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Inter-Talker Differences in Intelligibility for Two Types of Degraded Speech

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Abstract. Are the acoustic-phonetic factors that promote highly intelligible speech invariant across different listener populations and listening environments? Researchers have taken two approaches to investigate differences in intelligibility for a variety of listener populations: examining how speaking style affects intelligibility, and examining how inter-talker differences influence intelligibility. Following the latter approach, we compared the intelligibility of talkers under cochlear implant (CI) simulation (n=200), and in speech mixed with babble (n=200) with their intelligibility under quiet listening conditions (n=200, reported by Karl & Pisoni, 1994). The stimuli consisted of 20 native English talkers producing 100 sentences which were processed to simulate listening with an 8-channel CI or mixed with multi-talker babble. For each condition, stimuli were presented to listeners in a sentence transcription task. The results indicated that the most intelligible talkers in quiet were not the most intelligible talkers under CI-simulation or in babble. Furthermore, listeners demonstrated a greater degree of perceptual learning with the CI-simulated speech compared with the speech mixed with babble. While some of the acoustic-phonetic properties were correlated with intelligibility in all conditions, other properties differed in their degree of correlation among the three conditions. Overall, these results suggest that the acoustic-phonetic parameters that result in highly intelligible speech are dependent on listener characteristics and listening environment.

Introduction

What factors determine speech intelligibility?[2] Traditional views of speech intelligibility hold that intelligibility is a property of the specific words being perceived or of the talker whose speech is being perceived. There is empirical support for each of these views. For example, certain properties of words (e.g., segmental composition; length; frequency) have been shown to influence intelligibility (Black, 1957; Howes, 1952, 1957). Similarly, it has been shown that various properties of a talker's articulations (e.g., speaking rate; vowel dispersion) are essential in determining speech intelligibility (Bond & Moore, 1994; Bradlow, Toretta & Pisoni, 1996; Hood & Poole, 1980). However, recent studies indicate that the speech materials and the talker are not the only relevant factors in determining speech intelligibility. Instead, a variety of research findings suggest speech intelligibility is influenced by properties of the listener, listening environment, linguistic context as well as interactions among these factors. In this paper, we present experimental results indicating that inter-talker variation in speech intelligibility differs for different listeners and in different listening environments.

A number of studies have shown that the intelligibility of talkers varies even under ideal listening conditions (Bond & Moore, 1994; Bradlow et al., 1996; Hazan & Markham, 2004; Hood & Poole, 1980). One aim of this work has been to determine which acoustic-phonetic features correlate with intelligibility, as this may allow us to improve the intelligibility of speech for certain special populations who have particular difficulty in speech perception (e.g., hearing-impaired listeners; second language users). The results obtained in these studies have yielded discrepancies regarding the acoustic-phonetic parameters that are most important for highly intelligible speech. The acoustic-phonetic features that have been reported to correlate with speech intelligibility include increased vowel and word durations (Bond & Moore, 1994; Hazan & Markham, 2004), expanded vowel space (Bond & Moore, 1994; Bradlow et al.,

[2] Speech intelligibility is defined here as the listener's ability to accurately report the words that a talker has produced. This objective measure of speech intelligibility contrasts with other measures in which listeners subjectively rate the "intelligibility" of a speaker (also called comprehensibility) or tests in which the listener must provide an accurate paraphrase of the talker's message in order for the talker's communicative intent to be considered effective.

1996), more pauses (Bond & Moore, 1994), increased F0 range (Bradlow et al., 1996), and more energy in the 1 – 3 kHz region (Hazan & Markham, 2004). Furthermore, talker gender seems to be an important variable for intelligibility. Both Bradlow et al. (1996) and Hazan and Markham (2004) found that female talkers are significantly more intelligible than male talkers. Bond and Moore (1994) did not assess this variable as only male speakers were used. An additional concern with these studies is that the listener populations that are examined tend to be normal-hearing native language listeners (cf. Bond & Moore, 1994). If the ultimate goal of these studies is to improve intelligibility for listeners from special populations then it is important to determine which talkers are most intelligible for these listener populations, and which acoustic-phonetic parameters are important for enhancing intelligibility for the particular listener population. This goal motivates the use of cochlear implant (CI) simulated speech in the present study.

Previous research has also revealed that listener properties help determine which talkers are most intelligible, and thus that different acoustic-phonetic parameters may promote intelligibility for different listener populations. For example, several studies have demonstrated that a shared dialect between the talker and listener may facilitate intelligibility, whereas a mismatch of dialects between the talker and listener may hinder communication (Labov & Ash, 1997; Mason, 1946; cf. Clopper & Bradlow, in press). Similarly, a match or mismatch between talker and listener with respect to nativeness may also affect intelligibility; while native talkers tend to be more intelligible than non-native talkers for native listeners, non-native talkers can be equally intelligible as native talkers for non-native listeners (Bent & Bradlow, 2003; Imai et al., 2003; van Wijngaarden, 2001; van Wijngaarden et al., 2002). In contrast to these findings, Green, Katiri, Faulkner, and Rosen (2007) reported no differences in talker intelligibility among three groups of listeners, which included normal-hearing listeners and actual and simulated CI listeners. However, the lack of a difference in Green et al.'s work may have been an artifact of the small number of talkers used in their study, as discussed more below. Thus, the present investigation examines this issue with a large number of talkers, to determine whether the same relative differences in talker intelligibility are observed under normal listening conditions and degraded listening conditions.

It is also well-known that a listener's experience with a particular talker's idiolect also influences the talker's intelligibility. For example, as listeners become more familiar with the particular acoustic-phonetic properties of a talker's voice, their word recognition skills for that talker will be more accurate (Nygaard, Sommers & Pisoni, 1994). This effect of experience can also be talker-independent, as a beneficial effect of experience on speech intelligibility has been shown for listeners with extensive experience listening to foreign accented speech (Bradlow & Bent, in press; Clarke & Garrett, 2004; Weil, 2001), speech produced by talkers with hearing impairments (McGarr, 1983), computer manipulated speech (Dupoux & Green, 1997; Greenspan, Nusbaum & Pisoni, 1988; Pallier et al, 1998; Schwab, Nusbaum & Pisoni, 1985), and noise-vocoded speech (Davis et al., 2005). Critically, this benefit has been reported to extend to new talkers, and to new speech signals created using the same types of signal degradation. We address this type of perceptual attunement in the present work by comparing performance on an initial group of sentences in a novel listening condition to performance after the listener has been exposed to the condition for many sentences. The results of previous studies would suggest that we will obtain significantly better performance after exposure to a novel listening condition.

