening devices, the development of speech perception and spoken language skills, and the attainment of intelligible speech.

It is well documented in the literature that diagnosis of hearing loss before the age of 6 months, early fitting of appropriate listening devices such as cochlear implants and hearing aids, and early intervention programs increase the probability of developing intelligible speech and age-appropriate spoken language for children who are deaf and hard of hearing (Boothroyd, 1978; Geers, Nicholas, & Sedey, 2003; Ling, 1989; Moeller, 2000; Yoshinaga-Itano & Apuzzo, 1998; Yoshinaga-Itano & Gravel, 2001; Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998). Despite advances in hearing aid and cochlear implant technology, support for earlier diagnosis through neonatal hearing screening programs, and intensive educational management many children with hearing loss are delayed in their acquisition of spoken language skills when compared to their normally hearing peers (Blamey et al., 2001; Geers & Moog, 1994; Paatsch, Blamey, & Sarant, 2001; Serry & Blamey, 1999). A recent study by Blamey et al. (2001) followed spoken language performance for a group of 87 school-aged children who were deaf and hard of hearing and used hearing aids

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and/or cochlear implants. Although language performance improved steadily over a period of 3 years, the rate was only approximately 60% of that in hearing children. The findings suggested that by the time these children enter secondary school at the age of about 12 years, the average language delay would be approximately 4–5 years. Such empirical evidence supports the need for language-centered intervention programs to develop spoken language skills that enable children who are deaf and hard of hearing to comprehend the language of the secondary school curriculum and to function effectively in the wider community.

It is also well established that there are large individual differences in performance on spoken language, speech production, hearing and speech perception measures for children who are deaf or hard of hearing (Blamey et al., 2001; Boothroyd, 1995; Dawson et al., 1995; Paatsch, Blamey, Sarant, Martin, & Bow, 2004; Plant, 1995; Sarant, Blamey, Cowan, & Clark, 1997; Sarant, Blamey, Dowell, Clark, & Gibson, 2001; Tyler et al., 2000; Yoshinaga-Itano et al., 1998). Many of these studies have sought and found predictive relationships between the speech perception performance measures and various predictive factors such as age, hearing loss, assistive listening device, and mode of communication. One study (Blamey et al. 2001) found much stronger relationships between speech perception scores, speech production, and vocabulary performance than between speech perception, age, and hearing loss. These strong relationships can provide a deeper understanding of the differences between individual children, leading to more effective individual educational programs.

This idea has been developed further using a multiplicative mathematical model to describe the effects of hearing, speech production, and vocabulary on speech perception performance on tests of monosyllabic words (Paatsch et al., 2004). The mathematical details of the model are given in Appendix A. Thirty-three children who were deaf and hard of hearing were evaluated using speech production, speech perception, and vocabulary measures. Children were tested in two conditions: auditory alone and reading aloud. The model predicted that speech perception scores in the auditory-alone condition would be related to hearing, speech production, and vocabulary measures, and scores in the reading-aloud condition would be related to speech production and vocabulary measures but not to hearing. The assumptions and predictions of the model were confirmed by the experimental data. The mathematical model provides a method for separating out the effects of hearing and spoken language performance on the speech perception score for individual children.

The method makes it possible to identify the relative strengths and weaknesses in the child's performance and provides an individually tailored intervention program to address the weaknesses. Using the model for this purpose involves a further assumption: that improving speech production and vocabulary will produce an improvement in speech perception as predicted by the model. In other words, the relationships between speech production, vocabulary, and speech perception are causal and not merely associative. An example of an associative relationship that would not produce a causal effect is the strong correlation between spoken language performance and height. These two measures are correlated because children grow and learn language as they get older. In this case, training speech production and vocabulary would not increase the child's height because the relationship is not causal. If the causal assumption for speech perception is correct, then the multiplicative model can also be used to predict the effects of specific intervention in the areas of speech production and lexical knowledge on performance in speech perception.

This article tests the causality assumption by applying the mathematical model to speech perception scores before and after specific training for a group of children who were deaf and hard of hearing. The aims of the current study were (1) to measure the effect of specific training in speech production and lexical knowledge on lexical knowledge and speech production, and (2) to measure the effects of specific types of training on speech perception scores. Our hypotheses were

1. that speech production training would improve the percentage of consonants correctly produced in words and spontaneous conversations but would not improve word knowledge;

Table 1 Details of the 21 participants according to device, etiology, gender, age, and pure-tone average thresholds (at 500, 1,000, and 2,000 Hz)

Participant	Device	Etiology	Gender	Age (year: month)	PTA (dB HL)
Group 1					
1	CI	Unknown	F	6:9	110
2	HA	Genetic	F	7:2	88
3	CI	Meningitis	M	7:4	125
4	HA	Unknown	M	7:11	75
5	CI	Unknown	F	8:9	102
6	CI	Unknown	M	9:0	120
7	CI	Unknown	F	9:3	105
8	CI	Unknown	M	9:7	NR[a]
9	CI	Genetic	M	9:10	110
10	HA	Unknown	M	10:0	55
11	CI	CMV	M	10:5	97
12	CI	Unknown	F	10:7	110
13	CI	Meningitis	F	11:4	115
14	HA then CI	Genetic	F	12:2	90
Group 2					
15	CI	Unknown	F	5:9	113
16	CI	Unknown	M	5:10	98
17	HA	Unknown	F	6:2	32
18	CI	Unknown	F	6:4	107
19	HA	Unknown	M	6:10	70
20	CI	Unknown	F	6:11	NR[a]
21	CI	Unknown	F	7:5	105

[a]Denotes participants with no responses (NR) at 1,000 and/or 2,000 Hz. CI = cochlear implant; CMV = cyromegalovirus; F = female; HA = hearing aid; M = male.

2. that vocabulary training would improve word knowledge but would not improve speech production skills;

3. that vocabulary training and speech production training would improve speech perception scores in the auditory-alone condition;

4. that vocabulary training and speech production training would improve overall scores in the reading condition;

5. that neither vocabulary training or speech production training would improve the sensory (hearing) component of the multiplicative model.

Method

Participants

Twenty-one children (12 girls and 9 boys) aged between 5 years 9 months and 12 years 2 months participated in this study. Individual details are presented in Table 1. Hearing loss figures refer to the pure tone thresholds (PTA) in dB hearing level averaged over the three frequencies 500, 1,000 and 2,000 Hz in the better ear. PTA figures for children using cochlear implants were derived from the measurement of hearing in the better ear taken from the most recent preoperative audiogram. Participants 8 and 20 had no measurable response at frequencies greater than 1,000 Hz; therefore pure tone averages could not be calculated. Sixteen of the children had a hearing loss greater than 90 dB HL, three had a severe hearing loss (between 70 and 90 dB HL), one had a moderate hearing loss (between 40 and 70 dB HL), and one had a mild hearing loss (below 40 dB HL).

