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**Perception of “Elliptical Speech” by an Adult Hearing-Impaired Listener with
a Cochlear Implant: Some Preliminary Findings on
Coarse-Coding in Speech Perception¹**

Rebecca Herman and David B. Pisoni²

*Speech Research Laboratory
Department of Psychology
Indiana University
Bloomington, Indiana 47405*

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² Also DeVault Otologic Research Laboratory, Department of Otolaryngology–Head & Neck Surgery, Indiana University School of Medicine, Indianapolis, IN.

Perception of “Elliptical Speech” by an Adult Hearing-Impaired Listener with a Cochlear Implant: Some Preliminary Findings on Coarse-Coding in Speech Perception

Abstract. This paper examines the effects of elliptical speech (Miller & Nicely, 1955) on the speech perception performance of an adult hearing-impaired listener with a cochlear implant. A group of 20 normal-hearing adult listeners were used for comparison. Two experiments were carried out using sets of normal and anomalous English sentences. Two versions of each set of sentences were constructed. One version retained normal place of articulation; the other was converted to “elliptical speech” using a procedure in which different places of articulation were all converted to the same alveolar place of articulation. The patient completed a same-different task and a transcription task. The normal-hearing listeners completed the same tasks, but with noise-masking or low-pass filtering used to degrade the signal. In the same-different task, we found that normal-hearing listeners under conditions of signal degradation tended to label a sentence with normal place of articulation and its elliptical version as the “same.” The hearing-impaired listener with the cochlear implant also tended to label a sentence with normal place of articulation and its elliptical version as the “same.” Results provide support for Miller and Nicely’s claim that under conditions of signal degradation, the ellipsis can no longer be detected. In the transcription task, however, normal-hearing subjects showed better transcription performance for sentences with normal place of articulation than for “elliptical” speech sentences, which was an unexpected result given our findings in the first experiment. The patient with the cochlear implant also showed better transcription performance for sentences with normal place of articulation than for “elliptical” speech, which was also unexpected. The implications of these findings for how cochlear implant users perceive speech and recognize spoken words are discussed.

Introduction

One fundamental question in research on cochlear implants deals with what speech sounds like to users of cochlear implants. It is known that patients with cochlear implants often do not do well on open-set tests of word recognition in which the listener hears a word and has to identify it from a large number of words in his/her entire lexicon. Many of the confusions shown by users of cochlear implants are confusions of place of articulation in consonants. However, despite this apparent problem with place of articulation, some users of cochlear implants do very well in face-to-face conversations. How can these two diametrically opposed observations be reconciled?

In Miller and Nicely’s (1955) well-known study, they examined the perceptual confusions in consonants under low-pass filtering of the signal (in which all information above 1 kHz is removed) and under noise masking of the signal (in which the signal is mixed with Gaussian noise). They found that place of articulation was a common confusion under either low-pass filtering or noise masking of the signal. Miller and Nicely explained the patterns of errors by noting that consonants that were confusable under conditions of signal degradation could be considered to represent comparable equivalence classes of a sort. For example, if [p t k] are confusable with each other under some conditions of signal degradation, then one could argue that these sounds form a common equivalence class. Miller and Nicely suggested that a single member of each equivalence class could be chosen as a representative of that class, (such as [t], out of the class [p t k]). Now if speech were produced in which each representative sound replaced any other individual member of its equivalence class, then that speech would sound quite strange in the clear. They refer to this type of degradation as “elliptical speech,” because of the ellipsis, or leaving

out, of place of articulation information. For example, if speech were produced in which every [p t k] were simply replaced by a [t], that speech would sound very odd in the clear. However, they further note that if this so-called “elliptical” speech is now played back under conditions of noise-masking or filtering, then the ellipsis should be undetectable because the members of the equivalence class were found to be equivalent under exactly those degradation conditions. Miller and Nicely report informally that this is the case, although they never presented a complete experiment to demonstrate this phenomenon (Miller & Nicely, 1955; Miller, 1956).

Recently, Quillet, Wright and Pisoni (1998) noted the possible parallels in speech perception between normal hearing-listeners under conditions of signal degradation and patients with cochlear implants. Just as normal-hearing listeners show systematic confusions among different places of articulation under conditions of signal degradation, cochlear implant users also show confusions among places of articulation. Quillet et al. suggested that it might be possible to use “elliptical” speech to probe cochlear implant users’ perception of speech and understand how they often do so well even with highly impoverished input signals. If “elliptical” speech is undetectable as elliptical for normal-hearing listeners under conditions of signal degradation, then perhaps it will also be undetectable as elliptical for cochlear implant users as well, providing support for the use of broader equivalence classes for place of articulation in the speech perception of users of cochlear implants.

Quillet et al. attempted to replicate Miller and Nicely’s finding that “ellipsis” of place of articulation under conditions of signal degradation is undetectable as ellipsis with a same-different task. Normal-hearing listeners heard pairs of sentences and had to judge whether the two sentences were the same or different. Listeners heard pairs of sentences in which the two sentences were either lexically the same or lexically different. In one condition, both sentences in a pair had normal place of articulation. In the second condition, both sentences in a pair were transformed into “elliptical” speech. In the third condition, one sentence in a pair had normal place of articulation and the other had “elliptical” speech. The crucial case in their experiment was the last condition in which the two sentences were lexically identical, but one sentence had normal place of articulation and the other had an “elliptical” speech version of the sentence. In this case, normal-hearing listeners were expected to label the two sentences as “different” when heard in the clear. If Miller and Nicely’s phenomenon can be replicated, then normal-hearing listeners should label this pair of sentences as the “same” when heard under degraded conditions. In fact, Quillet et al. did find that in the clear, listeners identified the majority of such pairs as “different.” Furthermore, they found that under signal degradation using random-bit-flip noise, listeners identified a majority of these pairs as the “same,” indicating that the ellipsis of place of articulation was not detected by the listeners in these cases. Listeners seemed to perceive speech in terms of broad phonetic categories under conditions of degradation such as bit-flipped noise.

In order to probe whether “elliptical” speech is undetectable as elliptical to users of cochlear implants, the first experiment in this report used a same-different task similar to the one described above. Pairs of sentences were presented to an adult patient with a cochlear implant, and he was asked to judge whether the two sentences were the same or different. Again, the two sentences in the pair were either lexically the same or lexically different. In one condition, both sentences in a pair had normal place of articulation. In the second condition, both sentences in a pair were converted into “elliptical” speech. In the third condition, one sentence had normal place of articulation and the other had “elliptical” speech. Again, the crucial test case is the third condition in which the two sentences were lexically identical, but one had normal place of articulation and the other had an “elliptical” speech version of the sentence. In this case, we predicted that the patient with the cochlear implant would label the two sentences as the “same.” If indeed the patient labels the two sentences in this condition as the “same,” then this response pattern implies that consonants with the same manner and voicing features but different places of articulation form an equivalence class (are treated as functionally the same) and that the patient is

recognizing words in context using broad phonetic categories. This pattern of results would suggest that patients with cochlear implants hear speech as a sequence of familiar words and do not detect fine phonetic differences.

Up to this point, the discussion has centered on what speech might sound like to users of cochlear implants, and thus what obstacles might have to be overcome to achieve lexical recognition. A second question we are interested in concerns why some users of cochlear implants manage to do quite well in face-to-face conversations despite the degraded input they receive through their implants. One explanation for their good performance in face-to-face conversations is the observation that there are powerful constraints on sound patterns found in the lexicon (Shipman & Zue, 1982; Zue & Huttenlocher, 1983). For example, Zue and Huttenlocher (1983, p. 122) argue that the sound patterns in spoken languages are constrained not only by the inventory of sounds in a particular language but also by the “allowable combinations of those sound units,” or the phonotactic constraints of a given language. Shipman and Zue note that an analysis of English which distinguishes only between consonants and vowels can prune a 20,000 word lexicon down to less than 1%, given just the CV pattern of a given word. Since these strong constraints on sound patterns do exist, a very broad phonetic classification can serve to define the “cohort,” or the set of possible candidate words having the same pattern. As Shipman and Zue showed in their computational research, these candidate sets may be quite small, such that the “average size for these equivalence classes for the 20,000-word lexicon was found to be approximately 2, and the maximum size was approximately 2000.” (Zue & Huttenlocher, p. 122) Thus, even if a listener does not accurately perceive the exact place of articulation, he or she can still recognize the word using broad equivalence classes if he or she can recognize at least the sequence of consonants and vowels in the pattern.

Does coarse coding of the speech signal provide a rich and sufficient enough set of cues to allow normal-hearing listeners to understand what is being said in an utterance? In order to answer this question, Quillet et al. used a transcription task with normal-hearing listeners. In this task, listeners were asked to transcribe three of the five key words from each sentence. The sentences had either normal place of articulation or were produced using “elliptical” speech. The sentences were presented in the clear or in white noise at 0 dB SNR, -5 dB SNR, and -10 dB SNR. Quillet et al. predicted that while speech with normal place of articulation should show decreased intelligibility under conditions of noise-masking or low-pass filtering, “elliptical” speech should actually show the reverse pattern, that is, increased intelligibility as distortion of the signal increased. In their study, they found that speech with normal place of articulation did show decreases in transcription accuracy under conditions of signal degradation whereas the “elliptical” speech showed improvements in transcription accuracy from the 0 dB SNR level to the -5 dB SNR level before dropping at the -10 dB SNR level. Quillet et al. interpreted this finding as support for the proposal that normal-hearing listeners use broad phonetic categories to identify words in sentences under these conditions.