Although this review has highlighted how a listener's language background and prior experience may influence inter-talker differences in speech intelligibility, other studies suggest that listener properties are largely unimportant for determining intelligibility when compared to talker characteristics. For example, Hazan and Markham (2004) reported that intelligibility differences between male and female adult and child talkers were the same for listeners of all ages. Similarly, Bond and Moore (1994) reported that intelligibility rankings among several native talkers were the same for native and non-native listeners, suggesting that – at least for native talkers – the language background of the listener is less important than talker-based characteristics. Further, several studies of intelligibility among native and

non-native talkers and listeners have found that native and non-native talkers demonstrate the same relative intelligibility for native and non-native listeners (Major et al., 2002; Munro, Derwing & Morton, 2006), and that certain cue enhancement strategies (i.e., amplification of regions of the speech signal that are thought to carry more information) enhance intelligibility for both native and non-native listeners (Hazan & Simpson, 2000).

In a study that examined similar populations to the present work, Green et al. (2007) argued that a listener's hearing status is also relatively unimportant in determining relative intelligibility among talkers. They presented words from six talkers to CI users and normal-hearing listeners. Normal-hearing listeners heard the speech either mixed with babble at a very favorable signal to noise ratio or under cochlear implant simulation. The stimuli were from two adult male, two adult female and two child female talkers. In each group, one talker was characterized as a high intelligibility talker and one was characterized as a low intelligibility talker based on results from Hazan and Markham (2004). Green et al. reported that intelligibility was relatively consistent across listeners and degradation types, which suggests that at least some talker characteristics are beneficial across listener populations and listening conditions. However, the small number of talkers included in the study (six total), the use of word length stimuli (except for sentences by the adult male talkers), and the choice of talkers at the extremes of the intelligibility distribution limits the extent of generalization of these results. The current study addresses these limitations by using a larger number of talkers, sentence length stimuli and talkers with a wide range of intelligibility scores.

In addition to properties of the talker and the listener, the listening environment also contributes to intelligibility. Overall, speech in noise is less intelligible than speech in quiet (See Assmann & Summerfield, 2004, for a review). However, different types of noise affect speech intelligibility differently, both in overall intelligibility as well as determining what aspects of the signal are difficult to identify. For example, low frequency noise tends to reduce the intelligibility of speech more than high frequency noise (Miller, 1947), and broadband noise tends to impair listeners' abilities to identify place of articulation more than other consonant features (Miller & Nicely, 1955). Furthermore, some listeners are more affected by noise than others; bilinguals or second language users may perform similarly to native listeners on speech identification tasks in the quiet, but their performance decreases more than natives in the presence of noise (Mayo, Florentine & Buus, 1997; Meador, Flege & Mackay, 2000; Nabelek & Donahue, 1984; Rogers, Listeer, Febo, Besing & Abrams, 2006; Takata & Nabelek, 1990). Likewise, those with hearing loss may show relatively unimpaired speech perception performance under quiet listening conditions, but will have much more difficulty in the presence of background noise (e.g., Moore, 2003; Nabelek, 1988). Results from these studies demonstrate a clear interaction of listener characteristics and listening environment in determining intelligibility. Whether differences across talkers are maintained in different listening environments is an issue that has not been extensively studied. In one of the few extant studies, Cox, Alexander and Gilmore (1987) found that relative intelligibility rankings among six talkers were generally maintained across four levels of noise degradation (speech mixed with babble). Their results suggest that the same talkers may be least and most intelligible across listening environments, but the types of degradation studied were similar, with differences only in signal-to-noise ratio and reverberation characteristics. Therefore, the present study compares intelligibility of speech mixed with babble with the intelligibility of CI simulated speech and speech in quiet listening conditions, to determine whether relative intelligibility among talkers will change more extensively for these different types of degradation.

The Present Study

In this paper, we report on an investigation of how talker characteristics interact with listener characteristics and listening environment to determine speech intelligibility. The central aim of this experiment is to determine whether and how inter-talker differences in intelligibility change depending on

listener characteristics (e.g., status as a simulated cochlear implant listener) and listening environment (quiet environment versus noisy environment). Understanding how the interaction of talker and listener characteristics and listening environment influences intelligibility is an important goal in characterizing the factors that contribute to speech intelligibility. While many experimental paradigms and clinical tests use only one talker, it remains largely unknown whether talker specific acoustic-phonetic features that are beneficial to one listener population are beneficial to all listener populations. Investigating the responses of listeners from special populations will further contribute to our knowledge about how listener-related variables can interact with inter-talker differences in intelligibility.

In addition to providing a richer characterization of the factors that contribute to speech intelligibility, this research may have practical applications for people with cochlear implants. Specifically, identifying speech features which are beneficial to these listeners can help guide talkers in improving their intelligibility when communicating with a person with a cochlear implant. Additionally, the results may have applications for the selection of talkers used in clinical tests.

In the current experiment, intelligibility scores for 10 male and 10 female talkers were compared across three listening conditions: Quiet, CI simulation, and Babble. Listeners were presented with speech from only one talker in one listening condition. Six hundred listeners were tested in total: two-hundred listeners for each listening condition. Intelligibility scores were compared across listening conditions and the extent of adaptation to the speech across the course of the experiment was assessed. Lastly, acoustic-phonetic correlates of intelligibility for the two degradation conditions were identified.

Method

Stimuli

The sentences from the Indiana Multi-talker Sentence Database were used. This database includes recordings of 100 Harvard sentences (IEEE, 1969) produced by 20 talkers (10 male and 10 female), with a total of 2000 sentences. Sentences included in this database are shown in Appendix A. The sentences were processed in two ways to assess the intelligibility of these sentences for the simulated listener population as well as when mixed with noise.