Fifteen of the children were cochlear implant users implanted with the Nucleus 22 multichannel device (Clark et al., 1987) with either the SPEAK speech processing strategy (Seligman & McDermott, 1995) or the ACE speech processing strategy (Vandali, Whitford, Plant, & Clark, 2000) fitted by the Melbourne Cochlear Implant Clinic. Five children were fitted binaurally with behind-the-ear hearing aids by Australian Hearing. One of the children (Participant 14) commenced this study using hearing aids but was later implanted between the first and second training periods with the Nucleus 22 multichannel device. Participant 19 changed to more powerful digital hearing aids during the second training period.

All children were integrated into a mainstream primary school with a specialized unit for children who are deaf and hard of hearing where an oral/aural method of communication was used. Teachers of the deaf employed at the school provided support for these children during mainstream classroom activities and within small group and/or individual sessions in the unit. For the purpose of this study, the children were divided into two groups for specific types of training allowing the order effects of training to be considered. The children were grouped according to the classes they were enrolled in and which teacher of the deaf was responsible for their educational programs to assist with ease of implementation of the training program. None of the children in this study had known sensory dyslexia or uncorrected visual impairment that would have prevented them from being able to read the list of monosyllabic words in the test battery.

Evaluations

Evaluations took place at three times throughout this study. The first was at the commencement of the study, prior to any training (Evaluation 1). Evaluation 2 occurred after the first 15-week training period, and Evaluation 3 was conducted at the end of the second training period. At each evaluation, a test battery was administered to the 21 children to assess speech production, word knowledge, speech perception, and reading aloud.

Speech perception and reading-aloud measures. A set of 109 monosyllabic consonant–vowel–consonant (CVC) words was selected from five phonological neighborhoods to be used in measures of speech perception, reading aloud, and word knowledge (see Appendix B). The words were selected in this manner so that the results could be interpreted using the Neighborhood Activation Model of speech perception (Luce & Pisoni, 1998). This analysis has not yet been conducted and is beyond the scope of this article.

The CVC words were presented to each participant one at a time in a random order, without a carrier phrase, using live voice, at approximately 70 dB(A), by a female speaker, at a distance of approximately 1 m, in a quiet room. The words were first presented to each child in the auditory-alone condition, without lipreading. The child was required to listen, then repeat aloud each stimulus word presented. No repetitions of the stimulus words were given. After the auditory test, each participant was required to read the list of 109 CVC words presented randomly, one word at a time, from a computer screen.

All participants' oral responses for both the speech perception test and the reading-aloud test were scored online by the tester by pressing "correct" or "incorrect" buttons on the computer screen. The computer program calculated percent correct scores for each child for each test. A word was scored as correct if the child's response word matched the stimulus test word. All three phonemes had to be produced correctly in the correct order with no omissions, additions, or substitutions for the word to be counted as "correct". Subphonemic errors, such as distortions to phoneme production were not considered in the scoring process in either test. The speech perception and reading-aloud tests were administered and scored by either a teacher of the deaf or a linguist, both of whom were part of the same research team and experienced in listening to the speech of children who are deaf and hard of hearing.

Sensory abilities measure. Sensory abilities for the 21 participants who took part in this study were calculated by dividing the auditory-alone speech perception scores by the reading-aloud scores. This method of calculating the sensory contribution in speech perception performance on tests of monosyllabic words used the mathematical model described by Paatsch et al. (2004). Paatsch et al. found that overall scores in the auditory-alone condition were significantly associated with hearing, language, and speech production, whereas overall scores in the reading condition were significantly associated with measures of vocabulary and speech production but not with measures of hearing. The scores from the calculations of sensory probabilities were only associated with measures of hearing (See Appendix A for further mathematical details).

Speech production measures. Speech production skills for the 21 participants who took part in this study were assessed using the 108 Single-Word Articulation Test (108 SWAT) (Paatsch, 1997) and videotaped spontaneous conversational samples.

The 108 SWAT is a speech production test that assesses a child's production of all vowels and consonants of Australian English in all positions at a single-word level. The test includes a comprehensive list of monosyllabic and polysyllabic nouns, verbs and adjectives, and includes words containing consonant clusters. The 108 SWAT is widely used to assess the speech production skills of children who are deaf or hard of hearing by teachers of the deaf in Australia.

In a single test session, each child was presented with the 108 single words one at a time using a set of colored picture cards. Each child was asked to name the object on the card or state what was happening in each picture. When a child was unable to correctly label a picture card, leading prompts were provided. All responses were videotaped and transcribed using narrow phonetic transcription by a skilled linguist experienced in listening to the speech of children who are deaf or hard of hearing.

Spontaneous conversational speech samples were obtained from each participant to ensure a complete assessment of speech production skills. These samples were elicited using prompting questions about familiar topics and provided information for selecting specific speech targets for training. All conversations were videotaped, and on average a total of 60–70 utterances were transcribed both orthographically and phonetically by a linguist experienced in the transcription of the speech of hard-of-hearing children using narrow phonetic transcription. The rules used to separate utterances included change in speaker, a pause of two or more seconds, a single thought constituting a single utterance, and/or rising and falling intonation indicating the end of an utterance.

Analysis of speech production. Spontaneous conversation samples and responses from the 108 SWAT were analyzed using the Computer Assisted Speech And Language Analysis (CASALA) program (Serry, Blamey, Spain, & James, 1997). This program requires orthographic and phonetic transcriptions of both conversations and word tests to be entered. The correctness of phonemes was determined by comparing a child's responses with those of the target phonemes. The CASALA program calculated percentage correct scores for individual monophthongs, diphthongs, and consonants and gave total scores for all vowels, consonants, consonant clusters, phonemes, and words produced correctly.

For the purpose of this study, only singleton consonants were used in the analyses. Consonants in clusters were excluded so that the variability of scores across children with different vocabulary levels could be reduced. This practice also enabled a comparison of singleton consonants produced in spontaneous conversation with those produced in the 108 SWAT and the test of 109 monosyllabic CVC words. Training of phonemes also only included singleton consonants.