In order to explore whether coarse coding and broad phonetic categories are used by patients with cochlear implants, we carried out a second experiment in which the patient with the cochlear implant was asked to transcribe three key words in a sentence, similar to the experiment described above. Sentences were presented to the cochlear implant patient, and he was asked to transcribe three of the five key words in the sentence. Half of the sentences were produced using “elliptical” speech and half were normal sentences. Our prediction was that the patient with the cochlear implant would show the same transcription performance on sentences with normal place of articulation as he would on sentences produced with “elliptical” speech. If he did show similar transcription performance in these two cases, this pattern would indicate that coarse coding was a sufficient cue for lexical recognition to be carried out with spoken sentences.

Experiment 1: Same-different Task

Experiment 1 employed a same-different discrimination task. Subjects listened to pairs of sentences and categorized the pair as “same” or “different.” Subjects were told to label the pair of sentences as “same” if the two sentences that they heard were word-for-word and sound-for-sound identical or “different” if any of the words or speech sounds differed between the two sentences. Normal-hearing listeners have been found to label normal and elliptical versions of lexically identical sentences as the “same” under conditions of signal degradation. Also, there are parallels in confusions in place of articulation between normal-hearing listeners under conditions of signal degradation and listeners with cochlear implants. Thus, we predicted that our patient with a cochlear implant would label the normal and elliptical versions of the same sentence as the “same.”

Stimulus Materials

Normal Harvard Sentences. The stimulus materials consisted of 96 Harvard Sentences (IEEE, 1969) taken from lists 1-10 (Egan, 1948). These are English sentences made up of five key words with declarative or imperative structure. Quillet et al. used the same stimulus materials in their experiments.

Anomalous Harvard Sentences. Anomalous sentences were used in this experiment to prevent top-down semantic processing of these sentences. Ninety-six Anomalous Harvard sentences were created by substituting random words of the same lexical category (noun, verb, etc.) into lists 11-20 of the Harvard sentences. The inserted words were selected from lists 21-70 of the Harvard sentences (with five lists being used to supply replacement words for each list). This differs from Quillet et al.’s methodology, in which only normal Harvard sentences were used.

“Elliptical” Speech. Several new sets of “elliptical” sentences were generated through a process of featural substitution similar to that employed by Miller and Nicely. The stops, fricatives, and nasal consonants in each of the five key words were replaced with a new consonant that preserved the same manner and voicing features of the original consonant but changed the place feature to an alveolar place of articulation. Liquids /r l/ and glides /y w/ were excluded from the substitution process. The normal sentences and the elliptical versions are listed in the Appendix. Several examples are given in (1) below, with the key words underlined.

- (1) a. A wisp of cloud hung in the blue air.
A wist of tlood hund in the dlue air.
- b. Glue the sheet to the dark blue background.
Dlue the seet to the dart dlue datdround.

This method of replacing consonants with alveolar consonants follows Miller and Nicely’s original method of creating “elliptical” speech and differs from the methodology used by Quillet et al. They followed Miller (1956) by replacing consonants with consonants randomly selected from within the equivalence class sharing manner and voicing features. An example from Miller is shown in (2), in which it can be seen that the replacement consonants do not all have the same alveolar place of articulation:

- (2) a. Two plus three should equal five.
Pooh kluss free soub eatwell size.

In the present study, half of the utterances were spoken by a male speaker and the other half were spoken by a female speaker. Both talkers practiced saying the test sentences several times before the

recording session. An attempt was made to use the same intonation pattern in both versions of an utterance. Sentences were recorded using a head-mounted Shure model SM98A microphone and a Sony TCD-D8 DAT recorder. The recordings were then segmented into individual utterances, converted to a single channel, and downsampled to 22,050 Hz using CoolEdit.™ The use of natural speech stimuli in this study differs from Quillet et al.'s 1998 procedure, which used synthetic speech for all of their stimuli, which were generated using DECtalk.

Signal Degradation

Low-pass Filtering. For the normal-hearing listeners, a new set of stimuli was created from the original recordings. Low-pass filtering was applied to the signal using Matlab. Specifically, the signal-processing tool “Colea” was used (Loizou, 1998). Colea’s “filter tool” was used to apply a 10th order low-pass Butterworth filter with a cutoff of 1000 Hz. This procedure was applied to all of the sentences individually and each was saved as a separate file. Thus, the filtering was done off-line prior to presentation of the stimuli to the listeners.

Noise-masking. Gaussian noise was applied to each sentence to create another set of stimuli. Colea was used for this purpose as well. Noise was added at a –5 dB signal-to-noise ratio. Each noise-masked file was saved as a separate file for use during presentation of the stimuli to the listeners. This procedure also differs from Quillet et al.'s methodology. To degrade their signals, they used different levels of random-bit-flip noise in their same-different task and white noise at three different signal-to-noise ratios in their transcription task.

Subjects

The adult patient with the cochlear implant, “Mr. S,” was 36 years old at the time of testing. He had been profoundly deaf (with an unknown etiology) for 20 months before receiving his implant at age 32. “Mr. S” has participated as a listener in prior studies, and is considered to be an excellent user of his cochlear implant (see also Goh, Pisoni, Kirk, & Remez, 1999; Herman & Clopper, 1999).

Nine normal-hearing listeners were assigned to the low-pass filtered condition and another nine were assigned to the noise-masked condition. All listeners were enrolled in an undergraduate introductory psychology course and received course credit for their participation in this experiment. Listeners ranged in age from 18-22 years old. None of the listeners reported any hearing or speech disorders at the time of testing. All listeners were native speakers of American English.

Procedures

“Mr. S” heard the stimuli over a Harman/Kardon HK 195 loudspeaker. He was given four pre-experiment trials in which he could adjust the volume of the loudspeaker to a comfortable listening level. The experiment was controlled by a Visual Basic program running on a PC that also recorded subject responses. The experiment was self-paced. Each pair of sentences was presented only once. There was a 500 ms interval between the two sentences in each pair. He entered his responses by using the computer mouse to click on a box labeled “same” or a box labeled “different” on the computer monitor. “Mr. S” heard 96 pairs of sentences in four blocks of 24 trials each. He heard a block of normal Harvard sentences spoken by the male speaker, then a block of normal Harvard sentences spoken by the female speaker, then a block of anomalous Harvard sentences spoken by the male speaker, and finally a block of anomalous Harvard sentences spoken by the female speaker. Half were elliptical speech and half were speech with a normal place of articulation.

Normal-hearing subjects followed the same procedure as “Mr. S” except that they heard the stimuli through Beyerdynamic DT 100 headphones at a comfortable listening level of about 70 dB SPL. There was a one-second interval between the two sentences in each pair. (The inter-stimulus interval was changed to one second for the normal-hearing subjects after pilot testing showed that a one-second inter-stimulus interval worked better than a 500 ms inter-stimulus interval. This change was made after testing of “Mr. S” had already taken place, which explains the two different inter-stimulus intervals.) They heard 192 pairs of sentences in a random order. For the normal-hearing listeners, half of the pairs had signal degradation and half were heard in the clear. The signal degradation was either low-pass filtering for one group or noise masking for the other group. The type of signal-degradation used was a between-subjects variable.

All subjects received eight possible types of pairs of sentences, as shown in Table 1. In this report, pairs of sentences that are lexically identical are marked with two subscript “i’s”. Pairs of sentences that are lexically different are marked with a subscript “i” and a subscript “j”. The sentences with normal place of articulation are referred to by “N”. The “elliptical” sentences are referred to by “E”.

	Different sentence	Same sentence
both normal place of articulation:	NiNj	NiNi
both “elliptical” speech:	EiEj	EiEi
one normal, one elliptical	NiEj EiNj	NiEi EiNi

Table 1. The different types of pairs of sentences used in the same-different task.

Results: Normal-hearing Listeners

Normal Harvard Sentences. A summary of the results for “same” responses for the normal-hearing listeners listening to normal Harvard sentences, where the signal degradation was low-pass filtering, is shown in Figure 1. The types of sentence pairings are listed along the X-axis (i.e. NiNj, EiEj). The percent labeled as the “same” is shown along the Y-axis. Sentences heard in the clear are shown with open bars, and sentences heard with low-pass filtering at 1kHz are shown with dark bars.

A 2x2x4 analysis of variance (ANOVA) was carried out. The first factor was “sense,” with the two levels being normal Harvard sentences and anomalous Harvard sentences. (Both normal Harvard sentences and anomalous Harvard sentences are included in the analysis, although they are shown separately in Figures 1 and 3, for convenience so that they may be examined separately.) The second factor was degradation, with the two levels being sentences heard in the clear vs. sentences with low-pass filtering. The third factor was the type of pair, with four levels. This factor, whose levels can be seen in the four different cells in Table 1 or as four pairs along the X-axis in Figure 1, collapsed across orderings. We were interested in whether there was a statistical difference between sentences heard in the clear and sentences heard with low-pass filtering, particularly when one sentence had normal place of articulation and the other sentence was the “elliptical” version of the same sentence. Thus, we grouped together NiNj with EiEj (two different sentences, either both have normal place of articulation or both have “elliptical” speech), NiEj with EiNj (two different sentences, one has normal place of articulation and one has “elliptical” speech), NiNi with EiEi (the same sentence twice, both have normal place of articulation or both have “elliptical” speech), and the crucial test cases of NiEi with EiNi (the same sentence twice, one has normal place of articulation and one has “elliptical” speech).