CI Simulation. For the CI simulation condition, each sentence was processed through an 8-channel sinewave vocoder using the cochlear implant simulator TigerCIS (*http://www.tigerspeech.com/*). The 8-channel simulation was chosen because normal-hearing listeners perform similarly to CI-users when listening to 8-channel simulations compared to greater or fewer numbers of channels (Dorman et al., 1997). Furthermore, a sine-wave vocoder was employed rather than noise-band vocoder for the same reason. Additionally, when single electrodes are stimulated in CI-users they subjectively report that they hear a sound more like a pure tone than noise (Dorman et al., 1997).

Babble. For the babble condition, the original sentences were mixed with 6-talker babble at a signal to noise ratio of 0. This signal-to-noise ratio was chosen based on pilot data in which the intelligibility of the sentences mixed with babble was matched with intelligibility of the 8-channel CI-simulated sentences. The speech in this condition was not vocoded.

Participants

Four hundred normal-hearing listeners participated (268 females and 132 males with an average age of 21.4 years). All listeners were native speakers of English and reported no current speech or hearing impairments. Listeners were either paid $5.00 for their participation or received course credit in an

introductory psychology course. Participants were undergraduate students at Indiana University or members of the greater Bloomington community.

Task

In each condition, a talker's intelligibility was assessed by examining the performance of 10 normal-hearing listeners on a sentence transcription task (20 talkers x 2 degradation conditions x 10 listeners = 400 listeners total). Each listener was presented with speech from one condition (i.e. quiet, CI simulation or Babble) and heard only one talker during the course of the experiment. During testing, each participant wore Beyer Dynamic DT-100 headphones while sitting in front of a Power Mac G4. Each sentence was played over the headphones followed by a dialogue box presented on the screen which prompted the listener to type in what he or she heard. Each sentence was presented once in a randomized order, and the experiment was self-paced so participants could take as long as needed to enter a response. Listeners were not provided with feedback as to the accuracy of their responses. Prior to the first experimental trial, participants were familiarized with the type of degradation by hearing two familiar nursery rhymes ("Jack and Jill" and "Star Light, Star Bright") which had been processed in the same manner as the sentences in their experimental condition. During familiarization, listeners were not required to make any responses.

Scoring

The responses were scored based on number of keywords and sentences correct. Each sentence has five keywords (underlined words in Appendix A). Keywords were only counted as correct if all and only the correct morphemes were present. Therefore, words with added or deleted morphemes were counted as incorrect. Obvious misspellings and homophones were counted as correct. A sentence was counted as correct if all five keywords were correctly transcribed.

Results

The results will be presented separately for the CI simulation condition and the babble condition. Each of these sections contains several critical comparisons. First, the data in the experimental conditions reported here are compared with intelligibility scores from these same talkers under quiet listening conditions (reported in Karl & Pisoni, 1994). Second, male speakers are directly compared with the female speakers in terms of intelligibility; this was shown to be a significant predictor of intelligibility under quiet listening conditions (results reported in Bradlow et al., 1996). Third, we examined the rate of perceptual attunement under each experimental condition by comparing performance on the first 20 sentences with performance on the last 20 sentences. Each talker's proportion improvement was then compared to their overall intelligibility under quiet listening conditions. The final section of the results considers findings from the CI simulation and babble conditions with respect to a variety of acoustic-phonetic parameters.

Intelligibility of Cochlear-Implant Simulated Speech

Four subjects' data were removed as they were determined to be outliers (their keyword correct score was at least three standard deviations below the mean for that talker). Their data was replaced by data from four new listeners. The data reported below are *keywords correct* except when noted, as this is a more fine-grained measure of intelligibility than *sentences correct*.

Comparison to Intelligibility in Quiet. The intelligibility scores for each talker in the CI simulation condition were computed and compared to intelligibility scores in the quiet (gathered by Karl & Pisoni, 1994). This comparison is shown in Figure 1. For this initial analysis, *sentence* intelligibility

was considered rather than *keyword* intelligibility as Karl and Pisoni only reported sentence intelligibility scores (due to a lack of variation in keyword correct scores). Overall, intelligibility scores in Quiet were not significantly correlated with CI Simulated intelligibility (r=0.347, *ns*). As can be seen in the figure in which talkers are arranged from least to most intelligible in Quiet, talkers who were most and least intelligible in quiet listening conditions were not necessarily the talkers who were most and least intelligible under CI-simulated listening conditions.

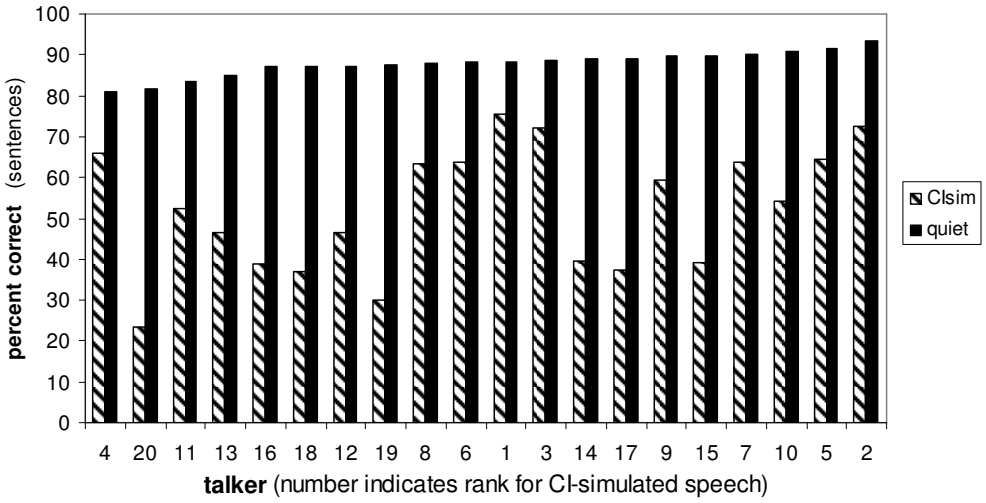

Figure 1: Comparison of intelligibility scores in quiet and under CI-simulated listening conditions. Talkers are ordered on the x-axis by their intelligibility in quiet. The intelligibility of talkers in the quiet and under CI-simulation was not correlated.