A second linguist transcribed randomly selected conversations and word tests for 6 of the participants in the study to assess reliability of the transcription data. The intertranscriber agreement for the 108 SWAT was 99% for consonants and 98% for words. An average of 2,321 consonants and 1,790 words from conversation samples were transcribed by the two experienced transcribers. Intertranscriber agreement was 93% and 98% for consonants and words, respectively. The mean percent phonemes correct was 94%. These agreement values are acceptable, being higher than values previously reported for the narrow transcription of speech of children with low intelligibility. For example, Shriberg and Lof (1991) found 74% agreement with an average of 80% phonemes correct, whereas Serry and Blamey (1999) reported 83% intertranscriber agreement.

Word knowledge evaluations. After each child's speech perception and reading aloud had been evaluated, the children were presented with the 109 monosyllabic CVC words, one at a time on a computer screen. Children were asked to give a definition of each word either by telling the testers what the word meant or by putting the word in a sentence. If the definition of the word was incomplete or needed further clarification, the testers asked further questions that would help determine whether or not the child knew the meaning of the word without providing any clues about particular word meanings.

The children's responses were scored online by the tester by marking whether the word was "known" or "unknown" on the computer screen. The computer program calculated the percent correct score for each child. Responses were also videotaped so that online scoring could be checked.

Training. Initial, medial, and final evaluations (Evaluations 1, 2, and 3) were separated by two training periods of 15 weeks each within the four school terms of 1 school year. Children were trained individually or in groups of 2 or 3 for 20 min each school day during times when they were normally withdrawn from their regular classes. These groups were organized according to availability of the teacher of the deaf to teach the training program and according to targeted goals for each student. Children in the same group received intervention on the same target phonemes or words.

Two types of training methods (A and B) were used in this study. Method A involved training speech production skills, whereas Method B involved training specific words. Both groups of participants were trained in both methods but in opposite order (AB/BA), allowing for the balance of order effects.

Method A: speech production training. The objective of training method A was to improve the production accuracy of specific phonemes in conversational speech and at a single-word level. Selection of phonemes for training was based on the accuracy of production in the initial speech production evaluations. Omissions, distortions, and errors in voicing, manner and place of articulation in initial, medial, and final positions at both phonemic and subphonemic levels were considered in the selection process. Five phonemes for each participant, where the child scored between 0% and 80% correct, were selected for training, except for Participant 17, for whom all but four phonemes were produced with 90% accuracy or higher. Only four phonemes were selected for training for Participant 17. All other phonemes were left untrained for all children throughout the 15-week training period. The level of accuracy amongst the participants for untrained phonemes varied from 0% to 100%. The phonemes selected for training for each participant are listed in Table 2.

Table 2 Details of the phonemes selected for training for each of the 21 participants

Participant	Trained phonemes				
Group 1					
1	n	t	l	r	s
2	d	s	t	d	l
3	_	d	j	l	r
4	d	r	s	t	v
5	n	l	r	t	z
6	d	t	_	l	r
7	d	j	s	t	_
8	d	r	s	t	z
9	d	t	_	d	k
10	d	t	l	r	s
11	j	n	r	s	t
12	t	r	s	t	z
13	d	_	r	t	z
14	j	r	s	t	z
Group 2					
15	h	f	s	t	z
16	d	t	r	t	l
17	s	r	t	z	[a]
18	d	l	r	s	t
19	j	_	r	t	s
20	j	t	l	r	t
21	...	t	j	t	z

[a]Participant 17 was trained in four phonemes due to scoring equal to or greater than 90% in the initial assessment for all other phonemes.

Session activities for each trained phoneme were developed in consultation with the teachers of the deaf at the school. Based on the findings of a study by Paatsch et al. (2001), which found that phonological level training was effective in improving speech production, phonemes in this article were trained within meaningful context using selected words, phrases, expressions, jingles, rhymes, and stories. Phonetic level training in nonsense syllables was not used.

All session activities were implemented by the teachers of the deaf who were working with the children at school. Programing included self-monitoring strategies, ongoing diagnostic evaluations, and age- and language-appropriate activities. Further practice of speech production at home was encouraged although not enforced. Ongoing monitoring of children's progress, the extent

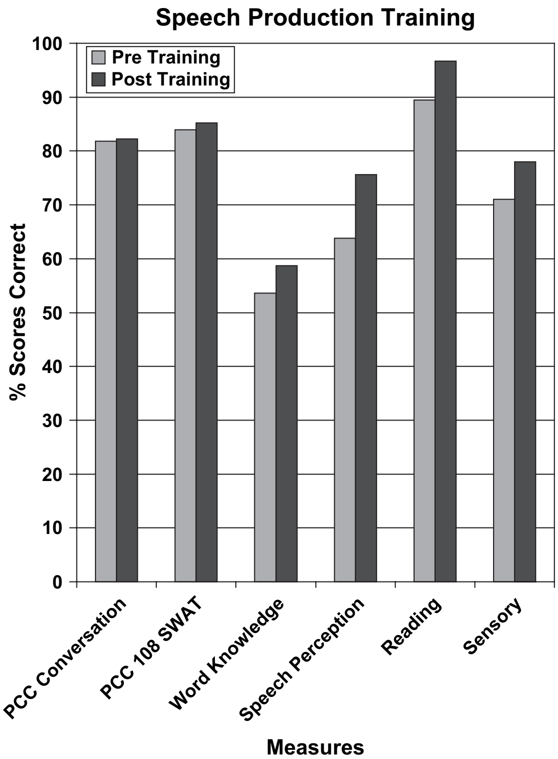

Figure 1 Pre- and postspeech production training mean scores for PCC from conversations and the 108 SWAT. Mean scores for word knowledge, speech perception, reading, and sensory abilities are included ($N = 21$).

to which the training program was being implemented, and observation of sessions occurred throughout the 15-week training period.

Method B: vocabulary training. The main objective of training method B was to increase the children's knowledge of specific words. Seventy of the 109 monosyllabic CVC words were selected for training for each participant. The 70 words to be trained during the 15-week training period were specifically selected from three of the five phonological neighborhoods so that, as previously mentioned, further analysis which is beyond the scope of this article could be conducted. The 70 words were the same for each participant. Prior to the commencement of training the total number of words correct for 70 words to be trained ranged between the children from 13% to 79% ($M = 52$), with Group 1 scores ranging from 27% to 79% correct ($M = 58$) and Group 2 scores ranging from 13% to 63% correct ($M = 41$). The total number of words correct for those words not to be trained was slightly lower. Correct untrained words ranged from 18% to 77% ($M = 39$), with Group 1 ranging from 18% to 77% ($M = 44$) and Group 2 from 18% to 54% ($M = 30$). The teachers of the deaf were given the list of words for familiarization and to enable planning for sessions prior to the commencement of training.