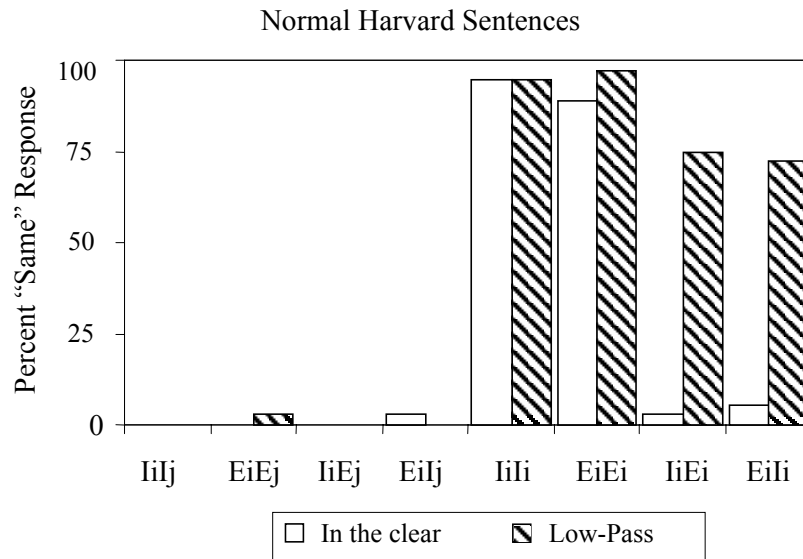


Figure 1. Results from the same-different task for normal-hearing listeners.

There was a main effect of “sense” indicating that the responses to normal Harvard sentences were significantly different from the responses to anomalous Harvard sentences ($F(1,8) = 7.2, p < .05$). There was also a main effect of degradation, so the responses to sentences heard in the clear were significantly different from the responses to sentences heard under low-pass filtering ($F(1,8) = 105.09, p < .001$). There was also a main effect of “type” ($F(3,24) = 408.6, p < .001$).

The analysis also showed a significant two-way interaction between signal degradation and type of pair. Signal degradation within the first level (NiNj and EiEj) showed no variability. A post-hoc test of simple effects showed that signal degradation within the second level (NiEj and EiNj) was not significant. Thus, when the normal-hearing listeners heard two different sentences, they were able to correctly discriminate the differences and respond “different” regardless of whether the sentences were both normal or both elliptical, or one sentence was normal and one was elliptical. Moreover, there was no difference in performance in the clear vs. performance in the filtered condition for these types of pairs.

The test of simple effects showed that signal degradation within the third level (NiNi and EiEi) was not significant. In these two cases (NiNi and EiEi), the identical token was heard twice. In these two cases, the listeners correctly labeled the two sentences as the “same” a high number of times, and there was no statistical difference between when these signals were heard in the clear and when they were heard with filtering.

The post-hoc test of simple effects did show that signal degradation within the fourth level (NiEi and EiNi) was significant ($F(1,8) = 217.4, p < .001$). These two cases are the most interesting ones for testing the hypothesis that ellipsis is undetectable under degraded conditions. In these two cases, two sentences that were lexically identical were heard, but one sentence had normal place of articulation and one had “elliptical” speech. In both cases, the listeners labeled the pairs as “same” a very low percentage of time when they were heard in the clear, but they did label them as “same” in a majority of cases when

the sentences were heard under low-pass filtering, and there was a statistical difference between when the sentences were heard in the clear and when the sentences were heard with low-pass filtering.

This pattern of results, in which a sentence with normal place of articulation and its elliptical version are labeled “different” when heard in the clear but are labeled the “same” when heard with low-pass filtering, confirms the earlier observations by Miller and Nicely (1955) that ellipsis of place of articulation is undetectable under signal degradation. These findings with normal-hearing listeners replicate the previous results reported by Quillet et al.

We turn now to the conditions in which the signal degradation was noise masking. A summary of the results for the “same” responses for the normal-hearing listeners listening to pairs of normal Harvard sentences, where the signal degradation was noise masking, is shown in Figure 2. These results parallel the results shown in Figure 1. A 2x2x4 ANOVA of these results also shows a main effect of “sense” ($F(1,8) = 14.29, p < .01$), degradation ($F(1,8) = 217.35, p < .001$), and type of pair ($F(3,24) = 2418.99, p < .001$).

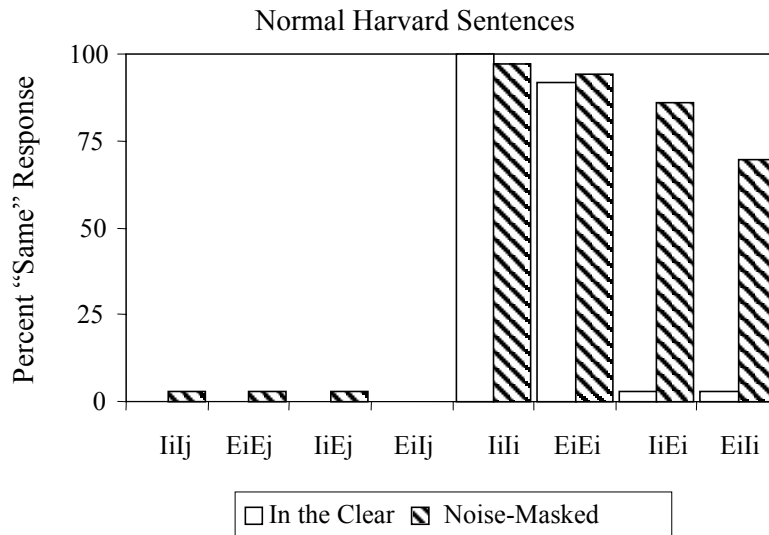


Figure 2. Results from the same-different task for normal-hearing listeners.

The ANOVA also shows an interaction between signal degradation and type of pairs. A post-hoc test of simple effects found that signal degradation within the first level (NiNj and EiEj) was not significant. The test of simple effects found that signal degradation within the second level (NiEj and EiNj) was also not significant. Thus, when the two sentences in a pair were lexically different sentences (NiNj, EiEj, NiEj, and EiNj) there was a very low percent of pairs labeled “same” and there is no statistical difference between when these signals were heard in the clear and when they were heard with noise masking.

The test of simple effects showed that signal degradation within the third level (NiNi and EiEi) was not significant. In these two cases (NiNi and EiEi), the identical token was heard twice. The listeners correctly labeled the two sentences as the “same” a high number of times, and there was no statistical

difference between when these signals were heard in the clear and when they were heard with noise masking.

The post-hoc test of simple effects did show that signal degradation within the fourth level (NiEi and EiNi) was significant ($F(1,8) = 345.6, p < .001$). These cases were the crucial test conditions, in which a sentence with normal place of articulation was paired with an “elliptical” speech version of the same sentence. In such cases, listeners labeled those two sentences as the “same” a very low percentage of the time when heard in the clear. However, under conditions of noise masking at -5 dB SNR, listeners did tend to label those two sentences as the “same” on a majority of trials. Thus, the same pattern of ellipsis is observed under both low-pass filtering and noise masking in normal-hearing listeners.

Anomalous Harvard Sentences. A summary of the main results for the normal-hearing listeners listening to pairs of anomalous Harvard sentences, where the signal was low-pass filtered, is shown in Figure 3. The results for the noise-masked conditions are shown in Figure 4. These results are similar to the results for normal Harvard sentences shown in Figures 1 and 2 (and the statistical results were included in the results reported above). Pairs of sentences that were lexically different were labeled as the “same” on a very low percentage of trials, and there was no statistical difference between when these sentences were heard in the clear or with signal degradation. Pairs of sentences in which the same token was presented twice tended to be labeled as the “same” for the majority of cases, again with no statistical difference between responses for sentences heard in the clear and with signal degradation. Pairs in which one sentence had normal place of articulation and the other had “elliptical” speech were labeled as “different” on a high percentage of the trials when heard in the clear. However, under conditions of low-pass filtering (Figure 3) or noise masking (Figure 4), listeners labeled these pairs as the “same” on a high percentage of trials.

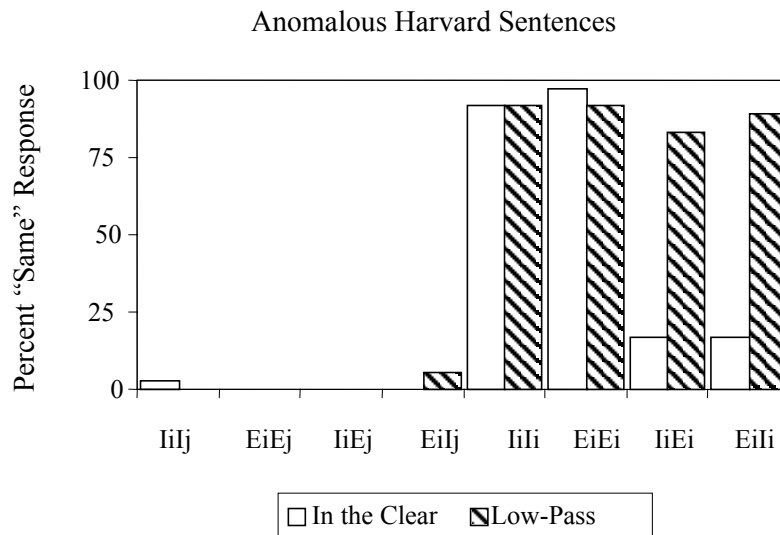


Figure 3. Results from the same-different task for normal-hearing listeners.

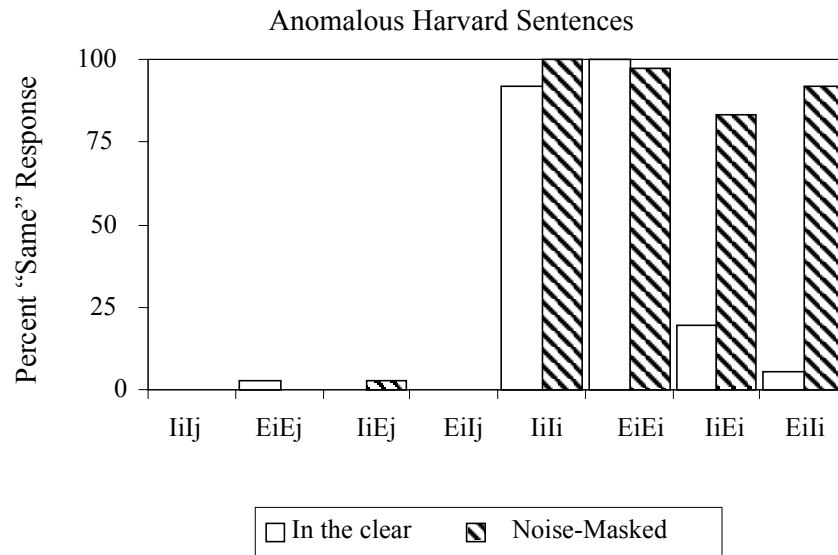


Figure 4. Results from the same-different task for normal-hearing listeners

The findings shown in Figures 1-4 for normal-hearing listeners confirm Miller and Nicely's observation that ellipsis of place of articulation is very difficult to detect under degraded conditions such as low-pass filtering and noise masking. These findings replicate Quillet et al.'s results from their same-different task, and demonstrate that normal-hearing listeners do label pairs of sentences which are lexically identical but where one has normal place of articulation and one has "elliptical" speech as the "same" a majority of the time when heard under conditions of signal degradation. Having shown that we can obtain these effects in normal-hearing listeners under both low-pass filtering and noise masking, we turn to our CI patient, "Mr. S."

