Perceptual Adjustment to Highly Compressed Speech: Effects of Talker and Rate Changes

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This study investigated the perceptual adjustments that occur when listeners recognize highly compressed speech. In Experiment 1, adjustment was examined as a function of the amount of exposure to compressed speech by use of 2 different speakers and compression rates. The results demonstrated that adjustment takes place over a number of sentences, depending on the compression rate. Lower compression rates required less experience before full adjustment occurred. In Experiment 2, the impact of an abrupt change in talker characteristics was investigated; in Experiment 3, the impact of an abrupt change in compression rate was studied. The results of these 2 experiments indicated that sudden changes in talker characteristics or compression rate had little impact on the adjustment process. The findings are discussed with respect to the level of speech processing at which such adjustment might occur.

It is well known that the relationship between the speech signal and underlying phonological representations is extremely complex. This complexity is the result of several different factors. First, no one-to-one mapping between cues in the acoustic signal and the underlying representations have been uncovered so far. Instead, many different acoustic cues distributed in the signal have been found to map onto the same representation. Second, the nature of these cues varies as a function of many different factors including surrounding phonetic context, syllabic position, changes in talker, speaking rate, speaking style, accent, and stress. Despite this variation, speech perception is amazingly accurate. This is comparable to visual perception, in which widely different retinal stimulations give rise to perception of the same object, a phenomenon called perceptual constancy. To achieve constancy, the perceptual system presumably uses different normalization mechanisms that compensate for the variations induced by various situations such as overall lighting conditions, distance, orientation, and others (Epstein & Broota, 1986; Jolicouer, 1988).

Previous studies have suggested that, in speech, similar normalization mechanisms exist that adjust perceptual criteria in the different contexts. For example, consider the problem of mapping acoustic parameters onto vowel categories across speaking contexts. Peterson and Barney (1952) demonstrated that formant frequencies corresponding to a single vowel category vary extensively across different speakers. Moreover, the formant values for different vowel categories show considerable overlap, creating a difficult problem for theories of vowel perception. Several studies have shown that vowel perception is influenced by the pitch (approximately, the FO) of the talker’s voice (Bladon, Henton, & Pickering, 1984; Johnson, 1990; Nearey, 1989). Because FO correlates with vocal tract size, some researchers have proposed that, during vowel perception, there is a stage of processing in which the formant values extracted from the acoustic signal are normalized with respect to the talker (Darwin, McKeown, & Kirby, 1989; Johnson, 1990; Ladefoged, 1967, 1989; Ladefoged & Broadbent, 1957; Remez, Rubin, Nygaard, & Howell, 1987).

Additional evidence for normalization has been found with respect to the rate at which speech is articulated. It has been shown that talkers make large and frequent changes in their speaking rate during a conversation (Miller, Grosjean,
in speech perception have demonstrated that the perceptual system alters its criteria for judging such cues in relation to the rate at which the speech was produced. For example, Miller and Liberman (1979) examined the stop-semivowel distinction of /ba/ versus /wa/ as cued by transition duration. They found that deleting the last 216 ms of the vowel caused the critical transition that separated the /b/-/w/ categories to shift toward a shorter duration. Miller and Liberman interpreted their results as demonstrating that analysis of the transition duration was done in relation to the overall speaking rate of the test syllable. In support of this notion, Miller, Aibel, and Green (1984) found that modifying /ba/-/wa/ syllables by deleting the final vowel had systematic influences on the judged speaking rate of the test syllables. Tokens with shorter overall syllable durations were judged to be produced at a faster speaking rate. Those with shorter transitions were identified as /wa/ more frequently at the fast rate than at the slow rate. Similar results have been found for a voiced–voiceless distinction cued by VOT and closure duration (Green & Miller, 1985; Green, Stevens, & Kuhl, 1994; Port & Dalby, 1982; Summerfield, 1981). Studies with young infants show that they also demonstrate sensitivity to overall syllable duration when discriminating speech tokens (Eimas & Miller, 1980; Miller & Eimas, 1983). Thus, adjustment to rate-induced variation occurs at a very early stage in development. However, it is not yet known whether such adjustment involves a speech-specific mechanism, because similar results can be obtained in primates (Stevens, Kuhl, & Padden, 1988) and with nonspeech signals (Diehl & Walsh, 1989; Fowler, 1990; Pisoni, Carrell, & Gans, 1983).