Gender Differences. The data from the CI simulation condition revealed that female talkers are more intelligible than their male counterparts. Using keywords correct as the dependent variable, female talkers (mean = 84%, SD = 11) were significantly more intelligible than male talkers (mean = 77%, SD = 11; t(198)=4.61, p<0.001). This is consistent with the findings of a gender difference in speech intelligibility in the Quiet condition.

Perceptual Attunement. In addition to overall intelligibility, the adaptation to the CI-simulated speech was assessed by examining improvement from the first 20 sentences to the last 20 sentences, a measure of perceptual attunement. This analysis was conducted using keywords correct as the dependent variable, and revealed rapid adaptation, with significantly more keywords correct in the last 20 sentences (mean = 84%, SD = 11) than in the first 20 sentences (mean = 73%, SD = 15; t(199)=16.6, p<0.001). Thus, listeners rapidly adapted to the CI simulated speech from all talkers without explicit feedback. Additionally, we found a great deal of variation in the extent of adaptation across talkers, with proportion improvement ranging from 0.21 to 0.56. These data are shown in Figure 2, sorted by the Karl and Pisoni (1994) measure of intelligibility in quiet. The rank-ordered correlation[3] between attunement scores and intelligibility in quiet was not significant (rho = 0.023, *n.s.*) indicating that the talkers with the greatest attunement were not necessarily the talkers with the highest intelligibility scores in quiet.

[3] We used a rank-ordered correlation because the two dependent variables are on different scales, with the Karl and Pisoni (1994) data measured in sentences correct and percent attunement in the CI simulation condition based on keywords correct.

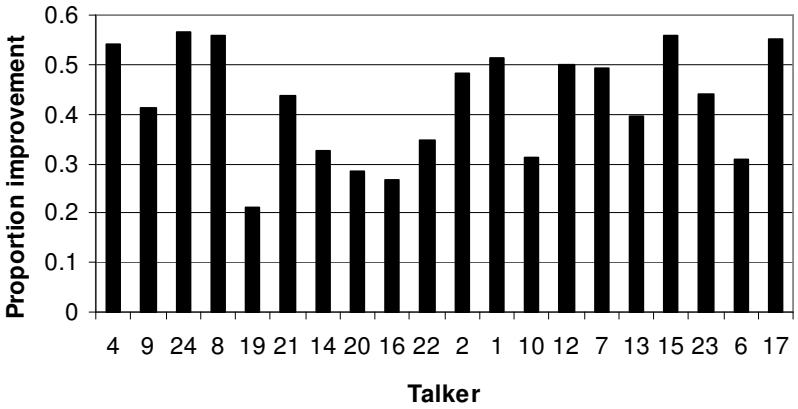

Figure 2: Proportion improvement from first 20 sentences to final 20 sentences for CI-simulated listening conditions. Talkers are ordered on the x-axis by their intelligibility in quiet. While listeners adapted to the speech from all talkers, the extent of adaptation depended on the particular talker.

Intelligibility of Speech Mixed with Multi-Talker Babble

Comparison to Quiet and CI Simulation. The sentence intelligibility scores in babble were compared with the sentence intelligibility scores under quiet listening conditions (from Karl & Pisoni, 1994). As with the CI-simulated intelligibility scores, the intelligibility scores in the babble condition were not correlated with the scores from the quiet listening condition (r=0.36, *ns*). This result indicates that talkers who were highly intelligible in quiet were not necessarily highly intelligible under noisy listening conditions. Comparisons of individual talker scores in the babble condition and in quiet are shown in Figure 3, sorted by intelligibility in quiet.

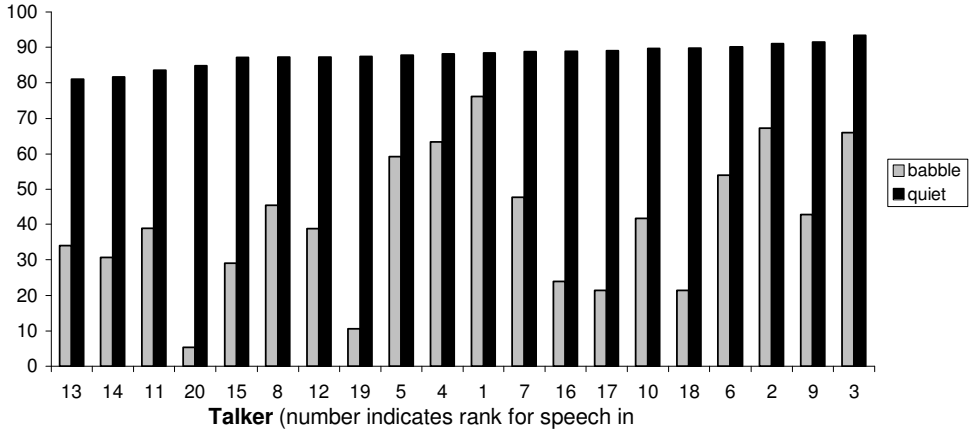

Figure 3: Comparison of sentence intelligibility scores in quiet and in noisy listening conditions (i.e. speech mixed with multi-talker babble). Talkers are ordered on the x-axis by their intelligibility in quiet. Scores in the quiet and babble conditions are not significantly correlated.

We also compared the intelligibility scores from the two experimental conditions: CI Simulation and Babble. This analysis was conducted using keyword accuracy as the dependent variable, as this finer grained measure is more appropriate; although ceiling effects were observed with keyword accuracy under quiet listening conditions, keyword intelligibility scores were not at ceiling in either of the

degradation conditions. The keyword accuracy scores for the CI-simulated condition and the babble condition were significantly correlated (r=0.73, $p < 0.001$). Therefore, while intelligibility under quiet listening conditions was not significantly correlated with intelligibility in either of the two experimental conditions, the CI simulation intelligibility scores were significantly correlated with the Babble intelligibility scores, suggesting that acoustic-phonetic parameters that promote intelligibility under one type of degradation may also promote intelligibility with the other type of degradation. Comparisons of keyword intelligibility scores in the two degradation conditions are shown in Figure 4.