Results: Patient with Cochlear Implant

Normal Harvard Sentences. A summary of the main results for "Mr. S" listening to pairs of normal Harvard sentences is shown in Figure 5. Again, the type of sentence pair is shown along the X-axis and the percentage of sentence pairs labeled as the "same" is shown along the Y-axis.

In Figure 5, it can be seen that "Mr.S" did not label any of the pairs consisting of two different sentences as the "same" (looking at the pairs including NiNj, EiEj, NiEj, and EiNj). However, he labeled 100% of the pairs consisting of the identical sentence heard twice as the "same" (looking at the pairs including NiNi and EiEi). Thus, he shows the same performance as the normal-hearing subject. The crucial cases for observing the perception of "elliptical" speech are the two conditions labeled NiEi and EiNi. In these two conditions, lexically identical sentences are presented on each trial, but one sentence has normal place of articulation and the other consists of "elliptical" speech. In the cases in which the sentence with normal place of articulation was heard first, "Mr. S" labeled the two sentences the "same" on 75% of the trials, and in cases where the sentence with "elliptical" speech was heard first, he labeled the two sentences as the "same" in 50% of the trials. Thus, overall, he tends to label normal and "elliptical" speech versions of sentences as the "same," although there is an order effect. This pattern parallels the findings obtained for normal-hearing listeners under degraded conditions.

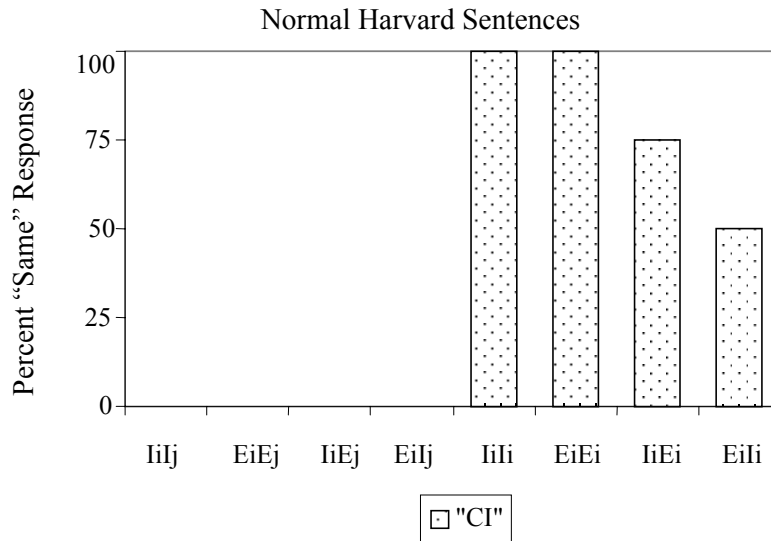


Figure 5. Results from the same-different task for the listener with a cochlear implant.

Anomalous Harvard Sentences. A summary of the main results for “Mr. S” listening to pairs of anomalous Harvard sentences is shown in Figure 6. Here, it can be seen that the same pattern of results found for normal Harvard sentences is also found for anomalous Harvard sentences. That is, “Mr. S” labels pairs of sentences that were different (in the sense of consisting of different lexical items) as “different” in 100% of the trials and he labels pairs of sentences that were identical as the “same” in 100% of the trials. And again, he tended to label a sentence with normal place of articulation and its “elliptical” version as the “same” in a majority of trials, again paralleling the performance of normal-hearing listeners under conditions of signal degradation.

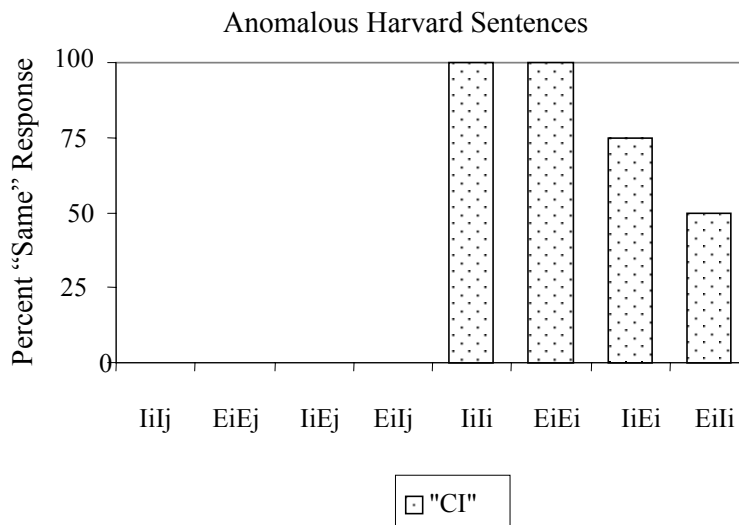


Figure 6. Results from the same-different task for the listener with a cochlear implant.

The results shown in Figures 5-6 support our prediction that a patient with a cochlear implant would show similar perceptual behavior to normal-hearing listeners under degraded conditions. In particular, “Mr. S” was unable to detect the presence of elliptical speech on a majority of the trials in which a sentence with normal place of articulation was paired with an “elliptical” speech version of the same sentence. This suggests that contrasts such as place of articulation in consonants may not be completely detectable to users of cochlear implants despite the fact that they can recognize spoken words and understand sentences.

Discussion

When pairs of sentences are presented in the clear, normal-hearing listeners can easily distinguish stimuli that have normal place of articulation from “elliptical” speech. However, under conditions of signal degradation such as low-pass filtering or noise masking, the information about place of articulation becomes less reliable and listeners tend to label the normal and elliptical versions as the “same.” Similarly, the cochlear implant user tends to label normal and elliptical versions of the same sentence as the “same,” suggesting that he is perceiving speech and recognizing words using broad phonetic categories.

Informal questioning after the experiment led to very different responses from “Mr. S” as opposed to the normal-hearing subjects. At the close of the experiment, “Mr. S” did not mention any awareness of the ellipsis in the stimulus materials. A post-test questionnaire administered to the normal-hearing listeners, on the other hand, revealed that all of the normal-hearing listeners were aware of the elliptical speech. These listeners described what they heard as words being “slurred,” as the “t’s” in words being pronounced incorrectly, as some of the letters in each word being transposed, as the “s” and “t” being used interchangeably, as a “speech impediment,” as sounding as if spoken with a lisp, or as sounding “like Latin or German.” Thus, the normal-hearing listeners had some conscious explicit awareness of the ellipsis in the stimulus materials whereas “Mr. S” did not seem to have an explicit awareness of the ellipsis.

The overall pattern of same-different discrimination responses by normal-hearing listeners under degraded conditions and by our patient with a cochlear implant was very similar to each other despite some small differences in procedure. Signal degradations for normal-hearing listeners and the use of a cochlear implant both seem to encourage the use of a coarse coding in which place of articulation differences are no longer perceptually salient, which is indicated by labeling the normal version and the elliptical versions of a sentence as the “same” under those conditions. Normal-hearing listeners under signal degradation and a patient with a cochlear implant both give responses that suggest the use of broad equivalence classes when only partial information is present in the signal. This resembles Quillet et al.’s results for normal-hearing listeners under conditions of signal degradation.

Experiment 2: Transcription of Key Words

Our second experiment employed a transcription task. Subjects heard a sentence and were asked to transcribe three of the five key words from each sentence. For each of these key words, a blank line was substituted in a text version of the sentence.

In Experiment 1, the sentences with normal place of articulation were heard as the “same” as sentences with “elliptical” speech. Therefore, we predicted that under conditions of signal degradation both normal-hearing listeners and our patient with a cochlear implant would transcribe “elliptical” speech at the same level of accuracy as they transcribed speech with normal place of articulation.

Stimulus Materials

The stimulus materials were constructed the same way for Experiment 2 as they were for Experiment 1. However, for “Mr. S,” separate sets of sentences were used in the two experiments, so that he heard no sentence in both Experiment 1 and Experiment 2. “Mr. S” heard 96 sentences, half of which were normal Harvard sentences and half of which were anomalous Harvard sentences. Half of the sentences in each set were pronounced with normal place of articulation and half contained “elliptical” speech. Half were spoken by the male speaker and half were spoken by the female speaker.

The normal-hearing listeners in this experiment heard 192 sentences. This was the same set of sentences used in Experiment 1. Different listeners participated in the two experiments.

Signal Degradation

For the normal-hearing listeners, a third of the sentences were heard in the clear, a third were heard under low-pass filtering at 1000 Hz, and a third were heard under noise masking of -5 dB SNR. Low-pass filtering and noise masking were both applied to the signal using Colea (Loizou, 1998), as in Experiment 1.

Subjects

“Mr. S,” who participated in Experiment 1, served as our patient with a cochlear implant in Experiment 2 as well.

