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Effects of noise and filtering on the intelligibility of speech produced during simultaneous communication

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Abstract

This study investigated the effects of noise and filtering on the intelligibility of speech produced during simultaneous communication (SC). Four normal hearing, experienced sign language users were recorded under SC and speech alone (SA) conditions speaking Boothroyd's forced-choice phonetic contrast material designed for measurement of speech intelligibility. Twenty-four normal hearing listeners audited the speech samples produced by the four speakers under the SC and SA conditions, three listeners in noise and three listeners in filtered listening conditions for each of the four speakers. Although results indicated longer sentence durations for SC than SA, the data showed no difference in the intelligibility of speech produced during SC versus speech produced during SA under either the noise or filtered listening condition, nor any difference in pattern of phonetic contrast recognition errors between the SA and SC speech samples in either listening condition. This conclusion is consistent with previous research indicating that temporal alterations produced by SC do not produce degradation of temporal or spectral cues to speech intelligibility or disruption of the perception of specific English phoneme segments.

Learning outcomes: As a result of this activity, the participant will be able to (1) describe simultaneous communication; (2) explain the role of simultaneous communication in communication with children who are deaf; (3) discuss methods of measuring speech intelligibility under filtered and noise conditions; and (4) specify the ability of listeners to

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perceive speech produced during simultaneous communication under noise and filtered listening conditions.

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Keywords: Simultaneous communication; Speech intelligibility; Noise; Filtered speech

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Simultaneous communication (SC), which combines speech with manually coded English to enhance communication with hearing-impaired persons and facilitate speech and language development of hearing-impaired children, has been the subject of much recent research (Baillargeon, McLeod, Metz, Schiavetti, & Whitehead, 2002; Kardack et al., 2002). Speech production studies have found temporal changes in the speech of both experienced and inexperienced signers, including slower speech rate and longer fricative and vowel durations, interword intervals, and voice onset times (VOT), during SC (Schiavetti, Whitehead, Metz, & Moore, 1999; Schiavetti, Whitehead, Metz, Whitehead, & Mignerey, 1996; Whitehead, Schiavetti, Metz, & Farell, 1999; Whitehead, Schiavetti, Whitehead, & Metz, 1995; Whitehead, Whitehead, Schiavetti, Metz, & Farell, 1999). However, these studies showed that a number of specific temporal rules of spoken English, such as the VOT difference between voiced and voiceless members of pairs of cognate plosive consonants, were followed correctly in speech produced during SC, supporting the conclusion that speech during SC presents an accurate model to persons with hearing impairment. Also, recent research by Baillargeon et al. (2002) has found appropriate second formant frequency transitions in SC consonant–vowel–consonant (CVC) syllables, indicating no degradation of stop consonant acoustic cues during SC, and Kardack et al. (2002) observed that spectral moments obtained from speech produced during SC were statistically indistinguishable from those obtained during speech alone, indicating no measurable degradation of obstruent spectral acoustic cues during SC.

In addition to these studies of speech production characteristics of SC, recent research has focused on the perception of speech produced during SC as a direct test of the effectiveness of SC both as a speech model for hearing-impaired children's development and as a communication mode for use with hearing-impaired adults. These studies found that perception of specific speech parameters by both hearing and hearing-impaired listeners was not disturbed by the use of SC. Metz et al. (1997) found that accurate perception by normal hearing listeners in a quiet listening condition of final consonant voicing in the speech of experienced signers was not impaired by alterations in temporal structure of speech during SC and D'Avanzo, Graziano, Metz, Schiavetti, and Whitehead (1998) obtained the same result with speech produced by inexperienced sign language users. Schiavetti et al. (2004) examined the perception of vowels produced in SC and found that normal hearing listeners in a quiet listening condition could identify vowels produced in SC as well as they could identify vowels produced in a speech alone condition. Whitehead, Schiavetti, MacKenzie, and Metz (2004) examined the overall intelligibility of speech produced during SC and found no differences in multiple choice intelligibility test results for speech recorded during SC versus speech alone recordings when these recordings were audited in the quiet by hearing-impaired students at the National Technical Institute for the Deaf (NTID).

All of the studies that have examined the perception of speech produced during SC so far have used quiet listening conditions in order to compare their data to normative speech perception studies in the speech and hearing science literature. The degree to which accurate speech intelligibility would be maintained under difficult listening conditions in SC, however, would be an important indicator of the appropriateness of SC for use as a speech model with deaf children and as an efficient method for communicating with deaf adults. Testing intelligibility under difficult listening conditions, such as speech in noise and filtered speech, would allow researchers to determine the degree to which speech during SC maintains the acoustic redundancy necessary to resist intelligibility degradation by masking or frequency distortion and would extend the external validity of SC research to common realistic listening conditions such as noisy classrooms or electronic transmission systems.