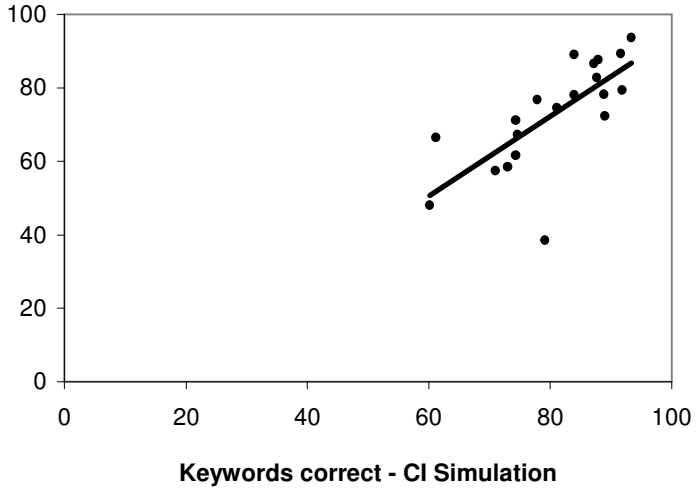

Figure 4: Comparison of keyword intelligibility for the two degradation conditions, CI-simulated speech and speech mixed with babble. Intelligibility scores under these two conditions were significantly correlated.

Gender Differences. The data from the Babble condition revealed that female talkers were more intelligible than their male counterparts in this listening condition. Using keywords correct as the dependent variable, female talkers (mean = 81%, SD = 14) were significantly more intelligible than male talkers (mean = 65%, SD = 13; $t(198)=8.47$, $p < 0.001$). This is consistent with the findings of a gender difference in speech intelligibility in the Quiet and CI Simulation conditions.

Perceptual Attunement. As with the CI simulation condition, perceptual adaptation to the speech in the Babble condition was assessed by examining improvement from the first 20 sentences to the last 20 sentences, a measure of perceptual attunement. This analysis was conducted using keywords correct as the dependent variable, and revealed rapid adaptation, with significantly more keywords correct in the last 20 sentences (mean = 75%, SD = 13) than in the first 20 sentences (mean = 69%, SD = 16; $t(19)=6.45$, $p<0.001$). Overall, listeners rapidly adapted to the speech from all talkers without explicit feedback. Additionally, a large amount variation was observed in the extent of adaptation for the talkers, with proportion improvement ranging from 0.01 to 0.40. These data are shown in Figure 5, sorted by the Karl and Pisoni (1994) measure of intelligibility in quiet. A rank-ordered correlation indicated that the talkers with the greatest attunement were not correlated with the talkers with the highest intelligibility scores in quiet (rho = -0.12).

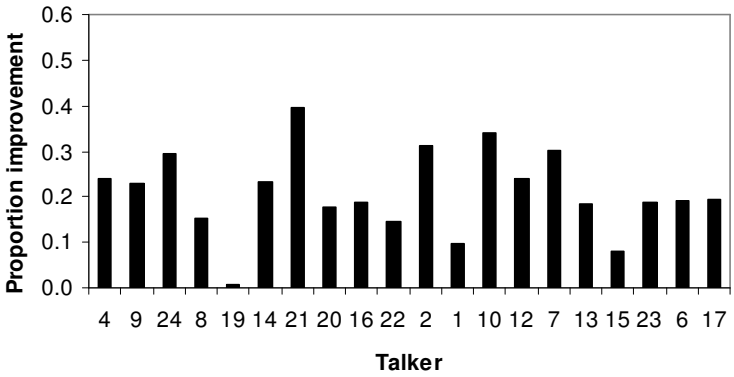

Figure 5: Proportion improvement from first 20 sentences to final 20 sentences for speech mixed with multi-talker babble. While listeners adapted to the speech from all talkers, the extent of adaptation depended on the particular talker.

In addition to comparing the perceptual adaptation in Babble to intelligibility in Quiet, we also compared the extent of adaptation in the two degradation conditions. A paired t-test revealed that listeners showed greater perceptual attunement improvement in the CI-simulated listening condition (mean = 0.43, SD = 0.11) than in the babble condition (mean = 0.21, SD = 0.09; $t(38) = 6.66$, $p<0.001$). However, the extent of adaptation in the two conditions was not correlated ($r=0.18$, *n.s.*).

Correlations among Acoustic-Phonetic Parameters and Intelligibility

To determine whether the acoustic-phonetic parameters that correlate with intelligibility in the Quiet condition also correlate with intelligibility under degraded conditions, the keyword intelligibility scores for the two degradation conditions were correlated with a variety of global acoustic-phonetic parameters measured from these sentences: fundamental frequency range (F0 range), mean fundamental frequency (F0 mean), vowel dispersion, first formant range (F1 range), second formant range (F2 range), and sentence duration. These measures were reported in Bradlow et al. (1996). We reanalyzed the data from Bradlow et al. using Pearson correlations rather than the Spearman correlations that they reported since we believe comparing the numerical values rather than rank orderings is more appropriate. With this reanalysis, under quiet listening conditions there were trends for F0 range and F0 mean to correlate with sentence intelligibility. No other acoustic-phonetic parameter was significantly correlated with intelligibility.

The parameters that showed a trend to correlate with intelligibility in quiet also tended to be correlated with intelligibility under the two degradation conditions. F0 range, which showed a trend to correlate with intelligibility in quiet, was significantly correlated with intelligibility under the CI-simulated conditions, ($r=0.549$, $p < 0.05$) and in the babble condition ($r=0.71$, $p < 0.001$). F0 mean, which also showed a trend to correlate with intelligibility in quiet, showed a trend for a correlation with intelligibility under CI-simulation ($r=0.361$, $p = 0.12$) and was significantly correlated in the babble condition ($r=0.58$, $p < 0.01$). F1 range which was not significantly correlated with intelligibility in quiet showed a trend to be correlated with intelligibility under CI simulation ($r=0.435$, $p = 0.06$) and was significantly correlated with intelligibility in babble ($r=0.53$, $p < 0.05$). F2 range and sentence duration were not correlated with intelligibility in any of the three listening conditions.