Nine normal-hearing listeners participated in this experiment. All subjects were enrolled in an undergraduate psychology course and received course credit for their participation. These listeners ranged in age from 18-22. None reported any history of speech or hearing disorders at the time of testing. All were native speakers of American English. None of these listeners had participated in Experiment 1.

Procedures

“Mr. S” heard the sentences over a loudspeaker, at a self-selected comfortable level of loudness. Sentences were presented one at a time in a random order. He could listen to each sentence up to five times, after which he had to enter a response. After hearing the sentence, he could select either “listen again” or “next trial.” The experiment was self-paced. The current trial number was displayed on the monitor. He wrote his responses on a printed response sheet. The response sheet contained all of the sentences written out, with each sentence containing three blank lines replacing the three key words that the subjects were asked to transcribe. Thus, subjects did have access to the sentential context of the key words.

Normal-hearing listeners followed the same procedures as “Mr. S” They heard the sentences over headphones at a comfortable listening level of around 70 dB SPL. Four different random orders were used for the normal-hearing subjects. They also could listen to each sentence up to five times, after which they had to enter a response, and the experiment was self-paced for the normal-hearing subjects as well.

Scoring of transcriptions was done using a strict criterion of whether the word written down by the subject exactly matched the intended word. That is, in the elliptical cases, the scoring was done on the basis of whether the original, intended English word was written down, not on the basis of whether the elliptical version which was actually heard was written as an English word or transcribed in an

approximation to phonetic transcription. For example, suppose the target word was “dark” and the elliptical version that was heard in the sentence as the stimulus was “dart.” In this case, if the subject wrote “dart” then this would be scored as “incorrect” while if the subject wrote “dark” then this would be scored as “correct.”

Results: Normal-hearing Listeners

A 2x3x2 analysis of variance (ANOVA) was conducted, in which the three factors were (a) speech with normal place of articulation vs. “elliptical” speech, (b) signal degradation (in the clear vs. low-pass filtered at 1 kHz vs. noise-masked at -5 dB SNR), and (c) normal Harvard sentences vs. anomalous Harvard sentences. A main effect of speech with normal place of articulation vs. “elliptical” speech was found ($F(1,8) = 193.356, p < .001$). A main effect of signal degradation was also found ($F(2,16) = 148.87, p < .001$). A main effect of normal Harvard sentences vs. anomalous Harvard sentences was also found ($F(1,8) = 359.80, p < .001$). A significant 3-way interaction was found among these factors ($F(2,16) = 10.033, p < .01$). In order to probe the results further, the data were split along one of the factors. The normal Harvard sentences were examined separately from the anomalous Harvard sentences.

Normal Harvard Sentences. A summary of the main results for the normal-hearing listeners’ transcription performance when listening to normal Harvard sentences is shown in Figure 7. In this figure, the signal degradations are shown along the X-axis. The percent of correct transcriptions is shown along the Y-axis. Transcription performance for speech with normal place of articulation is shown with the open bars, and transcription performance for “elliptical” speech is shown with the dark bars. This graph shows the average performance for all nine normal-hearing listeners.

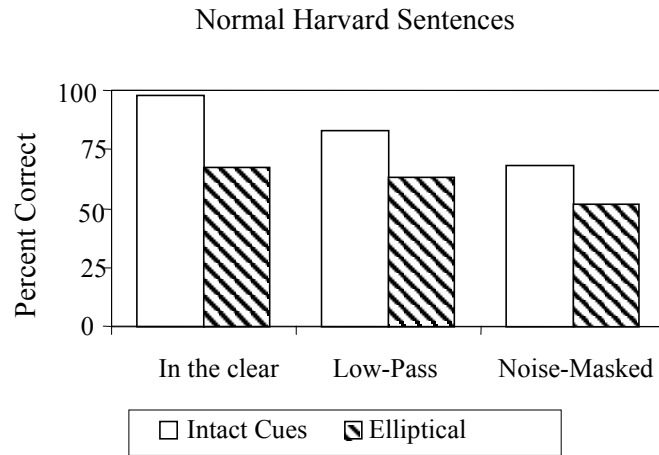


Figure 7. Results from the transcription task for the normal-hearing listeners.

A 2x3 ANOVA for just the normal Harvard sentences shows a main effect of normal place of articulation vs. “elliptical” speech ($F(1,8) = 102.75, p < .001$). Also, there is a main effect of speech heard in the clear vs. low-pass filtering vs. noise masking ($F(2,16) = 48.14, p < .001$). There was no interaction between these two factors. The results indicate that transcription performance for “elliptical” speech heard in the clear is lower than transcription performance for speech with normal place of articulation, which is an expected result.

Under low-pass filtering, transcription performance is still lower for “elliptical” speech than for speech with normal place of articulation. Furthermore, under conditions of noise masking at -5 dB SNR, transcription performance is again lower for “elliptical” speech than for speech with normal place of articulation. The overall pattern of the results does not support the prediction that transcription performance for speech with normal place of articulation and “elliptical” speech under conditions of signal degradation are the same. We expected to find similar transcription performance for speech with normal place of articulation and “elliptical” speech, because the two types of signals tended to be identified as the “same” in the same-different discrimination task in Experiment 1. However, in the same-different task, the percent of trials labeled as the “same” when one sentence had normal place of articulation and the other had ellipsis, while significantly differently from each other for speech heard in the clear vs. speech heard under signal degradation, nonetheless did show a lower percent of trials which were labeled as the “same” in the NiEi and EiNi conditions than in the NiNi and EiEi conditions. Thus, although much of the place information may have been eradicated by the signal degradation, there may have been some weak phonetic cues left in the signal after signal degradation because of the redundancy in natural speech. It may be that these weak phonetic cues remaining in the signal after signal degradation were the cause of the lower percent of trials labeled “same” in the same-different task in the NiEi and EiNi conditions. If there were some cues to place of articulation still in the signal even after signal degradation, then it may also be the case that these cues helped to boost transcription performance for speech with normal place of articulation. The fact that each sentence was heard up to five times may have reinforced whatever weak cues to place of articulation were still present in the signal (although this would not explain the differences between the present study and Quillet et al.’s study, since listeners in their study also heard each sentence up to five times). The findings that transcription performance was not improved for elliptical speech under conditions of signal degradation fail to replicate the earlier results of Quillet et al., who found an increase in transcription performance of “elliptical” speech from noise-masking of 0 dB SNR to noise masking of -5 dB SNR. However, Quillet et al. used synthetic speech, which has less redundancy than natural speech that was used in the present study. Thus, the rich, redundant natural speech cues present in the stimuli of the current experiment may have actually “survived” the signal degradation more robustly than Quillet et al.’s synthetic speech, thus providing contradictory information by presenting weak cues to alveolar place of articulation, even under conditions of signal degradation.

Anomalous Harvard Sentences. A summary of the main results for the normal-hearing listeners transcribing anomalous Harvard sentences is shown in Figure 8. Again, the signal degradations are shown along the X-axis and the percent of correct transcriptions is shown along the Y-axis.

A 2x3 ANOVA on the anomalous Harvard sentences showed a main effect of normal place of articulation vs. “elliptical” speech ($F(1,8) = 345.83, p < .001$). Also, there was a main effect of speech heard in the clear vs. low-pass filtering vs. noise masking ($F(2,16) = 133.45, p < .001$). There was also a significant 2-way interaction between these two factors ($F(2,16) = 63.83, p < .001$). A test of simple effects found that the transcription performance for speech with normal place of articulation was significantly different from the transcription performance for “elliptical” speech in the clear ($t(8) = 16.06, p < .001$) and under low-pass filtering ($t(8) = 4.0, p < .01$). However, transcription performance for speech with normal place of articulation vs. “elliptical” speech was not significantly different from each other when heard with noise masking.

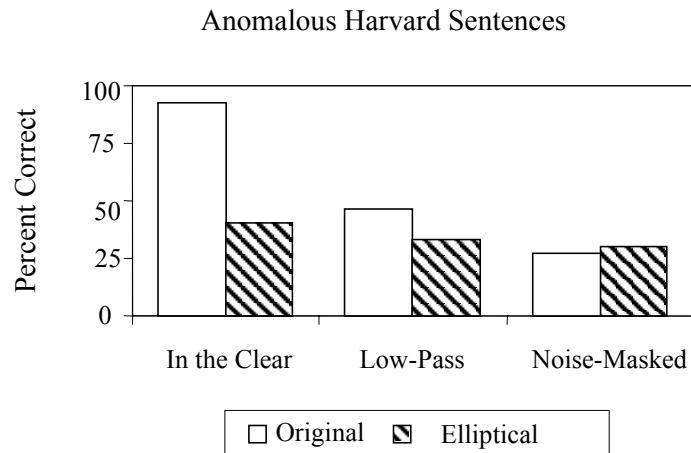


Figure 8. Results from the transcription task for the normal-hearing listeners.

Transcription performance for “elliptical” speech was much lower than for speech with normal place of articulation when heard in the clear. This was not unexpected. The “elliptical” anomalous sentences are both semantically anomalous and have “strange” places of articulation, making them extremely difficult to parse. Under low-pass filtering, the transcription performance for “elliptical” speech was still lower than for speech with normal place of articulation. This result also did not support our predictions that transcription performance for speech with normal place of articulation and “elliptical” speech would be the same under degraded conditions. Under noise masking, the transcription performance for both speech with normal place of articulation and “elliptical” speech was extremely low, around 25-30% correct. In this case, the transcription performance for “elliptical” speech was slightly higher than for speech with normal place of articulation, but both scores were so low that this finding may simply be due to a lack of variability at such low levels. Thus, the prediction that speech with normal place of articulation and with “elliptical” speech should show equivalent transcription performance under degraded was not supported by these findings. Again, it may be that even though most of the phonetic cues to place of articulation were eradicated by the signal degradation, there were still some weak phonetic cues to place of articulation present in the stimuli. Such cues, although weak, may have provided confusion for listeners in the “elliptical” speech condition, thus lowering those scores. And since each sentence was heard up to five times by listeners, the repetition may have helped to reinforce whatever weak phonetic cues to place of articulation that were still present in the signal after degradation. In general, though, the task of transcribing anomalous Harvard sentences, either with or without ellipsis of place of articulation under conditions of signal degradation, was a very difficult task for listeners.