Normalization appears to occur immediately in response to local variation in the speech signal. However, the question arises as to whether short-term mechanisms are the only ones responsible for perceptual constancy in speech, or whether there exist other mechanisms with different properties. For example, there are indications that perceptual adjustments occur in response to changes in speaking rate over longer intervals than a syllable such as a precursor phrase or sentence provides (Kidd, 1989; Miller, Green, & Schermer, 1984; Summerfield, 1981). However, even this phenomenon is fairly local, occurring within a few seconds of the changes in the immediately preceding context.

On a more anecdotal level, there is the experience of listening to a new talker with a heavy accent or dialect who is difficult to comprehend at first. After a couple of minutes, however, comprehension improves and it becomes possible to understand the talker. Schwab, Nusbaum, and Pisoni (1985) found a similar improvement in comprehension of synthetic speech. This suggests that the adjustment to a new speaking style occurs gradually, with recognition improving over several minutes of experience for a particular type of speech signal. A similar situation appears to occur when listeners are presented with highly compressed speech. For example, Voor and Miller (1965) found that comprehension of compressed speech increased significantly over the first 8 to 10 min of listening, with little increase after that. Two questions can be raised with respect to these findings. First, is the slow improvement the result of perceptual normalization mechanisms that are used to achieve perceptual constancy? Or does it reflect the operation of more cognitive strategies such as learning to guess words based on partial information? Second, if the locus of these effects is perceptual (as opposed to cognitive), what is the relationship between such a mechanism and the rate normalization mechanisms that have been previously examined in phonetic perception?

The purpose of the current study was to address these two questions by examining how listeners adjust to compressed speech. Compressed speech is an ideal vehicle for studying normalization mechanisms for a number of reasons. First, it provides a quantifiable way of manipulating the speech signal to create speech that is clearly outside the bounds of normal experience. This is important because it is only when speech exceeds such bounds that evidence is obtained for gradual adjustment over time. This does not mean that such adjustments do not take place with more typical signals, but that typical signals make it difficult to obtain evidence for gradual adjustments due to ceiling effects in the performance of the listener. Second, present-day signal processing techniques enable one to compress the signal without actually deleting portions of it or creating discontinuities as occurred with older compressors (Foulke & Sticht, 1969; de Haan, 1982; Heiman, Leo, Leighbady, & Bowler, 1986; Schmitt, Moore, & Lass, 1986). Thus, in the current study, the compressed speech signal is smooth and its spectral characteristics are unchanged. Finally, compressing speech affects the perceived rate at which the speech was produced. It is therefore possible to compare the normalization that occurs to highly compressed speech with the normalization that occurs with more typical changes in speaking rate. Such a comparison is important for providing a complete understanding of the adjustment mechanisms involved in phonetic perception.

The three experiments in the current study address the nature of the perceptual adjustments to highly compressed speech. The first experiment uses a carefully constructed set of speech tokens along with a counterbalanced design to demonstrate that adjustment to compressed speech can occur. More important, this experiment also establishes the amount of exposure needed to obtain improved recall scores of the compressed sentences. This information is necessary for the next two experiments, which examine the effect of changing talkers and the preceding rate context on the adjustment process. Both of these variables have already been investigated with respect to their impact on local rate normalization during phonetic perception (Diehl, Souther, & Convis, 1980; Kidd, 1989; Summerfield, 1981). Experiment 2 examines whether the improvement that occurs generalizes to new talkers. Experiment 3 investigates whether the performance is affected by the intervention of uncompressed materials. These experiments constitute an initial examination of the locus of adjustments to compressed speech during processing and its relationship to previous findings in rate normalization. We first describe the stimuli and the general methodology used in the experiments.
General Method

Participants

Participants were undergraduate students at the University of Arizona. Some were given course credit for their participation; others were paid. All were native speakers of English. None of the participants reported any history of a speech or hearing disorder.