In consultation with the investigators, teachers developed programs for each child that incorporated the teaching of the 70 words into other curriculum areas. For example, teachers grouped many of the words into lists that fitted into theme work being studied in the curriculum. Session activities included oral discussions of word meanings, picture representations of words, putting words into sentences and discourse to illustrate semantic and syntactic use of words, and the use of dictionaries to seek meaning. School-based activities were also sent home via the children's workbooks for further practice. Continual liaison between the teachers of the deaf at the school and the investigators about the progress and the development of the trained words occurred throughout the 15-week training period.

Results

Mean scores for percent consonants correct, word knowledge, speech perception, and reading are presented in Figures 1 and 2. Paired t tests between pretraining and posttraining scores were used to measure the effects of training types A (speech production) and B (vocabulary) on the production of consonants, word knowledge, and speech perception scores in the group of children. Further statistical analyses were conducted to measure the effects of training on sensory abilities and on overall scores in the reading-aloud condition. Repeated measures analyses of variance (ANOVAs) were used to examine whether there was an order of training effects by comparing the improvements for the two groups for each measure and each type of training. Further analysis of the effectiveness of speech production training compared to the effectiveness of vocabulary training on each measure of speech production and word knowledge was conducted using relative measures of improvement (actual improvement divided by maximum possible improvement).

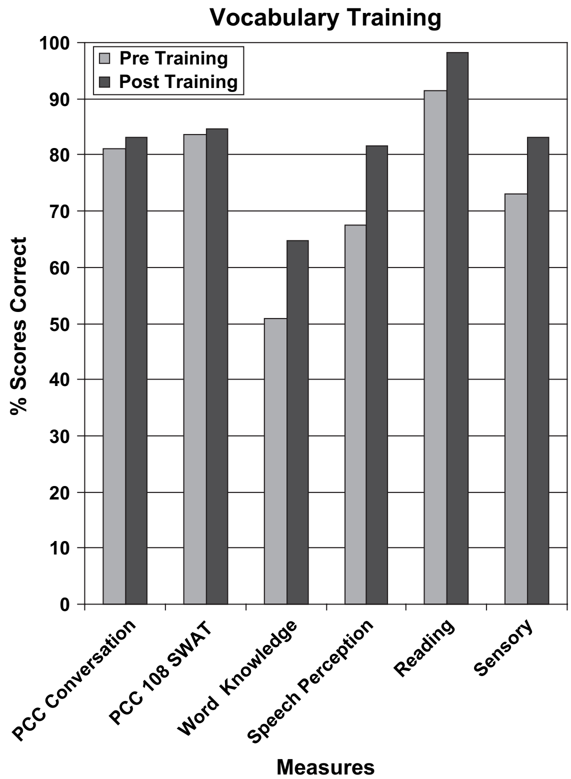

Figure 2 Pre- and postvocabulary training mean scores for PCC from conversations and the 108 SWAT. Mean scores for word knowledge, speech perception, reading, and sensory abilities are included ($N = 21$).

Effects of Speech Production and Vocabulary Training on Speech Production

The total number of phonemes produced by individual participants in the conversation samples ranged from 541 phonemes to 960 phonemes ($M = 734$) prior to the first training period, from 577 to 1,046 phonemes ($M = 791$) at Evaluation 2, and from 511 phonemes to 1,166 phonemes ($M = 785$) at the end of the second training period. The total number of words ranged from 211 words to 411 words ($M = 297$), from 245 to 420 words ($M = 318$), and from 208 words to 442 words ($M = 311$) at the three evaluations. Individual scores for percentage of consonants correct (PCC) from conversations and the 108 SWAT before and after speech production training are presented in Table 3.

It was hypothesized that speech production training would improve the PCC in words and conversations. Pre- and postspeech production training mean scores for PCC from narrow transcriptions of conversations and the 108 SWAT are shown in Figure 1. There was no significant change in PCC for conversations after speech production training (t [20] $= .84$, $p = .413$). For the 108 SWAT, the mean improvement in PCC was 1.6% after speech production training (t [20] $= 2.47$, $p = .023$), thus supporting Hypothesis 1.

It was hypothesized that vocabulary training would not improve speech production skills. Individual results from conversations and the 108 SWAT before and after vocabulary training are shown in Table 4, and Figure 2 shows mean scores pre- and postvocabulary training. The mean changes in PCC for conversations and the 108 SWAT were 1.9% and 1.1%, respectively, and these differences were not statistically significant (t [20] $= 1.70$, $p = .104$ for conversations; and t [20] $= 1.23$, $p = .234$ for the 108 SWAT). This result is consistent with the hypothesis.

Prior to speech production and vocabulary training, many scores were close to ceiling on the speech production measures. In order to compare the relative benefits of training, measures of relative improvement were calculated by dividing actual improvement by the maximum possible improvement for each child. Results of t tests comparing relative measures of improvement scores across the two training types showed that there was no significant difference in effectiveness between the two types of training on speech production skills as measured by PCC in conversations (t [20] $= -.26$, $p = .800$) and in the 108 SWAT (t [20] $= .56$, $p = .584$).

Effects of Speech Production and Vocabulary Training on Word Knowledge

Table 3 shows individual scores for definitions from the 109 monosyllabic CVC word test pre- and post-speech production training. Figure 1 shows mean scores for word knowledge before and after speech production training. The mean improvement in the percentage of words correctly defined was 5.9% after speech production training. This improvement was statistically significant (t [20] $= 3.93$, $p < .001$), which was surprising, as it was not expected that speech production training would affect word knowledge.

Table 3 Pre- and postspeech production training individual scores for PCC from conversations and the 108 SWAT