Therefore, the purpose of this study was to examine the intelligibility of speech produced by experienced hearing sign language users under two experimental speaking conditions: (1) using speech alone (SA) versus (2) using simultaneous communication (SC) when the speech was presented to normal hearing listeners under two experimental listening conditions: (1) speech in noise and (2) filtered speech.

1. Method

1.1. Speakers

Speakers for this study were four normally hearing adults (two females and two males), who were faculty members at the NTID. Each speaker had taught young deaf adults for more than 15 years, using simultaneous communication in their classes. Each speaker's sign language performance had been evaluated on the Sign Communication Proficiency Index (Caccamise, Updegraff, & Newell, 1990) and all speakers were classified at the advanced level or higher on this instrument. Thus, the speakers were considered to be fluent in the use of speech combined with signed English and fingerspelling.

1.2. Speech materials

The speech material spoken by the participants was the forced-choice phonetic contrast word list constructed by Boothroyd (1985) that can be used to measure speech intelligibility with only phonological information made available to the listener by the acoustic output of the talker. Forty-eight monosyllabic words were recorded embedded in the carrier sentence "Mark the word_next" in both SA and SC modes of communication. This monosyllabic word list permits an analysis of receptive speech pattern contrast errors involving eight different phonetic contrasts (vowel height and place, initial consonant place, continuance, and voicing, and final consonant place, continuance, and voicing) as well as prediction of phoneme, word, and sentence intelligibility from the overall phonetic contrast intelligibility score.

1.3. Recording procedures

The experimental words embedded in the sentences were spoken at a comfortable conversational loudness level as they were presented on flashcards. Audio recordings were made in a sound-treated booth using an Audio-Technica AT-816 microphone that was placed 15 cm from each speaker's mouth and was connected to a Tascam 202MKII tape deck. The speakers produced each group of sentences under the two experimental speaking conditions: SA versus SC. In the SC condition, speakers combined speech with sign language for "Mark the word" and "next" and with fingerspelling for the monosyllabic words. The sentences were presented on flashcards in a different random order for each speaker and experimental speaking condition (SA versus SC) and the order of experimental speaking condition (SA versus SC) was counterbalanced across speakers. The speakers were shown the experimental words before the recording so they could familiarize themselves with the signing of the carrier phrase and the fingerspelling of the monosyllabic words to be used in SC.

1.4. Sentence duration analysis procedure

We measured total sentence duration in the two experimental conditions to verify that speech rate was slower in SC than in the SA condition. For each of the 192 speech samples (48 words × 4 speakers) in each experimental condition, total sentence duration for the word and its carrier sentence was measured in milliseconds (ms). The acoustic signal from the audio recording of each sentence was digitized with 16 bit precision at a sampling rate of 20 kHz using Kay Elemetrics Computerized Speech Lab (CSL Model 4300B). When the digitizing process is initiated, CSL applies an appropriate internal low-pass anti-aliasing filter to the raw acoustic signal (at a sampling rate of 20 kHz the upper frequency cutoff is 8 kHz), stores the digital results in memory, and displays the resultant waveform on a VGA graphics monitor.

Total sentence duration was measured by visually isolating the first positively going portion of the waveform associated with the initiation of speech and marking the location with a cursor. The cursor position was then stored and the cursor moved to the end of the sentence and the last positive going portion of the waveform was visually isolated and marked as the second cursor position. The temporal interval between the two cursor positions was taken as the value for total sentence duration. Reliability of the sentence duration measurements have been previously reported (Schiavetti et al., 1996; Whitehead et al., 1995; Whitehead, Whitehead, et al., 1999) and shown to be adequate.

1.5. Listening procedure

Speech intelligibility analysis was accomplished by means of a forced-choice phonetic contrast test in which 24 normal hearing listeners audited the speech samples provided by the four speakers. Six listeners were randomly assigned to each of the four speakers, three to listen in noise and three to listen in the filtered condition. Listeners were student volunteers, ranging in age from 21 to 28 years (mean age = 23.12 years), enrolled at the State University of New York who passed a pure tone hearing screening at 20 dB HL (ANSI, 1996) for the frequencies 0.5, 1, 2, and 4 kHz at the beginning of the listening session. Twelve listeners were randomly assigned to listen in the noise condition with speech and white noise presented at a signal-to-noise ratio of 0 dB at 50 dB HL. Twelve listeners were randomly assigned to listen in the filtered condition with speech presented at