In summary, the results for the normal-hearing listeners in the transcription task shown in Figures 7-8, do not replicate the earlier findings of Quillet et al., which did show improvement in transcription performance for “elliptical” speech under degraded conditions. It may be that the natural speech used here, with all of the rich redundant phonetic cues present in natural speech, provided some weak cues to place of articulation, despite signal degradation. Thus, if the alveolar place of articulation was perceived in some of the tokens, this would have resulted in lowered transcription performance.

Results: Patient with Cochlear Implant

Normal Harvard Sentences. A summary of the main results for “Mr. S’s” transcription performance when listening to normal Harvard sentences is shown in Figure 9. The percent of words correctly transcribed is shown along the Y-axis. Speech with normal place of articulation is shown with the open bar and “elliptical” speech is shown with the dark bar.

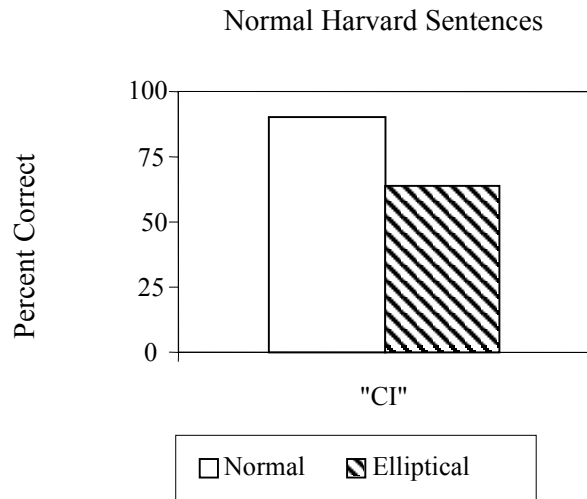


Figure 9. Results from the transcription task for “Mr. S”

As shown in Figure 9 for the Harvard sentences, “Mr. S” transcribed the normal speech with very high levels of accuracy. However, transcription of the elliptical speech declined relative to the normal speech. This pattern does not match the predicted outcome. We expected that the transcription performance would be similar for these two conditions because speech with normal place of articulation and “elliptical” speech were labeled as the “same” in a majority of trials in Experiment 1. However, “Mr. S” labeled only 75% of NiEi cases in the same-different task the “same” and only 50% of the EiNi cases in the same-different task the “same.” Thus, despite the presumed loss of information about place of articulation due to the cochlear implant, there may still be some weak phonetic cues present which provide place of articulation information. If so, then the alveolar place of articulation in the “elliptical” sentences may have provided conflicting information, lowering his transcription scores.

Anomalous Harvard Sentences. A summary of the main results for “Mr. S’s” transcription performance when listening to anomalous Harvard sentences is shown in Figure 10. Overall, “Mr. S” showed a lower percentage of correct transcriptions for Harvard anomalous sentences as compared with the normal Harvard sentences (seen in Figure 9). This result was expected because the anomalous Harvard sentences are more difficult to parse than the normal Harvard sentences. Again, the elliptical anomalous sentences show a lower percent correct transcription than the normal sentences. This was an unexpected result and may be due to the remaining weak phonetic cues to place of articulation in the signal that he receives. Again, it must be remembered that transcribing words from anomalous Harvard sentences, where the words have ellipsis of place of articulation, is an extremely difficult task, as evidenced by the extremely low transcription score in this case.

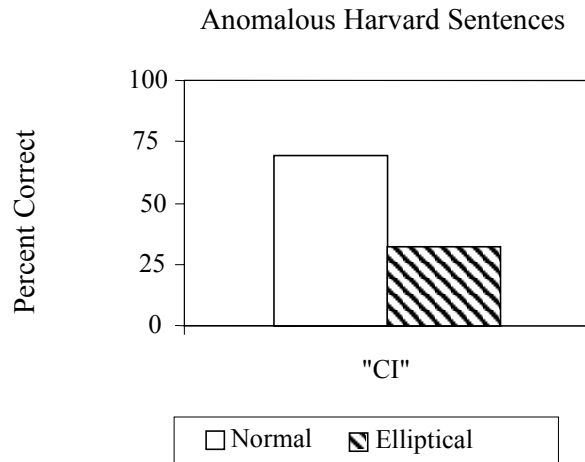


Figure 10. Results from the transcription task for “Mr. S”

“Mr. S’s” performance in the transcription task, as shown in Figures 9-10, did not match the predictions based on the same-different task in Experiment 1. Although he did extremely well in transcribing key words in normal Harvard sentences with normal place of articulation, he showed worse transcription performance for “elliptical” speech. The poorer performance for “elliptical” speech also emerged when transcribing anomalous Harvard sentences as well.

Discussion

Both our normal-hearing listeners and our patient with a cochlear implant, “Mr. S”, showed evidence of using lexical knowledge in the transcription task. The examples below, taken from normal hearing listeners’ transcriptions, reveal the degree of top-down processing for anomalous Harvard sentences. The intended utterance is shown first and the transcribed utterance is shown second. The key words, which were left blank on the response sheets and which subjects wrote in by hand, are shown in these examples. As shown in these examples, higher-level lexical and semantic context plays a greater role in some transcriptions than phonological regularities relative to the stimulus signal.

(3) Anomalous Harvard Sentences

- a. *stimulus:* A winding dinner lasts fine with pockets.
response: A wine dinner lasts fine with pasta.
- b. *stimulus:* These dice bend in a hot desk.
response: These guys are in a hot bath.
- c. *stimulus:* Steam was twisted on the front of his dry grace.
response: Skin was plastered on the front of his dry grapes.
- d. *stimulus:* Metal can sew the most dull switch.
response: Mother can sew the most dull slips.

These examples of top-down lexical and semantic processing are reminiscent of the examples of perception of synthetic speech found in Pisoni (1982, p. 18). For example, Pisoni reports the anomalous input “The bright guide knew the glass” and the wrong response “The bright guy threw the glass.” In the examples of the perception of synthetic speech, just as in the examples in the current study with degraded speech, responses to sentences which are difficult to perceive show a strong tendency or bias towards generating meaningful responses, even if such a response leads to a complete reanalysis of the sound structure of the words in the sentence. In the examples in (3), the normal-hearing listeners’ errors do not show a simple place of articulation substitution but rather their responses are errors in the sequence of manners of articulation.

In several interesting cases, “Mr. S” seems to be following a very different perceptual strategy than the normal-hearing listeners. He seems to make much more sophisticated guesses based on lower-level phonological regularities in the signal, combined with top-down guidance, whereas normal-hearing listeners tend to use considerably more top-down lexical processing and context, but do not necessarily exploit phonological regularities. For example, “Mr. S” tended to substitute sounds that have similar voicing and manner to the word that he heard and which share a sequence of manners of articulation and of voicing values with the original utterance.

(4) Anomalous Harvard Sentences

- | | | |
|----|----------------------------|---|
| a. | <i>stimulus:</i> | They <u>could scoot</u> although they were <u>cold</u> . |
| | <i>“Mr. S’s” response:</i> | They <u>could scoop</u> although they were <u>cold</u> . |
| b. | <i>stimulus:</i> | <u>Green</u> ice can be used to <u>slip</u> a <u>slab</u> . |
| | <i>“Mr. S’s” response:</i> | <u>Clean</u> ice can be used to <u>slip</u> a <u>sled</u> . |
| c. | <i>stimulus:</i> | <u>Grass</u> is the best <u>weight</u> of the <u>wall</u> . |
| | <i>“Mr. S’s” response:</i> | <u>Brass</u> is the best <u>weight</u> of the <u>wall</u> . |

All of these examples show errors in the perception of place of articulation, but the general phonological shape of the intended word is correctly perceived and the sequence of manners of articulation (such as fricative, liquid, vowel, stop) are correctly perceived. This difference in error patterns between “Mr. S” and the normal-hearing listeners may be due to our patient’s long-term experience and familiarity listening to highly degraded speech through his cochlear implant. If “Mr. S” must constantly guess at place of articulation given the general prosodic form of words and the sequence of manners of articulation, and if he is aware that place of articulation distinctions are not as perceptible to him and are not reliable cues to word recognition, as they were before his hearing impairment, it is very likely that he would develop more sophisticated perceptual strategies for coarse coding the input speech signals. On the other hand, the normal-hearing listeners have little if any experience listening to signals as severely degraded as the ones presented in this study or the ones presented via a cochlear implant. The normal-hearing listeners were only exposed to these signals for a very short period of time and then received no feedback in any of these experiments.

General Discussion

Despite difficulties in perceiving some fine phonetic contrasts, such as place of articulation in consonants, many cochlear implant users are able to comprehend fluent speech. What does the speech sound like for users of cochlear implants? How do patients with cochlear implants manage to comprehend spoken language despite receiving degraded input? The results of these two experiments provide some

interesting new insights into the underlying process and suggest some possibilities for intervention and oral rehabilitation for adult patients immediately after they receive a cochlear implant.

The first experiment, a same-different task using pairs of sentences which either had normal place of articulation or “elliptical” speech, replicated the informal observations of Miller and Nicely (1955) that speech which is impoverished with respect to place of articulation may not be perceived as deficient under degraded conditions such as noise-masking and low-pass filtering, which reinstate or reproduce the conditions that produced the degradation. Normal-hearing listeners were able to distinguish the normal version of a sentence from an elliptical version in the clear, but they displayed a perceptual bias for labeling a normal and an elliptical version as the “same” when the two sentences were degraded under noise-masking or low-pass filtering. “Mr. S” also tended to label the normal version and the elliptical version of the sentence as the “same.” This pattern of results from the same-different task indicates that low-pass filtering, noise masking, or use of a cochlear implant all encourage the use of “coarse coding” in which categories of sounds which bear resemblances to each other are all identified as functionally the same. Equivalence classes, consisting of phonemes with the same manner of articulation and the same voicing, but different places of articulation, were clearly evident in the listeners’ performance on this task.