	Speech production training											
	PCC conversation		PCC 108 SWAT		Word knowledge		Speech perception		Reading		Sensory	
Participant	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Group 1												
1	80	72	78	77	23.9	25.7	54.1	57.8	75.2	76.1	72	76
2	75	69	68	70	23.9	28.4	30.3	62.4	47.7	86.2	63	72
3	82	88	88	92	35.8	48.6	66.1	78	86.2	100	77	78
4	82	81	81	79	78	68.8	10.1	42.2	98.1	97.2	10	43
5	82	88	89	94	55	60.6	78	83.5	94.5	100	83	83
6	84	83	80	85	53.2	67.9	83.5	88.1	87.2	100	96	88
7	76	85	80	81	51.4	51.4	47.7	64.2	65.1	92.7	73	69
8	84	80	87	90	65.1	75.2	84.4	80.7	97.2	100	87	81
9	73	77	80	81	42.2	55	64.2	73.4	74.3	98.2	86	75
10	79	85	89	87	50.5	52.3	66.1	51.4	90.8	89.9	73	57
11	78	86	78	82	49.5	50.5	50.5	80.7	91.7	99.1	55	81
12	86	86	85	88	71.6	77.1	52.3	70.6	98.2	99.1	53	71
13	85	89	95	94	71.6	75.2	80.7	83.5	98.2	100	82	83
14	83	84	81	87	66.1	72.5	16.5	56.9	91.7	98.2	18	58
Group 2												
15	85	83	94	91	41.3	58.7	77.1	91.7	94.5	100	82	92
16	88	87	86	89	64.2	64.2	83.5	88.1	98.2	100	85	88
17	79	82	83	89	67	67.8	90.8	98.2	100	100	91	98
18	81	80	79	81	78	78.9	78	78.9	96.3	98.2	81	80
19	83	77	80	76	47.7	64.2	65.1	77.1	96.3	95.4	68	81
20	73	74	80	79	65.1	79.8	78	81.7	97.2	100	80	81
21	91	91	94	97	69.7	71.6	83.5	98.2	99.1	100	84	98

Note. Individual scores for word knowledge, speech perception, reading, and sensory abilities are also included ($N = 21$).

Individual and mean scores pre- and postvocabulary training for word knowledge are presented in Table 4 and Figure 2, respectively. The participants showed statistically significant improvements in word knowledge after vocabulary training (mean improvement = 16.0%, t [20] = 5.62, $p < .001$). This result supports Hypothesis 2, that is, vocabulary training is effective at improving word knowledge. The mean improvement for word knowledge was greater after vocabulary training than after speech production training (difference in mean improvement = 10.1%). Results of t tests using relative measures of improvements to compare the effectiveness of training types also supported the finding that vocabulary training was a more effective training method for improving children's knowledge of words (t [20] = −3.61, $p = .002$).

Effects of Training on Speech Perception, Reading Aloud, and Sensory Abilities

Figures 1 and 2 show mean scores for speech perception, reading, and the sensory component of the mathematical model prior to and at the end of the two 15-week training periods. After speech production training, the mean improvements were 11.8% for speech perception, 7.3% for reading aloud, and 6.4% for sensory abilities. After vocabulary training, the mean improvements were 14.2% for speech perception, 6.9% for reading aloud, and 9.7% for sensory abilities. The effectiveness of each type of training on speech perception, reading loud, and sensory abilities was evaluated using paired t tests. Both speech production training (t [20] = 4.07, $p = .001$) and vocabulary training (t [20] = 5.09, $p < .001$) improved

Table 4 Pre- and postvocabulary training individual scores for PCC from conversations and the 108 SWAT

	Vocabulary training											
	PCC conversation		PCC 108 SWAT		Word knowledge		Speech perception		Reading		Sensory	
Participant	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Group 1												
1	72	79	77	82	25.7	33.9	57.8	84.4	76.1	94.5	76	89
2	69	78	70	67	28.4	39.4	62.4	67	86.2	91.7	72	73
3	88	90	92	92	48.6	55	78	88.1	100	100	78	88
4	81	84	79	85	68.8	85.3	42.2	49.5	97.2	99.1	43	50
5	88	82	94	91	60.6	77.1	83.5	97.2	100	100	83	97
6	83	76	85	83	67.9	88.1	88.1	93.6	100	100	88	94
7	85	81	81	79	51.4	66.1	64.2	79.8	92.7	98.2	69	81
8	80	85	90	93	75.2	90	80.7	87.2	100	100	81	87
9	77	83	81	80	55	61.5	73.4	86.2	98.2	99.1	75	87
10	85	88	87	90	52.3	62.4	51.4	88.1	89.9	100	57	88
11	86	79	82	82	50.5	67.9	80.7	85.3	99.1	100	81	85
12	86	88	88	86	77.1	85.3	70.6	86.2	99.1	100	71	86
13	89	90	94	94	75.2	78	83.5	91.7	100	100	83	92
14	84	81	87	80	72.5	81.7	56.9	73.4	98.2	99.1	58	74
Group 2												
15	80	85	83	94	29.4	41.3	81.7	77.1	89.9	94.5	91	82
16	82	88	83	86	29.4	64.2	66.1	83.5	92.7	98.2	71	85
17	83	79	87	83	54.1	67	91.7	90.8	94.5	100	97	91
18	72	81	76	79	14.7	78	46.8	78	55	96.3	85	81
19	76	83	73	80	34.9	47.7	21.1	65.1	67	96.3	32	68
20	70	73	75	80	36.7	65.1	50.5	78	90.8	97.2	56	80
21	88	91	92	94	59.6	69.7	84.4	83.5	91.7	99.1	92	84

Note. Individual scores for word knowledge, speech perception, reading, and sensory abilities are also included ($N = 21$).

overall group performances in speech perception scores. This result supports Hypothesis 3, that is, that vocabulary and speech production training would be effective at improving speech perception scores in the auditory-alone condition. Speech production training (t [20] = 3.14, p = .005) and vocabulary training (t [20] = 2.98, p = .007) were also effective in improving reading-aloud scores for this group of participants, thus supporting Hypothesis 4, that vocabulary training and speech production training would improve overall scores in the reading condition. Hypothesis 5 predicted that neither type of training would improve the sensory component of the multiplicative model, however, results of the t tests showed unexpectedly that the hearing component improved significantly during vocabulary training (t [20] = 3.80, p = .001). The analysis for speech production was close to statistical significance (t [20] = 2.08, p = .051).

Order of Training effects

Table 6 shows the results of ANOVAs that were used to compare the improvements for each measure (PCC in conversations and the 108 SWAT, word knowledge, speech perception reading, and sensory abilities) for the two groups of children after each type of training (A = speech production and B = vocabulary). "Improvement" is the difference in scores for each child before and after training. Results show that for the 12 combinations of measures and training, 9 show no significant difference between the two groups of children. For example, the mean improvement in word knowledge after speech production training was 5.1% for Group 1 and 7.5% for Group 2. There was no significant difference between these mean values (F = .54, p = .472). There were three cases where significant differences were found between the groups.