For the correlations between vowel dispersion and intelligibility, in addition to using overall intelligibility scores, intelligibility was measured with just a subset of sentences that included the point vowels (i.e., /i, a, o/) (see Bradlow et al. (1996) for more specifics). /o/ was chosen as the back vowel

rather than /u/ due to the high degree of allophonic variation in American English for this phoneme. In all three listening conditions, overall intelligibility did not correlate with vowel dispersion. In quiet, intelligibility for the 18 sentence-subset was not correlated with vowel dispersion. For the CI-simulated listening conditions, there was a trend for a correlation between keyword intelligibility and vowel dispersion (r=0.42, p = 0.07) while for the babble condition the correlation was not significant (r=0.04, *ns*). A summary of these results is shown in Table 1.

	Listening condition		
Acoustic measure	**Quiet**	**CI Simulation**	**Babble**
F0 range	0.39[t]	0.55*	0.71**
F0 mean	0.40[t]	0.36	0.58**
F1 range	0.32	0.44[t]	0.53*
F2 range	0.09	0.25	0.18
Vowel dispersion (all sentences)	0.11	0.37	0.05
Vowel dispersion (18 sentences)	0.27	0.42[t]	0.04
Sentence duration	-.01	0.33	0.34

Table 1: Correlations between acoustic-phonetic parameters and intelligibility in the three listening conditions (Quiet, CI-simulation and Babble). Correlation values are listed with asterisks indicating significance levels: one asterisk indicates a p-value of 0.05 or less, two asterisks indicates a p-value of 0.01 or less and a "t" indicates a trend with a p-value of 0.10 or less.

In both degradation conditions, talkers differed substantially in the degree to which listeners could adapt to their speech. The same acoustic-phonetic parameters that were correlated with intelligibility were also correlated with the proportion improvement scores to assess if certain acoustic-phonetic parameters can explain the large range in the extent of adaptation for individual talkers. For the CI-simulated listening conditions, vowel dispersion (r=0.46, $p < 0.05$) and F2 range (r=0.45, $p < 0.05$) correlated with proportion improvement whereas for the speech mixed with babble condition, none of the measured acoustic-phonetic parameters correlated with the proportion improvement scores.

Discussion

Results from the current study provide clear and consistent evidence that differences in intelligibility among talkers are not absolute; rather, inter-talker intelligibility scores are strongly dependent on the characteristics of the listener (CI simulation) and of the listening environment (Babble). This overall pattern converges with previous studies examining relative intelligibility among talkers, indicating that intelligibility rankings may change depending on listener language background (Bent & Bradlow, 2003; Imai et al., 2003; van Wijngaarden, 2001; van Wijngaarden et al., 2002). We add to this literature by demonstrating that other characteristics of the listener and the listening environment affect talker intelligibility. Our findings diverge from those of Green et al. (2007) who suggest that inter-talker differences are maintained across different listener groups (i.e., CI users, normal-hearing listeners presented with speech in a low level of babble or with CI simulated speech). The discrepancy between the current results and their results may be primarily due to the small number of talkers they tested who demonstrated intelligibility scores at the high and low ends of the intelligibility distribution. That is, we may expect that talkers of particularly high or low intelligibility in quiet (or very favorable signal to noise ratios as with Green et al.) will also be of high and low intelligibility for CI listeners or in CI simulated listening conditions as can be seen for talkers 17 and 6 in our study who were the top two most intelligible talkers in the quiet and were 2nd and 5th most intelligible in CI simulated listening conditions.

On the other hand, talkers with more moderate intelligibility scores may show more variation across different listener populations and listening environments, as is the case for talkers 10 and 2 in our study who were 8th and 10th most intelligible in quiet but were 14th and 1st most intelligible in CI simulated listening conditions. Furthermore, while intelligibility was tested here with sentences, Green et al. used word length materials. It remains possible that the factors that make words more or less intelligible may be more consistent across listener groups and listening conditions than the factors that influence sentence intelligibility. Future studies should test both word and sentence intelligibility for a large number of talkers to assess how the type of linguistic material interacts with talker characteristics.

The results of the Babble condition reveal that intelligibility under quiet listening conditions is not correlated with intelligibility under noisy listening conditions. However, the extent to which this result can be extended to other types of signal degradation remains an empirical issue. It is worth noting that the finding of a strong correlation between the two signal degradation conditions suggests the existence of features that enhance intelligibility in a wide range of difficult listening conditions. Significant correlations (or trends) between intelligibility and several of the acoustic-phonetic parameters measured (i.e., F0 range and F1 range) in both degradation conditions also suggest that certain acoustic-phonetic parameters may be important for enhancing intelligibility in multiple difficult listening situations.

Although mixing speech with babble is typically considered an ecologically valid noise-addition process, it should be noted that the same recordings – collected in quiet conditions – were used in the quiet and noise-added listening conditions. Therefore, modifications which talkers make when they are in noisy environments (e.g., Lombard speech, Lombard, 1911) are not performed in these recordings. It may be the case that certain talkers are more effective at making modifications that help listeners in noisy environments when they are producing speech with noise present. This issue remains a topic for future research.

The remainder of this section explores several issues raised by the data reported here. In particular, we address the issue of the acoustic-phonetic parameters that facilitate speech intelligibility, and discuss gender differences, perceptual adaptation, and the potential clinical implications of this work.