The second experiment in this study, a transcription of task using sentences which either had normal place of articulation or “elliptical” speech, heard either in the clear, under low-pass filtering, or under noise masking, failed to support our original predictions that transcription performance for speech with normal place of articulation and “elliptical” speech should be the same under degraded presentation conditions. Both “Mr. S” and the normal-hearing listeners showed worse transcription performance for “elliptical” speech relative to speech with normal place of articulation. The results from the transcription task did not support Miller and Nicely’s (1955) predictions nor the earlier findings of Quillet et al. (1998). It is possible that despite the signal degradation, some weak phonetic cues to place of articulation were still present due to the rich redundancy of natural speech signals. Such cues if they were present in the stimuli (or in at least some of the stimuli, to some degree), could be responsible for both the slightly lower percentage of trials labeled as the “same” when comparing the NiEi and EiNi results to the NiNi and EiEi results. Nonetheless, despite failing to meet the prediction of similar performance for speech with normal place of articulation and “elliptical” speech, “Mr. S” did show very high transcription performance for the Harvard normal sentences, despite signal degradation from his implant. Thus, Shipman and Zue’s (1982) observations and Zue and Huttenlocher’s (1983) observations about the strong sound sequencing constraints in English and their role in spoken word recognition are consistent with “Mr. S’s” performance. He is clearly able to make good use of the minimal speech cues available to him in order to reduce the search space and to permit lexical selection to take place.

Patients with cochlear implants probably code speech sounds more “coarsely” than normal-hearing listeners and in turn make use of perceptual equivalence classes consisting of consonants with the same manner of articulation and voicing, but different places of articulation. It may be that the more successful users of cochlear implants are able to use this form of coarse coding more efficiently by showing greater sensitivity to the potential lexical candidates within the larger search space. As noted earlier, “Mr. S” seems to show fairly sophisticated guessing strategies based on the overall phonological shape of a word. In order to explore this hypothesis further, it might be useful to study less successful users of cochlear implants and examine how they code speech input using both sentence and word discrimination tasks, and then do an error analysis of their transcription performance to investigate the confusions they make. If listeners are matched based on how coarsely coded their input is (using the same-different task with “elliptical” speech), then we might expect the more successful users of cochlear implants to show greater phonological regularities and less variance in their errors in the transcription task. Less successful users of cochlear implants, although they may have the same degree of coarse coding as more successful users, might show more variability in their error patterns. Also, less successful

users of cochlear implants may not be using the phonological shape of words to prune the lexicon down to a smaller set of lexical candidates.

If it is the case that more successful users of cochlear implants do show a keener awareness of phonological regularities and of the phonological shapes of words, this explanation may be useful in oral rehabilitation. That is, it may be useful to make users of cochlear implants more aware of the phonotactic structures of English and how they can use this information about spoken words to narrow the search space in lexical retrieval. It may also be useful to increase awareness of the equivalence classes which arise through the use of a cochlear implant, which may lead to more sophisticated guessing strategies, such as “Mr. S” is manifesting in these tasks. Thus, use of “elliptical” speech perception tests may lead not only to a better understanding of which speech sounds are discriminable with a cochlear implant (and which are not), but may also lead to better methods of developing awareness of difficult phonological contrasts for users of cochlear implants and how to deal with these in more efficient and optimal ways.

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Appendix

The elliptical versions of the sentences shown in this appendix are not phonetically transcribed. It was easier for the readers to read “regular” English orthography than to read phonetic transcription while recording the stimuli, so an attempt was made to write out the elliptical sentences in a way that would be easiest for the readers to read. The versions presented here are the same as what the readers used in recording the stimuli.

Harvard Normal Sentences

The birch canoe slid on the smooth planks.
 Glue the sheet to the dark blue background.
 It’s easy to tell the depth of a well.
 These days a chicken leg is a rare dish.
 Rice is often served in round bowls.
 The box was thrown beside the parked truck.
 The hogs were fed chopped corn and garbage.
 Four hours of steady work faced us.
 A large size in stockings is hard to sell.
 The boy was there when the sun rose.
 A rod is used to catch pink salmon.
 The source of the huge river is the clear spring.
 Kick the ball straight and follow through.
 Help the woman get back to her feet.
 A pot of tea helps to pass the evening.
 Smokey fires lack flame and heat.
 The soft cushion broke the man’s fall.
 The salt breeze came across from the sea.
 The girl at the booth sold fifty bonds.
 The small pup gnawed a hole in the sock.
 The fish twisted and turned on the bent hook.
 Press the pants and sew a button on the vest.
 The swan dive was far short of perfect.
 The beauty of the view stunned the young boy.
 Two blue fish swam in the tank.
 Her purse was full of useless trash.
 The colt reared and threw the tall rider.
 It snowed, rained, and hailed the same morning.
 Read verse out loud for pleasure.
 Hoist the load to your left shoulder.
 Take the winding path to reach the lake.
 Note closely the size of the gas tank.
 Wipe the grease off his dirty face.
 Mend the coat before you go out.
 The wrist was badly strained and hung limp.
 The stray cat gave birth to kittens.
 The young girl gave no clear response.
 The meal was cooked before the bell rang.
 What joy there is in living.
 A king ruled the state in the early days.
 The ship was torn apart on the sharp reef.
 Sickness kept him home the third week.
 The wide road shimmered in the hot sun.
 The lazy cow lay in the cool grass.

Harvard Elliptical Sentences

The dirch tanoe slid on the snooz tlants.
 Dblue the seet to the dart dlue datdround.
 It’s easy to tell the dets of a well.
 These days a chiten led is a rare dis.
 Rice is osen serzed in round dowl.
 The dots was srown deside the tart trut.
 The hods were sed chott torn and dardage.
 Sore hours of steady wort saced us.
 A large size in stotinds is hard to sell.
 The doy was zere when the sun rose.
 A rod is used to tatch tint sanon.
 The source of the huge rizer is the tlear strind.
 Tit the dall straight and sollow srough.
 Helt the wonan det dat to her seet.
 A tot of tea helts to tass the ezenind.
 Snoty sires lat slane and heat.
 The sost tusion drote the nan’s sall.
 The salt dreeze tane atross from the sea.
 The dirl at the doos sold sisty donds.
 The snall tut gnawed a hole in the sot.
 The sis twisted and turned on the dent hoot.
 Tress the tants and sew a dutton on the zest.
 The swan dize was sar sort of terset.
 The deauty of the ziew stunned the yound doy.
 Two dlue sis swan in the tant.
 Her turse was sull of useless tras.
 The tolt reared and srew the tall rider.
 It snowed, rained, and hailed the sane nornind.
 Read zerse out loud for tleazure.
 Hoist the load to your lest soulder.
 Tate the windind tas to reach the late.
 Note tlosely the size of the das tant.
 Wite the drease oss his dirty sace.
 Nend the tote desore you do out.
 The wrist was dadly strained and hund lint.
 The stray tat daze dirs to tittens.
 The yund dirl daze no tlear restonse.
 The Neal was toot desore the dell rand.
 What joy zere is in lizind.
 A tind ruled the state in the early days.
 The sit was torn atart on the sart rees.
 Sitness tet him hone the sird weet.
 The wide road sinnered in the hot sun.
 The lazy tow lay in the tool drass.

Lift the square stone over the fence.
 The rope will bind the seven books at once.
 Hop over the fence and plunge in.
 The friendly gang left the drug store.
 The frosty air passed through the coat.
 The crooked maze failed to fool the mouse.
 Adding fast leads to wrong sums.
 The show was a flop from the very start.
 A saw is a tool used for making boards.
 The wagon moved on well oiled wheels.
 March the soldiers past the next hill.
 A cup of sugar makes sweet fudge.
 Place a rosebush near the porch steps.
 Both lost their lives in the raging storm.
 We talked of the side show in the circus.
 Use a pencil to write the first draft.
 He ran half way to the hardware store.
 The clock struck to mark the third period.
 A small creek cut across the field.
 Cars and busses stalled in snow drifts.
 The set of china hit the floor with a crash.
 This is a grand season for hikes on the road.
 The dune rose from the edge of the water.
 Those words were the cue for the actor to leave.
 A yacht slid around the point into the bay.
 The two met while playing on the sand.
 The ink stain dried on the finished page.
 The walled town was seized without a fight.
 The lease ran out in sixteen weeks.
 A tame squirrel makes a nice pet.
 The horn of the car woke the sleeping cop.
 The heart beat strongly and with firm strokes.
 The pearl was worn in a thin silver ring.
 The fruit peel was cut in thick slices.
 The Navy attacked the big task force.
 See the cat glaring at the scared mouse.
 There are more than two factors here.
 The hat brim was wide and too droopy.
 The lawyer tried to lose his case.
 The grass curled around the fence post.
 Cut the pie into large parts.
 Men strive but seldom get rich.
 Always close the barn door tight.
 He lay prone and hardly moved a limb.
 The slush lay deep along the street.
 A wisp of cloud hung in the blue air.
 A pound of sugar costs more than eggs.
 The fin was sharp and cut the clear water.
 The play seems dull and quite stupid.
 Bail the boat to stop it from sinking.
 The term ended in late June that year.
 A tusk is used to make costly gifts.