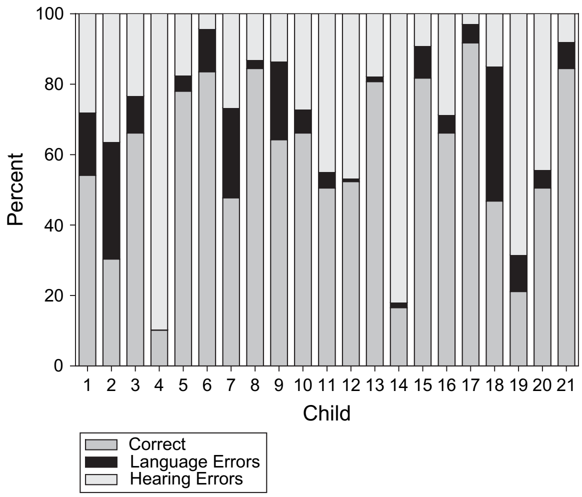

Figure 3 Speech perception scores at the start of the study for each child, with errors partitioned into language errors and hearing errors using the mathematical model.

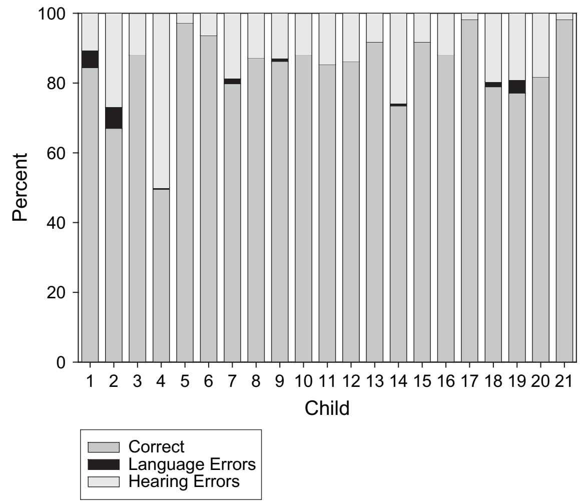

Figure 4 Speech perception scores at the end of the study for each child, with errors partitioned into language errors and hearing errors using the mathematical model.

These were the 108 SWAT after vocabulary training, word knowledge after vocabulary training, and reading after vocabulary training. In each case, Group 2 improved more than Group 1.

Figures 3 and 4 show the speech perception results for individual children before and after the two training periods. The mathematical model has been used to partition the errors that each child made into hearing errors and language errors (i.e., lexical access and speech production errors). The darker gray bars at the bottom of the graph show the percentage of words correct in the speech perception test. The black bars in the center show the percentage of language errors, and the lighter gray bars at the top show the percentage of hearing errors (see end of Appendix A for calculations). The percentage of words where there is no hearing error is calculated by dividing the speech perception score by the reading-aloud score. Figure 3 shows that many children were making a substantial number of language errors before the study commenced (e.g., Children 1, 2, 7, 9, and 18). Figure 4 shows that very few language errors were made after training and that almost all remaining errors were hearing errors.

Analysis of Results Without Children 14 and 19

Child 14 received a cochlear implant during the study, and Child 19 was fitted with a more powerful hearing aid. Both these changes are likely to have affected the results for these children, especially the speech perception scores, and the hearing component calculated from the mathematical model. Examination of the results in Figures 3 and 4 for these children shows that both did indeed have larger improvements in these measures than the other children in the study. To determine whether the results for these children had biased the conclusions of the study, the statistical analyses were repeated excluding Children 14 and 19 (see Table 5). The pattern of statistically significant and nonsignificant *t*-test results was not changed when the results of these two children were omitted.

Discussion

The children in this study made significant improvements in word knowledge, speech production, speech perception, and reading-aloud scores during the study. In general, the results were consistent with the hypotheses, but there were three surprising results: It appears that speech production training improved word knowledge, and that both types of training improved the sensory (hearing) component in the mathematical model. Although these improvements were unexpected from a scientific perspective, they are very positive outcomes for the children because the training was more effective than predicted.

Table 5 Statistical analyses excluding Children 14 and 19 ($N = 9$)

Training	Measure	Mean improvement (%)	Paired t	p
A	PCC conversation	1.2	1.13	.273
	PCC 108 SWAT	1.7	2.73	.014
	Word knowledge	5.3	3.42	.003
	Speech perception	10.2	3.68	.002
	Reading	7.7	3.07	.007
	Hearing component	4.3	1.52	.146
B	PCC conversation	1.9	1.61	.126
	PCC 108 SWAT	1.3	1.44	.167
	Word knowledge	16.6	5.28	<.001
	Speech perception	12.5	4.80	<.001
	Reading	6.0	2.71	.014
	Hearing component	8.0	3.35	.004

The main goal of the study was to determine whether the strong relationships that exist between measures of speech perception, speech production, and vocabulary are causal. The results show quite clearly that vocabulary training and speech production training have a strong effect on speech perception, even though there was no specific auditory training component in the study. Thus, improvements in speech production and vocabulary have a direct causal effect on speech perception performance. Once again, this is a very positive result because it implies that there is added benefit to speech perception when other aspects of spoken language are trained.

The mathematical model predicted that training speech production and word knowledge would affect speech perception and reading aloud in similar ways and by similar amounts. The results of the study actually show that the improvements in speech perception were greater than the improvements in reading aloud. This manifests as an increase in the sensory (hearing) component in the mathematical model. This increase may be a real effect, or it may be a shortcoming of the model itself. The model makes some rather simplistic assumptions about the contributions of hearing, lexical knowledge, and speech production to measures of speech perception and reading aloud. If these assumptions are incorrect, then the model predictions are also likely to be faulty. On the other hand, there are other more complex models of speech perception that make it more plausible that speech production and vocabulary training might have a direct effect on the auditory information extracted from a speech signal during the "hearing" of a word. One example is the Word Recognition and Phonological Structure Acquisition (WRAPSA) model of Jusczyk (1993). The WRAPSA model suggests that spoken language knowledge is used to refine the early stages of auditory processing in children, so that they become finely attuned to the sounds of their native language. If the WRAPSA model is correct, then the speech production and word knowledge training may have had a direct causal effect on the hearing component in the speech perception testing, as well as on the lexical access and verbal response components.

Effects of Speech Production Training

Results from this study indicate that speech production training was effective at improving the PCC in words as measured in the 108 SWAT. This finding is consistent with the findings from an earlier study by Paatsch et al. (2001), where the practice of articulation of phonemes at a phonological level improved articulation of phonemes in single words as measured in the 108 SWAT. A slightly disappointing aspect of the current study is that the mean improvements in PCC were all quite small (less than 2%), and there were no significant improvements in PCC for conversations. The training methods in this article were previously used by Paatsch et al., who observed larger, statistically significant improvements in the 108 SWAT and in conversations. Thus, the reason for the small improvements is not likely to be ineffective training methods.