Acoustic-Phonetic Parameters

Three types of acoustic-phonetic parameters were examined in this study: those relating to fundamental frequency, vowel space characteristics, and measures of duration. Previous studies (Bond & Moore, 1994; Bradlow et al., 1996; Hazan & Markham, 2004) have measured other acoustic-phonetic parameters such as total energy in specific frequency regions, amplitude characteristics and specific cues to consonant contrasts. The comparison of the results from the current study with previous studies suggests that the particular talkers and materials used in a study may influence the acoustic-phonetic parameters that are significantly correlated with intelligibility. Furthermore, Hazan and Markham (2004) as well as studies investigating the acoustic-phonetic correlates of clear speech (Bradlow, Kraus & Hayes, 2003) suggest that speakers may be able to achieve highly intelligible speech through the manipulation of different combinations of acoustic-phonetic characteristics.

The results reported above support the claim that the acoustic-phonetic properties of a talker's speech that enhance intelligibility differ to some extent when listener and listening environment characteristics are changed. That is, only F0 range was correlated with intelligibility both for normal-hearing listeners in quiet listening conditions and under CI simulation, while others were only correlated with intelligibility under CI-simulation (F1 range and vowel dispersion). Similarly, F0 range was also correlated with intelligibility in the Babble condition as were F0 mean and F1 range, but vowel dispersion was not correlated with intelligibility in this condition.

In comparison with previous studies, fundamental frequency characteristics were a larger factor in the determination of speech intelligibility in the current study. In particular, both Hazan and Markham (2004) and Bond and Moore (1994) failed to find the correlations between fundamental frequency characteristics and intelligibility that were reported above. The other large discrepancy between the current study and previous studies came from measures of sentence or word duration. In the current study, as well as in Bradlow et al. (1996), intelligibility was not correlated with sentence duration. However, both Hazan and Markham (2004) and Bond and Moore (1994) found correlations between word duration and intelligibility. Because in naturally produced speech speakers manipulate multiple acoustic-phonetic parameters at the same time, it is difficult to definitively determine which parameters are most essential for highly intelligible speech. Future studies should, therefore, assess the contribution of individual acoustic-phonetic parameters by synthetically manipulating them and determining how changes in each parameter affect intelligibility. Furthermore, future studies should address how these synthetic manipulations interact with the linguistic materials (e.g., comparing words and sentences).

Perceptual Attunement

Listeners are able to quickly adapt their internal speech categories to more accurately perceive speech in a variety of different listening conditions. For example, listeners can adjust their category boundaries for phoneme contrasts (e.g., Eisner & McQueen, 2005). Also, listeners have shown both talker-dependent and talker-independent perceptual learning of speech such that experience or training with specific talkers, talker populations or synthesis conditions improves listeners' ability to accurately identify words from familiar talkers (e.g., Nygaard & Pisoni, 1998), new talkers from the same special population as they were exposed to in training (e.g., Bradlow & Bent, in press; McGarr, 1983) or speech that has been degraded in the same way as the training materials (e.g., Schwab, Nusbaum & Pisoni, 1985; Davis et al., 2005). Investigating listeners' adaptation to new talkers or speech patterns and the conditions that allow for this adaptation provides information about the extent of neural plasticity in the speech perception system. Furthermore, testing the conditions under which the most learning occurs can potentially help in the development of training programs for listeners with speech perception difficulties such as the hearing impaired or second language learners.

In the present experiment, the analysis of adaptation to the degraded speech revealed the flexibility of the speech perception system. Even in the absence of feedback, listeners interpreted the talker's utterances more accurately after several minutes of exposure to the experimental stimuli (i.e., last 20 sentences) compared to the beginning of exposure to these stimuli (i.e., first 20 sentences). The extent of adaptation varied for each talker and in each type of degradation, but the present data did not allow us to determine the source of this variability.

In the present research, the correlation between proportion improvement for each talker in the two degradation conditions was not significant. In addition, the analyses examining the relationship between perceptual attunement and acoustic-phonetic properties of the speaker did not yield conclusive results, and there was not a significant correlation between a talker's intelligibility in quiet and the perceptual attunement on that talker's speech in the experimental conditions. Furthermore, the extent of adaptation did not depend on overall intelligibility as proportion improvement was not correlated with overall intelligibility scores in either degradation condition. This result differs from the findings regarding adaptation to foreign accented speech (Bradlow & Bent, in press) in which listeners were better able to adapt to individual talkers who demonstrated high overall intelligibility than talkers of low intelligibility.

One likely cause of the greater adaptation in the CI Simulation condition compared to the Babble condition is the novelty of the former type of degradation. The listeners in the study had never experienced CI Simulated listening conditions before participating in the experiment, but each listener has

perceived speech with competing talkers daily. Thus, listeners are already practiced at picking out a given talker in noisy listening environments that are similar to the Babble condition, and must only adapt to the specifics of the multi-talker babble added to the speech in the experiment. We suggest here that this leaves listeners with less room to improve in the Babble condition than in the CI Simulation condition.

It is worth noting that the listeners in this experiment did not receive feedback, which suggests that they could have taken advantage of semantic and syntactic cues to enable them to learn how to perceive the speech under the two degradation conditions. It remains an open question whether perceptual learning would be as robust with anomalous sentences or nonsense words.

Gender

Previous studies have found that for normal-hearing adult and child listeners, adult female talkers are more intelligible than adult male talkers (Bradlow et al., 1996; Hazan & Markham, 2004). This result was consistent across different types of materials (i.e., both words and sentences).

The findings from the current study are consistent with previous results and support the claim that female talkers tend to be more intelligible then male talkers. The present study adds to the previous data by demonstrating that this result holds in a variety of listening environments (quiet and Babble) and for different listener populations (normal-hearing listeners and CI Simulation).

The source of this difference is not known at this point. It is possible that female talkers are generally more intelligible than their male counterparts because of physical differences in the vocal tracts For example, the higher mean fundamental frequency for most female talkers compared to male talkers will result in wider spacing of their vowel formants. This increased spacing between formants may lead to fewer formants being collapsed into one spectral channel that would presumably hinder vowel intelligibility. However, it remains possible that the gender differences come from a learned source of behavior. For example, female talkers could make articulatory adjustments that result in more intelligible speech. If this latter type of explanation is the source of this difference, it would suggest that male talkers may be able to be taught to alter their articulatory patterns to increase their intelligibility. It is clear that more work is critical to resolving this issue.