Materials

A set of 40 sentences was constructed using the following criteria: Each sentence consisted of 10 words with seven content words and three function words: no, some or any, and one or too.

The 20 sentences were partitioned into four sets of five sentences with the same partitioning being used for both talkers. The sentences were presented at a comfortable listening level (approximately 74 dB SPL). The sentences were low-pass filtered (9.8 KHz), amplified (Yamaha AX 630), and then presented to individual participants over loudspeakers (Realistic minimus) in a small, sound-attenuated room. Each participant sat about 4 feet in front of the loudspeakers. The sentences were presented individually to participants who were asked to listen to a sentence and write down as much of it as they could recall, taking as much time as necessary. At the start of the sentence, each participant was presented with a single sheet of paper to a group of 14 participants who were asked to rate the plausibility of each sentence on a scale from 1 to 7.1 Plausibility, as used in this article, refers to how likely or ordinary an event is that is described by a sentence. Thus a plausible sentence will describe a very ordinary event that has a high probability of occurring in everyday life, whereas an implausible sentence will describe a very bizarre or unexpected event that is not very likely to occur.

The 20 sentences were partitioned into four sets of five sentences with the same partitioning being used for both talkers. The presentation order of these four sets of sentences was varied across different groups of participants according to a Latin square design. However, the presentation order within a set did not vary. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure allowed us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall at a compression rate of 35%). The list of 20 sentences is their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores (being neither particularly easy or difficult to recall. The 20 sentences was 39% to 62% correct). This screening procedure enabled us to select sentences that were roughly comparable in their recall scores.

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**Data Analysis**

For each participant, the number of content and function words that were correctly recalled was determined for each sentence. The data described in the current study only report the percentage of content words that were correctly recalled. A narrow form of scoring was used, with even slight deviations from what was said being counted as errors, with the following exceptions. First, any form of the noun or verb was counted as correct. Second, added words were not counted as errors.²

**Experiment 1**

As reported earlier, there is some indication, both anecdotal and experimental, that perceptual adjustment can occur to compressed speech. On the anecdotal side, participants often report that compressed speech sounds unnaturally fast at first and difficult to understand. With exposure, they find it easier to understand and report that it sounds less compressed. In addition, when switched back to uncompressed sentences, listeners report that the uncompressed speech sounds abnormally slow. Such anecdotal reports are suggestive of some kind of adjustment to rapid rates of speech. On the experimental side, there is the finding that, with practice, perceptual performance on highly compressed speech shows some measurable increase (Voor & Miller, 1965). This is expected if some type of adjustment to the compressed signal takes place. However, these earlier studies used a compression technique that involved deletion and subsequent concatenation of portions of the acoustic signal. Such effects tend to disrupt the speech signal. Using the less disruptive techniques, Mehler et al. (1993) showed that performances on compressed speech improve over time for a French–English bilingual talker as well as a Spanish–Catalan bilingual.

The purpose of Experiment 1 was to replicate this finding using the speech of two monolingual English talkers and to provide a baseline for Experiments 2 and 3. In addition, this first experiment extended the study of Mehler et al. by documenting in more detail the gradient of adaptation as a function of the amount of experience with compressed speech. Finally, two different compression rates were used to determine the generality of the results.

**Method**

**Participants.** One hundred sixty undergraduate students at the University of Arizona participated in the experiment. Each participant was randomly assigned to 1 of 16 groups of 10 participants.

**Materials.** The materials were the four sets of five sentences spoken by a male and female talker, compressed to 38% and 45% of their original durations.

**Procedure.** Eight groups of participants listened to the sentences produced by the male talker, and eight groups heard the sentences of the female talker. For each talker, half of the groups heard sentences at the 38% compression rate and the remainder at the 45% compression rate. Finally, the presentation order of the four sentence sets was counterbalanced across the four groups receiving a particular compression rate, using a Latin square design.