Speech production training was unexpectedly effective in improving word knowledge for this group of children. A possible explanation for this result could be that the list of 109 CVC words used to assess word knowledge included many frequently used words in English such as “had,” “at,” and “that.” Presumably, it would have been difficult not to use such words in many of the connected discourse activities throughout speech production training, therefore providing opportunities for incidental learning to take place. Similar results of unexpected effects of speech production training were reported in a recent study by Bow, Blamey, Paatsch, and Sarant (2004). This study reported unexpected significant improvements in grammatical judgments after phonological training of phonemes in meaningful language for 17 children who were deaf or hard of hearing. The findings of this study and those of Bow et al. suggest that speech production training is an important inclusion in language intervention programs for children with hearing loss.

Another potential explanation for the measured improvement in word knowledge after speech production training may be related to the process of learning new words. It appears that there are at least four kinds of information that are associated with acquiring new words in the lexicon—the meaning, the syntactic form, the morphological structure, and the phonological shape. The phonological aspect of word learning is linked to the understanding of the sound patterns as phonetic segments, syllables, and stress (Clark, 1993; Jusczyk, 1997). In the case of a child with hearing loss, access to the sound patterns of words can be significantly reduced, thus affecting the acquisition of new words. It may be possible that the children in this study were storing incorrect items (i.e., meanings without associated sound patterns) or may have encountered sound patterns that did not match any words already stored in their lexicon. After specific speech production intervention, these children may have been able to sort out the confusions and reorganize the existing items in their lexicon. This interpretation is supported by Jusczyk (1997), who suggests that there are situations in which the use of speech production abilities to accurately reproduce the patterns within a word would allow one to seek out information about the meaning that is attached to that particular word.

In addition to the effects on PCC and word knowledge, speech production training improved performance on the CVC speech perception and reading-aloud measures. These improvements were predicted by the mathematical model and are probably due to a combination of three factors: improved articulation of the phonemes in the child’s verbal responses, improved word knowledge (noted in the previous paragraphs) leading to more effective lexical access, and improved processing of auditory information (as noted in the initial paragraphs of the Discussion section). Similar effects of speech production training on speech perception were reported in an earlier study by Novelli-Olmstead and Ling (1984). Two groups of 7 children with severe-to-profound hearing loss, aged from 5 to 7 years, participated in either speech production or listening-alone training. The results showed that the group of children who participated in speech production training made highly significant gains in both speech production and speech perception skills, whereas the group of children who participated in the listening-alone training showed no gains in speech perception and only slight gains in speech production.

Effects of Vocabulary Training

As predicted in the second hypothesis, vocabulary training was effective at improving word knowledge for the children in this study. Individual scores, presented in Table 4, show that every child benefited from intensive daily intervention in learning new words. Activities that included oral discussions of word meanings, picture representation of words, and constructing sentences that illustrated a word’s correct semantic and syntactic use were effective strategies that assisted in vocabulary development in this group of children.

The vocabulary training also improved speech perception and reading-aloud scores. This result is consistent with the strong relationships between speech perception scores and word knowledge measured by the Peabody Picture Vocabulary Test found in studies by Blamey et al. (2001) and Paatsch et al (2004). Given that no significant improvement in PCC was found during the vocabulary training period, the effects of vocabulary training on speech perception and reading aloud are probably due to improved lexical access and processing of auditory information in the recognition of the word but not improved articulation of the response.

Individual Differences in Speech Perception

At the start of the study, some children were already performing at high levels, whereas others were performing quite poorly. Children 1, 2, 7, 9, and 18 were making substantial numbers of language errors, as shown in Figure 3. Children 4, 14, and 19 had the lowest scores and were making mostly hearing errors. At the end of the study, language errors had almost been eliminated for every child. Children 14 and 19 had reduced their number of hearing errors sufficiently to be similar to the other children, probably because of their new hearing devices. Child 4 was still the lowest scoring individual and had reduced the proportion of hearing errors from 90% to 50% of words presented in the speech perception task. Child 4 is an interesting case: the child is about 8 years old, has excellent reading skills, and better hearing thresholds than Child 2, for example, and yet scored much lower on the speech perception test both before and after training. There are several possible explanations for Child 4's level of performance. Audiological reports indicate that he was born with normal hearing thresholds, experienced deteriorating hearing, and was diagnosed with a severe-to-profound hearing loss at the age of 3 years. It was also reported that he experienced fluctuating hearing after the age of 3. It is possible therefore, that Child 4 may have had a fluctuating hearing loss at the time of testing and throughout the training. It is also possible that he would benefit from an improved listening device such as a more powerful hearing aid or a cochlear implant. Throughout the 12-month period during which the this study was conducted, the possibility of cochlear implantation was being investigated. Six months after the end of the final training study, Child 4 was implanted with a Nucleus CI-24.

Every child improved its speech perception and reading scores during the study, but there was a substantial amount of time and effort involved to achieve this result for the 109 words that were trained and tested in the study. Use of the mathematical model and examination of the results in the format of Figure 3 allows teachers to identify those children who will benefit most from language-based training and those who will benefit most from improved amplification devices. The test is quick and easy to apply and will help to identify the needs of individual children and make optimal use of the time available for training.

Effects of Incidental Learning

In interpreting the results of this study, it is important to consider the effects of incidental learning. The study spanned a full school year, and during this time, it is likely that performance on all the measures would have improved even in the absence of specific training. For various reasons, including the fact that children and teachers were committed to improving spoken language as quickly as possible, the study did not include a "no training" period. The specific training occurred in short daily sessions on school days, and it is likely that additional incidental learning occurred at other times. Despite the absence of baseline measures derived from "no training" periods, we can be sure that both kinds of training accelerated learning because the only significant improvement in speech production occurred during the speech production training period, and the observed improvement in word knowledge was much greater in the vocabulary training period (16.0%) than in the speech production training period (5.9%). The most conservative interpretation of the results would be to assume that all of the unexpected or surprising improvements (i.e., improvement in word knowledge during speech production training and improvements in sensory processing) were the result of incidental learning or other extraneous effects and not related to the specific training at all. However, this explanation would not provide a reason for the improvement in sensory processing being greater during the period of vocabulary training (8.0%) than during the period of speech production training (4.3%). Note that the figures used in the

Table 6 Statistical analyses showing the improvements for each measure for the two groups of children after training A (speech production) and training B (vocabulary)