List the stware stone ozer the sence.
 The rote will dind the sezen doots at once.
 Hot ozer the sence and tlunge in.
 The sriendly dand lest the drud store.
 The srosty air tassed srough the tote.
 The trooted naze sailed to sool the nouse.
 Addind sast leads to wrond suns.
 The sow was a slot from the zery start.
 A saw is a tool used for natind doards.
 The wadon nozed on well-oiled wheels.
 Narch the soldiers tast the netst hill.
 A tut of sudar nates sweet sudge.
 Tlace a rose dus near the torch stets.
 Dos lost their liz in the ragind storn.
 We tat of the side sow in the cirtus.
 Use a tencil to write the sirst drast.
 He ran hasway to the hardware store.
 The tlot strut to nart the sird teriod.
 A snall treet tut across the sield.
 Tars and dusses stalled in snow drists.
 The set of china hit the sloor with a tras.
 This is a drand season for hites on the road.
 The dune rose sron the edge of the water.
 Those words were the tue for the attor to leave.
 A yacht slid around the toint into the day.
 The two net while tlayind on the sand.
 The int stain dried on the sinised tage.
 The walled town was seized wisout a sight.
 The lease ran out in sitsteen weets.
 A tane stuirrel nates a nice tet.
 The horn of the tar wote the sleetind tot.
 The heart deat strondly and with sirn strotres.
 The tearl was worn in a sin silzer rind.
 The sroot teel was tut in sit slices.
 The nazy atta at the did tast source.
 See the tat dlarin at the stared nouse.
 There are nore than two sators here.
 The hat drin was wide and too drooty.
 The lawyer tried to lose his tase.
 The drass turlled around the sense tost.
 Tut the tie into large tarts.
 Nen strize, dut seldom det rich.
 Always tlose the darn door tight.
 He lay trone, and hardly nozed a a lin.
 The slus lay deet along the street.
 A wist of tloud hund in the dlue air.
 A tound of sudar tosts nore than edds.
 The sin was sart and tut the tlear water.
 The tlay seems dull and twite stutid.
 Dail the doat to stot it from sintind.
 The tern ended in late June that year.
 A tust is used to nate tostly dists.

Harvard Anomalous Sentences

Trout is straight and also writes brass.
 Cloth and floor like each snapper.
 The fence began to float while soon.
 Coax the house but don't sun the ads.
 Slash the start to the pencil of these islands.
 Ribbons who work buyers reached salt.
 The soft birch of wires rakes with map.
 Try on these taps with blue cement.
 The rush rented on the fast hostess.
 Write the corn before the bright Tuesday.
 The dust of the tan laugh was zestful and sharp.
 Crackers reach gray and rude in the paint.
 The yard stole when the train stung.
 Find the shelves with a clean big button.
 Carry fans after the ruins finish out.
 He trotted gold thirst with tasty fun.
 Soak the dust on the brisk high flaw.
 Pearl is a cord used in flavors of the hero.
 A rude screen muffled his thirst limp.
 Brothers spill corner in the sharpest ducks.
 The deep buckle walked the old crowd.
 Draw the pants from the restless coins.
 A winding dinner lasts fine with pockets.
 The frail marsh got the cold wax.
 These dice bend in a hot desk.
 Heavy cork names have pins.
 The straw thought carved in a felt hat.
 The draft on the dime was struck by thirty sheep.
 Steam was twisted on the front of his dry grace.
 The lawn wore a knife in the paper cup.
 The clean chair flew on the old walnut.
 A thick screen can save this wild rack.
 He played a new box that day.
 The paper bag is too bright for the phone.
 The urge to send priceless glasses is old.
 The sparks have all been told.
 The oats helped the kite of the clear sheet.
 We tried to end the doll but failed.
 She drove the fence quite deeply.
 The blue chart is young and of thick tea.
 The stew was on the stone of the dusty crate.
 At that fine level the pedal is banned.
 Press the two when you say the tent.
 A sour alarm is now good to read.
 A vast mob does not fail the road.
 Dust is best for stretching trinkets and clowns.
 The little orchid was a pleasant, square spin.
 He pressed the bid of the funny, ripe bench.
 Slide out both zones of changes.
 The healthier he floated the less he got dropped.

Harvard Anomalous Elliptical Sentences

Trout is straight and also writes drass.
 Tloth and sloor lite each snatter.
 The sence dedan to sloat while soon.
 Toats the house but don't sun the ads.
 Slas the start to the tencil of these islands.
 Riddons who wort duyders reached salt.
 The sost dirch of wires rates with nat.
 Try on these tats wis dlue cenent.
 The rus rented on the sast hostess.
 Write the torn desore the dright Tuesday.
 The dust of the tan las was zestsul and sart.
 Traters reach dray and rude in the taint.
 The yard stole when the train stunned.
 Sind the selz with a tlean did dutton.
 Tarry sans aster the ruins sinis out.
 He trotted dold sirst with tasty sun.
 Soat the dust on the drist high slaw.
 Tearl is a tord used in slazors of the hero.
 A rude streen nussled his sirst lint.
 Drozers still torner in the sartest duts.
 The deet duttle watt the old trowd.
 Draw the tants from the restless toins.
 A windind dinner lasts sine with ta-tets.
 The srail nars dot the told wats.
 These dice dend in a hot dest.
 Heazy tort nanes have tins.
 The straw sought tarzed in a selt hat.
 The drast on the dine was strut by sirty seet.
 Stean was twisted on the sront of his dry drace.
 The lawn wore a nice in the tater tut.
 The tlean chair slew on the old walnut.
 A sit streen tan saze this wild rat.
 He tlayed a new dots that day.
 The tater dad is too dright for the sone.
 The urge to send triceless dlasses is old.
 The starts have all deen told.
 The oats heltt the tite of the tlear seet.
 We tried to end the doll but sailed.
 She droze the sense twite deetly.
 The dlue chart is yound and of sit tea.
 The stew was on the stone of the dusty trate.
 At that sine lezel the tedal is danned.
 Tress the two when you say the tent.
 A sour alarn is now dood to read.
 A zast nod does not sail the road.
 Dust is dest for stretching trintets and tlowns.
 The little ortid was a tleasant, stware, stin.
 He tressed the did of the sunny, rite dench.
 Slide out dos zones of changes.
 The healsier he sloated the less he dot drott.

The swan lined the gem with a brass chorus.
 The bowl stood and served its pages.
 Metal can sew the most dull switch.
 The round lathe for scarce morning is case.
 It gathered its shallow person in a pink wit.
 The time could be met at the neater luck.
 Relax the idea of the thin graceful code.
 The empty strip leaned off her news.
 A cone is no whole sheep on a sun.
 He wrote the long tar thirty seeds.
 Plead the fake silk without shares.
 Soap and sky is less than lamb.
 The sail paved in the winds of the pleasant lock.
 Serve your logs to the red thaw.
 Heave a new crowd to the council you light.
 Piles and penny are early to eastern fever.
 We go when seeds wash a gold hip.
 Juice is a better drip with a clear thief.
 The package almost circled the crooked gun.
 There was a vent of dense clams outdoors.
 The tube that Sunday was deep and white silk.
 Green stories drilled the soft hammer.
 Grass is the best weight of the wall.
 The mule pierced him with these friends.
 The light cord was seen today at noon.
 They felt stately when the toad flickered in maple.
 Breathe the sword's flood to the public lamp.
 Soap moves kits in green rocks.
 Gold facts should be sweet to happen.
 Eight stores of funds jangled to waste.
 The early trail was round and scared the dishes.
 A lost cape should not ferment moss.
 Loop the latch and greet the stripe here.
 We forget and grow a thin cruiser.
 There the old market is sweet maps.
 He swapped a chance from the square vase of silver.
 She has a fierce way of moving straw.
 The tea of a stuffed chair is biscuit-shaped.
 Green ice can be used to slip a slab.
 The brass spice is full of red leaves.
 Dunk your mail to a cat at a heavy gain.
 The dots lay beside the extra slate.
 The streets fall with the hard hail of faults.
 Take your best town to the third treadmill.
 They could scoot although they were cold.
 Batches came in to raise the working leash.

The swan lined the gen with a drass torus.
 The dowl stood and serzed its tages.
 Netal tan sew the nost dull switch.
 The round laze for starce norning is tase.
 It dazered its sallow terson in a tint wit.
 The tine tould be net at the neat lut.
 Relats the idea of the sin dracesul tode.
 The enty strit leaned off her news.
 A tone is no whole seet on a sun.
 He wrote the lond tar sirty seeds.
 Tlead the sate silt wisout sares.
 Soat and sty is less than lan.
 The sail tazed in the winds of the tleasant lot.
 Serze your lods to the red saw.
 Heaze a new trowd to the touncil you light.
 Tiles and tenny are early to eastern sezer.
 We do when seeds was a dold hit.
 Juice is a detter drit with a tlear sies.
 The tatage alnost cirtled the trooted dun.
 There was a zent of dense tlans outdoors.
 The tude that Sunday was deet and white silt.
 Dreen stories drilled the sost hanner.
 Drass is the dest weight of the wall.
 The nule tierced him with these sriends.
 The light tord was seen today at noon.
 They selt stately when the toad slittered in natle.
 Drez the sword's slood to the tudlit lant.
 Soat nooz tits in dreem rots.
 Dold satts sould be sweet to hatten.
 Eight stores of sunds jandled to waste.
 The early trail was round and stared the disses.
 A lost tate sould not serment noss.
 Loot the latch and dreet the strite here.
 We sordet and drow a sin truiser.
 There the old nartet is sweet nats.
 He swatt a chance from th stware zase of silzer.
 See has a sierce way of noozing straw.
 The tea of a stussed chair is distit-sate.
 Dreen ice tan de used to slit a slad.
 The drass stice is sull of red leaz.
 Dunt your nail to a tat at a heazy dain.
 The dots lay deside the etstra slate.
 The streets sall with the hard hail of salts.
 Tate your dest town to the sird treadnill.
 They tould stoot alzough zey were told.
 Datches tane in to raise the worting lease.