50 dB HL after passing through a Kron-Hite Model 3200 Filter set at a low-pass cutoff frequency of 600 Hz and a slope of 24 dB per octave. Filter frequency response was monitored with a Tectronix Model TDS 420A Digitizing Oscilloscope and found to be within 2 dB of the manufacturer's specification at each octave frequency from 150 to 9600 Hz. The specific filter and noise conditions were chosen on the basis of a pilot study in which phonetic contrast scores dropped from approximately 100% for two normal hearing listeners in an unfiltered listening condition with no noise presented to values between 50 and 75% for these filter and noise settings. These pilot results indicated that these noise and filter settings should adequately test the relative degree to which speech produced during both SA and SC would be degraded in intelligibility.

All testing was conducted in a sound-treated audiometric test booth that met the American National Standards Institute specifications for permissible ambient noise levels (ANSI, 1999), and all audiometric equipment had been recently calibrated according to ANSI (1996) specifications. Recordings of the speakers were presented monaurally using a Aiwa XC-RW700 compact disc player routed through the speech audiometry circuit of a Grason-Stadler GSI 61 clinical audiometer to Telephonics TDH-50P earphones mounted in MX41/AR cushions. The audiometer's VU meter was used to monitor the output during presentation of the recorded stimuli and signal and noise levels were monitored with a B&K Model 148 calibration system, including a 2204 sound level meter with a 4152 artificial ear and 4132 microphone.

Speech intelligibility was measured with a forced-choice phonetic contrast test that contained 48 panels, each of which included four response alternatives for the listeners to mark the test word or one of its three foils. As described by Boothroyd (1985, p. 187) this procedure provided "the possibility of independent errors along two phonetic dimensions" for each forced-choice response, yielding the eight different phonetic contrast measures across four different subgroups of 12 words each within the 48 word test. The phonetic contrast scores were adjusted for guessing using Boothroyd's probability theory derived formula:

$$P_{\mathrm{c}} = 2P_{\mathrm{m}} - 1$$

where P_{c} is the guessing-adjusted probability of correct response and P_{m} is the measured proportion of correct responses. All proportions were converted to percentages for descriptive statistical presentation in the results section to be consistent with previous speech intelligibility literature.

The recordings of the words were presented to the listeners monaurally in the right ear according to the randomized and counterbalanced orders described above for speakers and modes of communication. Overall correct phonetic contrast percentages were computed for both the SA and SC conditions and an analysis was completed of the eight specific phonetic contrast errors made by the listeners in each condition. Reliability of the intelligibility measures was assessed by contrasting the odd and even numbered responses in the listeners' phonetic contrast tests results. Mean differences between number of odd and even responses in each listening condition for each speaking condition ranged from 0.02 to 0.67 per listener and the overall correlation between the odd and even responses was 0.94 indicating adequate reliability. In addition, predictions of phoneme recognition, isolated word recognition, and sentence context word recognition measures of speech intelligibility were made from the phonetic contrast data using Boothroyd's (1985) intelligibility equations:

(1) for predicting phoneme intelligibility (p) from the phonetic contrast intelligibility (c)

$$p = 1 - \left[1 - \left(\frac{c+1}{2}\right)^{4.3}\right]^{1.5}$$

(2) for predicting word intelligibility (w) from phoneme intelligibility (p)

$$w = p^{2.3}$$

(3) for predicting sentence intelligibility (s) from word intelligibility (w)

$$s = 1 - (1 - w)^{4.5}$$

to make these predictions.

1.6. Statistical analysis of duration and intelligibility data

Statistical analyses of the sentence durations were accomplished by comparing the mean duration values for the 192 SA sentences versus the 192 SC sentences with a *t*-test for repeated measures at a pre-selected alpha level of 0.01. We calculated the overall intelligibility score on the phonetic contrast test as the percentage of words heard correctly by each listener and calculated predicted phoneme, word, and sentence intelligibility score using the Boothroyd (1985) conversion formulae. Each of the intelligibility means was compared for SA versus SC with a Bonferroni *t*-test for repeated measures at a pre-selected alpha level of 0.01; the critical Bonferroni t value for eight comparisons with 22 ($2N - 2$) degrees of freedom is 3.03. We also tabulated errors made on each of the eight different phonetic contrasts in the data of each listener for each speaker and reported the sums of these contrast error tabulations for the SA and SC conditions. These results, then, enabled us to compare speech rate in SC versus SA and to complete a detailed analysis of the intelligibility of the speech in the two experimental speaking conditions (SA and SC) and the two experimental listening conditions (speech in noise and filtered speech).