Measure	Training	Mean improvement	t	p	Group 1 improvement	Group 2 improvement	F	p
Conversation PCC	A	0.86	0.84	.413	1.7	−0.9	1.43	.246
	B	1.9	1.70	.104	0.8	4.1	2.11	.162
108 SWAT PCC	A	1.6	2.47	.023	2.0	0.9	0.66	.426
	B	1.1	1.23	.234	−0.2	3.9	5.12	.036
Word knowledge	A	5.9	3.93	.001	5.1	7.5	0.54	.472
	B	16.0	5.62	.001	11.6	24.9	6.01	.024
Speech perception	A	11.8	4.07	.001	13.5	8.3	0.72	.408
	B	14.2	5.09	.001	13.2	16.2	0.26	.615
Reading	A	7.3	3.14	.005	10.0	1.7	3.19	.090
	B	6.9	2.98	.007	3.2	14.3	6.48	.020
Sensory	A	6.4	2.08	.051	6.2	6.7	0.01	.941
	B	9.7	3.80	.001	11.1	6.7	0.66	.426

preceding sentence for improvement in sensory processing are from Table 5, which excludes Children 14 and 19. The changes in their hearing devices during the study are examples of how extraneous influences could affect the outcomes of the study.

Order of Training Effects

There were other limitations on the experimental design that are worth noting. The two groups of children were of unequal size and there was a significant age difference between Group 1 ($M = 9.29$ years) and Group 2 ($M = 6.04$ years; $t = 5.46$, $p = .0001$). The teachers for Group 1 were not the same as the teachers for Group 2. These limitations were imposed by the timetable and curriculum requirements of the school where the training took place. The main reason for using two groups of children and two training methods in this reverse block design was to balance out any order effects. Clearly, the desired balance was only partially achieved.

Group 1 was trained with the speech production method first, followed by word knowledge training. An examination of the results in Table 6 shows that there were three cases where Group 2 improved significantly more than Group 1. This may have been because Group 2 received vocabulary training first and therefore had more to learn or because the children in Group 2 were younger and therefore had more to learn or both. If age had been the overriding factor, then Group 2 would always have improved more than Group 1, and this was not the case. If the order of training was the overriding factor, then the group trained first would always have improved more that the group trained second. For the 12 combinations of measures and training highlighted in Table 6, 9 measures show a larger improvement for the group trained first than the group trained second. Thus, there is likely to be an order effect in the data. However, the only cases to reach statistical significance with $p < .05$ are where the younger group was trained first. Thus, the most likely explanation for the results is that there was an age effect as well as an order effect. When there are unbalanced or uncontrolled variables such as order and age, the effect is to increase the variability between subjects and thus to reduce the statistical significance of main effects or averages over the whole subject group. The conclusions of the study are based on main effects, assessed by t tests. The presence of order effects and age effects is likely to lead to Type II errors (i.e., calling a difference nonsignificant when it is actually significant) rather than Type I errors (calling a difference significant when it is not). Thus, the conclusions of this study that are based on statistically significant t test comparisons are valid.

Conclusions

The results of the study show that speech production training and vocabulary training affect speech perception and reading performance as well as the directly targeted speech production and word knowledge of the children. This result is proof that the strong correlations between spoken language measures and speech perception found in previous studies are the result of causal effects and are not just coincidental. This conclusion justifies the provision of spoken language training to children who are deaf or hard of hearing and who use cochlear implants and/or hearing aids. Effective training of speech production and vocabulary will also result in improved speech perception performance. Furthermore, the use of the mathematical model will help to identify those children who will benefit most from language-based training, and those who will benefit most from improved amplification devices.

Appendix A: Mathematical Model of Speech Perception Scores

The nonlinear mathematical model below is described and validated in an earlier study (Paatsch et al., 2004). It relates the proportion of correct responses to words in a speech perception test to the probabilities of correctly extracting the auditory information from the signal, correctly recognizing the word from the auditory information and responding correctly by producing the word. The probability of giving a correct response is expressed in the following equation:

$$P_T = P_S \times P_L \times P_P. \qquad (1)$$

In this equation P_T is the total probability of a correct response, P_S is the probability of sensory information being transmitted to the lexicon, P_L is the probability of identifying the stimulus in the lexicon, and P_P is the probability of correct speech production of all phonemes. Two different sensory conditions, auditory alone and reading, were measured in this study. Equation (1) was applied to these two measured sensory conditions:

$$P_{TA} = P_{SA} \times P_L \times P_P \quad (\text{A} = \text{auditory alone}), \qquad (2)$$

and

$$P_{TR} = P_{SR} \times P_L \times P_P \quad (\text{R} = \text{reading}). \qquad (3)$$

In Equation (2) P_{TA} is the total probability of a correct response and P_{SA} is the probability of sensory (auditory) information being transmitted to the lexicon in the auditory-alone condition. In Equation (3) P_{TR} and P_{SR} are the total probability of a correct response and the probability of sensory (visual) information being transmitted to the lexicon in the reading condition, respectively. The probabilities of lexical correctness (P_L) and speech production correctness (P_P) were hypothesized to be the same in both the A and R conditions. It was assumed that there would be no sensory (visual) errors in the reading condition so that $P_{SR} = 1$. Given these assumptions, the probability that auditory information is correctly transmitted to the lexicon is given by

$$P_{SA} = P_{TA}/P_{TR}. \qquad (4)$$

The probability of a hearing error in the speech perception test is therefore $(1 - P_{SA})$, and the probability of a language (lexical or production error) is $(1 - P_{SA} - P_{TA})$.

Appendix B: List of 109 CVC Words Used in Tests of Speech Perception, Word Knowledge, and Reading Aloud

Had	Heed	Hid	Head	Hard
Hoard	Hood	Who'd	Herd	Hoed
Hide	Haired	Hat	Hack	Hag
Have	Has	Hang	Hatch	Ham
At	Pat	Cat	Fat	Vat
That	Sat	Chat	Mat	Gnat
Rat	Heat	Hit	Heart	Hot
Hoot	Hut	Hurt	Hate	Height
Bat	Bad	Lad	Mad	Fad
Dad	Pad	Add	Bag	Bass
Bash	Batch	Badge	Ban	Bade
Bide	Bowed	Buoyed	Beard	Bared
Back	Bang	Bead	Bid	Bed
Barred	Bored	Booed	Bud	Bird
Keep	Key	Peep	Beep	Deep
Seep	Sheep	Heap	Cheap	Jeep
Leap	Reap	Weep	Kip	Cap
Coop	Cope	Keyed	Keys	Quiche
Keen	Keel	Dog	Hog	Log
Bog	Jog	Nog	Cog	Fog
Doll	Dodge	Dong	Dig	Dug
Dot	Dob	Dock	Doff	

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