Cochlear Implant Users

One of the practical goals of this research was to develop strategies to increase the intelligibility of speech for listeners who have particular difficulty in speech communication. The current findings suggest several modifications that talkers could make when communicating with a CI user, and clinicians could make these suggestions to the family members and friends of cochlear implant recipients. First, talkers should be encouraged to increase their fundamental frequency range. Second, talkers should increase the distances between vowel categories. They can be instructed to do this by being told to speak clearly as tests of clear speech have shown that talkers tend to have greater vowel dispersion in clear speech than conversational speech (e.g. Bradlow, 2002). According to the findings from this study, talking at a slower speaking rate will not be particularly helpful to CI users. Liu et al (2004) also found that sentence produced in a clear speaking style were more intelligible to CI users than those produced in a conversational style. However, note that while generally clear speech is more intelligible to hearing impaired listeners (Picheny, Durlach & Braida, 1985), Ferguson and Kewley-Port (2002) found that certain clear speech modifications to vowels can actually be detrimental to hearing impaired listeners.

While the finding that normal-hearing listeners in quiet and listeners under CI simulated listening conditions find different talkers more and less intelligible is suggestive, it is necessary to test the validity of this approach by testing CI-users with the same stimuli. We currently have a study underway to test

whether the talkers who are of high and low intelligibility under CI-simulation will also be of high and low intelligibility for CI-users.

Conclusion

The current study suggests that intelligibility minimally needs to be characterized by a combination of talker-, listener- and listening environment- factors. This conclusion is in contrast to those studies that have suggested that acoustic-phonetic features of a talker's voice are the primary determinants of intelligibility levels (e.g. Hazan & Markham, 2004; Green et al., 2007). Furthermore, the acoustic-phonetic correlation analysis here suggests that while certain parameters may be beneficial for a wide range of listeners and listening environments, the importance of other parameters may vary depending on the listener and listening environment. Lastly, listeners were shown to adapt rapidly to speech in both the CI simulated and Babble conditions although the extent of adaptation differed widely across talkers.

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Appendix A

1. The birch canoe slid on the smooth planks.
2. Glue the sheet to the dark blue background.
3. It's easy to tell the depth of a well.
4. These days a chicken leg is a rare dish.
5. Rice is often served in round bowls.
6. The juice of lemons makes fine punch.
7. The box was thrown beside the parked truck.
8. The hogs were fed chopped corn and garbage.
9. Four hours of steady work faced us.
10. Large size in stockings is hard to sell.
11. The boy was there when the sun rose.
12. A rod is used to catch pink salmon.
13. The source of the huge river is the clear spring.
14. Kick the ball straight and follow through.
15. Help the woman get back to her feet.
16. A pot of tea helps to pass the evening.
17. Smoky fires lack flame and heat.
18. The soft cushion broke the man's fall.
19. The salt breeze came across from the sea.
20. The girl at the booth sold fifty bonds.
21. The small pup gnawed a hole in the sock.
22. The fish twisted and turned on the bent hook.
23. Press the pants and sew a button on the vest.
24. The swan dive was far short of perfect.
25. The beauty of the view stunned the young boy.
26. Two blue fish swam in the tank.
27. Her purse was full of useless trash.
28. The colt reared and threw the tall rider.
29. It snowed, rained, and hailed the same morning.
30. Read verse out loud for pleasure.
31. Hoist the load to your left shoulder.
32. Take the winding path to reach the lake.
33. Note closely the size of the gas tank.
34. Wipe the grease off his dirty face.
35. Mend the coat before you go out.
36. The wrist was badly strained and hung limp.
37. The stray cat gave birth to kittens.
38. The young girl gave no clear response.
39. The meal was cooked before the bell rang.
40. What joy there is in living.
41. A king ruled the state in the early days.
42. The ship was torn apart on the sharp reef.
43. Sickness kept him home the third week.
44. The wide road shimmered in the hot sun.
45. The lazy cow lay in the cool grass.
46. Lift the square stone over the fence.
47. The rope will bind the seven books at once.
48. Hop over the fence and plunge in.
49. The friendly gang left the drug store.

50. Mesh wire keeps chicks inside.
51. The frosty air passed through the coat.
52. The crooked maze failed to fool the mouse.
53. Adding fast leads to wrong sums.
54. The show was a flop from the very start.
55. A saw is a tool used for making boards.
56. The wagon moved on well oiled wheels.
57. March the soldiers past the next hill.
58. A cup of sugar makes sweet fudge.
59. Place a rosebush near the porch steps.
60. Both lost their lives in the raging storm.
61. We talked of the side show in the circus.
62. Use a pencil to write the first draft.
63. He ran half way to the hardware store.
64. The clock struck to mark the third period.
65. A small creek cut across the field.
66. Cars and busses stalled in snow drifts.
67. The set of china hit, the floor with a crash.
68. This is a grand season for hikes on the road.
69. The dune rose from the edge of the water.
70. Those words were the cue for the actor to leave.
71. A yacht slid around the point into the bay.
72. The two met while playing on the sand.
73. The ink stain dried on the finished page.
74. The walled town was seized without a fight.
75. The lease ran out in sixteen weeks.
76. A tame squirrel makes a nice pet.
77. The horn of the car woke the sleeping cop.
78. The heart beat strongly and with firm strokes.
79. The pearl was worn in a thin silver ring.
80. The fruit peel was cut in thick slices.
81. The Navy attacked the big task force.
82. See the cat glaring at the scared mouse.
83. There are more than two factors here.
84. The hat brim was wide and too droopy.
85. The lawyer tried to lose his case.
86. The grass curled around the fence post.
87. Cut the pie into large parts.
88. Men strive but seldom get rich.
89. Always close the barn door tight.
90. He lay prone and hardly moved a limb.
91. The slush lay deep along the street.
92. A wisp of cloud hung in the blue air.
93. A pound of sugar costs more than eggs.
94. The fin was sharp and cut the clear water.
95. The play seems dull and quite stupid.
96. Bail the boat, to stop it from sinking.
97. The term ended in late June that year.
98. A tusk is used to make costly gifts.
99. Ten pins were set in order.
100. The bill as paid every third week.