2. Results

2.1. Sentence duration

The *t*-test revealed a significant effect of communication mode (SA versus SC) on sentence duration ($t = 12.98$; d.f. $= 191$; $P < 0.0001$). Mean sentence duration for the 192 samples in the SA condition was 1935 ms (S.D. = 138 ms) and mean sentence duration for the 192 samples in the SC condition was 2505 ms (S.D. = 554 ms). These data indicate that sentence duration was longer on average in the SC condition than in the SA condition because of the slowing of speech while speakers attempted to sign and speak at the same time.

2.2. Speech intelligibility and phonetic contrast error analysis

Table 1 displays the means and standard deviations of speech intelligibility scores for the overall Boothroyd forced-choice phonetic contrast test and the predicted phoneme, word, and sentence intelligibility from Boothroyd's conversion formulae. Inspection of Table 1 reveals similar means and standard deviations for SA and SC conditions on all four intelligibility measures in the noise listening condition and almost exactly the same SA and SC means in the filtered listening condition. All of the pair-wise comparison Bonferroni *t*-tests were non-significant, indicating no difference in intelligibility between speech produced in the SA and SC speaking conditions for either the speech in noise or the filtered speech listening condition. Listener performance was quite accurate for these difficult listening conditions because of the closed response set used in the intelligibility task and word recognition performance would have been lower for an open set response task at this signal-to-noise ratio and filter setting.

Table 2 displays the sums of the phonetic contrast errors across listener-speaker pairs on the Boothroyd forced-choice phonetic contrast test in the SA and SC conditions. Inspection of Table 2 reveals a very similar error pattern in the phonetic contrasts across the types of errors for both the SA and the SC conditions. These error patterns are also very similar to the error patterns across speaker–listener pairs found by Whitehead et al. (2004) for hearing-impaired

Table 1
Means and standard deviations of Boothroyd's phonetic contrast test and predicted phoneme, word, and sentence intelligibility scores (%) for speech alone and simultaneous communication in both the filtered speech and speech in noise listening conditions and Bonferroni *t*-tests comparing the two speaking conditions in each listening condition

	Contrast	Phoneme	Word	Sentence
Speech in noise				
Speech alone				
Mean	49.31	41.71	16.48	47.83
Standard deviation	17.30	17.16	13.52	29.16
Simultaneous communication				
Mean	52.78	43.49	15.17	51.27
Standard deviation	6.24	6.46	4.59	12.51
Bonferroni *t*	0.7823	0.3916	0.3555	0.4343
p	0.4506	0.7028	0.7289	0.6725
Filtered speech				
Speech alone				
Mean	76.39	73.07	50.12	92.00
Standard deviation	8.21	11.05	17.21	8.41
Simultaneous communication				
Mean	76.74	73.49	50.56	92.76
Standard deviation	7.63	10.26	16.38	6.83
Bonferroni *t*	0.1205	0.1087	0.0733	0.2819
p	0.9063	0.9154	0.9429	0.7832

Table 2
Number of phoneme contrast errors for speech alone and simultaneous communication speaking conditions in the filtered speech and the speech in noise listening conditions

	Vowel height	Vowel place	Initial consonant voicing	Initial consonant continuance	Final consonant voicing	Final consonant continuance	Initial consonant place	Final consonant place
Speech in noise								
Speech alone	0	14	13	28	3	39	21	42
Simultaneous communication	1	19	12	30	2	36	20	31
Filtered speech								
Speech alone	2	11	4	6	0	11	18	21
Simultaneous communication	0	7	3	6	1	18	21	14

listeners, indicating that the difficult listening conditions produced similar phoneme errors as the effect of hearing impairment. These results are consistent with the notion that filtering and noise masking often simulate the effect of hearing impairment on speech perception.

The most common phonetic contrast errors in both speaking conditions were consonant place of articulation and continuance errors and vowel place errors. Vowel place errors would be expected to be more common than vowel height errors in this type of intelligibility task with these listening conditions because vowel place is cued by the higher frequency second formant whereas vowel height is cued by the lower frequency first formant. Consonant place and continuance errors would also be expected from the high frequency spectral place cues, second formant transition cues, and continuance timing characteristics that would be perceptually difficult under both the noise masking and low pass filtering conditions. It is also interesting to note that the speech in noise condition was more difficult for the listeners than the filtered speech condition as indicated by the lower intelligibility scores under noise than under filtering. Also, the broad band noise caused more errors than the low pass filtering on consonant voicing which would be cued by lower frequency components of the speech stimulus and on continuance which would be cued by temporal characteristics of the speech stimulus.

3. Discussion

Despite the temporal slowing of speech demonstrated during SC, speech produced during SC was as intelligible overall to listeners as speech produced during SA under both the speech in noise and the filtered speech listening conditions. These results are consistent with previous research that has revealed increased sentence duration in simultaneous communication as a result of the slowing of the faster speech task to maintain simultaneity with the slower manual task (Windsor & Fristoe, 1989, 1991).

These results are also consistent with previous research showing maintenance of phonetic rules of spoken English despite the temporal elongation shown during SC (Schiavetti et al., 1996; Whitehead, Schiavetti, et al., 1999; Whitehead et al., 1995; Whitehead, Whitehead, et al., 1999). It is reasonable to conclude, therefore, that because the speech produced during SC did not disrupt the phonetic rules of spoken English, speech intelligibility was preserved for listeners in SC even under these more difficult listening conditions as the acoustic redundancy of speech was appropriately maintained. The similarity of the present results concerning both the average performances in the two listening conditions and the phonetic contrast error patterns to the results of Whitehead et al. (2004) for hearing-impaired listeners is instructive in pointing out the robustness of the acoustic and perceptual characteristics of the speech produced during SC, and support the external validity of the current findings. These results support the usefulness of SC, indicating that it is appropriate as a speech model for hearing-impaired children and as a mode of communication with hearing-impaired adults because speech produced by normal hearing, experienced sign language users during SC maintains its intelligibility under difficult listening conditions. The spoken message produced during SC passed from speaker to listener with the same accuracy as was obtained with SA in both the noise and filtered listening conditions.

An important, but difficult, question to test in future research concerns the degree to which the acoustic information in speech produced during SC would be maintained relative to SA under difficult listening conditions for listeners with severe hearing impairment, especially children. It has long been known (Cohen & Keith, 1976) that even moderately hearing-impaired listeners demonstrate more severe effects of masking and that children are more affected by difficult listening conditions than adults (Neuman & Hochberg, 1983). Neuman and Hochberg (1983) have pointed out the importance of these psychoacoustic data for the design of classrooms for children with hearing impairment and the role of SC use in such classrooms needs to be investigated in future research. Studies aimed at determining the appropriateness of the use of SC in classrooms for hearing-impaired children need to consider the variations in environmental acoustical parameters such as reverberation times and background noise levels as well as the frequency responses of assistive listening devices employed.

The practical benefits of speech produced during SC that were discussed by Vernon and Andrews (1990) have been supported by recent empirical analyses of the acoustic and perceptual characteristics of SC in a number of research studies. The use of SC for communication between hearing and hearing-impaired persons appears to be appropriate given the maintenance of both acoustic and perceptual phonetic contrasts. Future research should be aimed at empirical analysis of the relative advantages and disadvantages of using SC in other environmental settings such as classrooms for children with hearing impairment in order to extend the generalizability of these results and examine the external validity of the research completed so far.

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Appendix A. Continuing education

Effects of noise and filtering on the intelligibility of speech produced during simultaneous communication

A.1. Questions

1. As used in this study simultaneous communication (SC) involved:
   - A. Speech only produced by normal hearing speakers
   - B. American Sign Language produced by Deaf signers
   - C. Speech combined with signed English and fingerspelling
   - D. Speech only produced by Deaf speakers
   - E. American Sign Language produced by normal hearing signers
2. In the present article, speech intelligibility was measured using:
   - A. A two-interval forced-choice procedure
   - B. The SPIN Test
   - C. The SCAN Test
   - D. The CID W22 Auditory Test
   - E. Boothroyd's multiple-choice phonetic contrast test
3. Speech intelligibility in noise and filtered conditions:
   - A. Was better in SC than in SA
   - B. Was poorer in SC than in SA
   - C. Was the same in SA and SC
   - D. Was too difficult to measure in SA
   - E. Was too difficult to measure in SC
4. Phonetic contrast error patterns in noise and filtered listening conditions:
   - A. Were much more evident in SC than in SA
   - B. Were much more evident in SA than in SC
   - C. Were essentially the same in SA and SC
   - D. Were more difficult to measure in SC than in SA
   - E. Were more difficult to measure in SA than in SC
5. In the conclusion, it was stated that in noise and filtered listening conditions:
   - A. Speech produced during in SC is more intelligible than produced during SA
   - B. Speech produced during in SA is more intelligible than produced during SA
   - C. Speech intelligibility is very similar in SC and SA conditions
   - D. Speech is more difficult to understand in SC than in SA
   - E. Speech is more difficult to understand in SA than in SC

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