**Results**

The percentages of content words correctly recalled from each sentence were determined for each participant. These values were averaged over the five sentences of each set to yield four set scores for each participant. The set scores were then submitted to a single four-way analysis of variance (ANOVA) with Compression Rate (38% vs. 45%), Talker (male vs. female), Set Position (sentence sets presented in Position 1, 2, 3, and 4) and Counterbalancing (the 4 counterbalanced participant groups) as the main factors. Unless otherwise noted, F values not discussed in the text were not significant with p > .05. The cell means collapsed across participant groups are presented in the upper half of Table 2. An examination of this table reveals several things. First, there is an overall difference in the percentage of content words that were correctly recalled in the two compression rates. Not surprisingly, the sentences that were compressed to 45% of their original duration produced much higher accuracy in the recall scores of the content words. This resulted in a significant effect of Compression Rate, F(1, 144) = 655.4, p < .0001.

Second, there is a small difference in the recall scores for the two different talkers with the female talker producing slightly higher recall scores, F(1, 144) = 10.67, p < .005. This difference occurred at both compression rates; there was no interaction between Compression Rate and Talker, F(1, 144) = 2.45, p > .12. It is not clear why the female talker’s utterances produced slightly higher recall scores. However, it is probably due to the female talker’s utterances being more formally produced than the male’s.

Of primary interest is whether there is any evidence of an increase in recall rates across the different sentence sets. Such an improvement would provide evidence that experience with the compressed speech resulted in perceptual adjustment or adaptation. As can be seen in Table 2, there was an increase in the recall scores across the first four sentence sets for both talkers at both compression rates, F(3, 432) = 76.9, p < .0001. Set Position interacted with Compression Rate, F(3, 432) = 3.42, p < .02, because, whereas the recall scores for the 38% compression rate increase from the first to the second and from the second to the third sentence sets, for the 45% compression rate, there is only an increase from the first to the second sentence set. To examine this interaction further, separate three-way ANOVAs were conducted on the two compression rates. Because our specific interest was whether there was any improvement in recall scores from one sentence set to the next, planned comparisons were carried out on pairwise set means for each compression rate.

At the 38% compression rate, the effect of Set Position was significant, F(3, 216) = 26.19, p < .0001. However, the planned comparisons indicated significant differences only between the cell means for Set 1 and Set 2 (p < .0001) and between Set 2 and Set 3 (p < .05). There was also a significant

² That is, missing or added plurals on the noun or verbal inflections were not counted as errors, and additions such as "every one" versus "every" were scored as correct.
replicate the earlier findings of Mehler et al. (1993) and participants listening to the two different talkers is very talkers of English. Moreover, the overall performance of the ways. First, similar findings were obtained for two new provide empirical support to the anecdotal reports of those ment in recall of compressed speech can occur with expo-

Discussion

The results from this experiment indicate that improve-
ment in recall of compressed speech can occur with expo-
sure to only 5 or 10 compressed sentences. These results replicate the earlier findings of Mehler et al. (1993) and provide empirical support to the anecdotal reports of those who have listened to compressed speech. In addition, this experiment extends the findings of Mehler et al. in two ways. First, similar findings were obtained for two new talkers of English. Moreover, the overall performance of the participants listening to the two different talkers is very similar probably because the durations of the sentences for the talkers were closely matched before compression. Second, these results show that the form of the improvement depends on the nature of the experience. When the sentences are compressed to 38% of their original duration, they are extremely difficult to understand, and the adjustment process requires more time than when they are compressed to 45% of their original durations.

One important implication of this finding is that listeners' performance did not improve over the course of the experiment simply due to practice with the task itself (e.g., memorizing and recalling sentences under a time constraint). If this had been the only reason for their improvement, then similar rates of improvement should have been obtained for the two different compression rates.

To rule out definitively that task familiarity might play some role in performance, we conducted an additional control experiment. Four new groups of 10 participants each were presented with a set of five test sentences compressed to 38%. Before the critical set of test sentences, each group of participants heard a set of context sentences. The first group of participants heard the remaining three sentence sets compressed to 38%. We call this the compressed condition, and it serves as a replication of one of the earlier participant groups. The second group of participants heard the remaining sentence sets uncompressed. These sentences were easy to comprehend and provide a context in which participants can practice the recall task without getting any exposure to compressed speech. We call this group the uncompressed condition. The third group of participants heard the uncompressed sentences in white noise at a signal-to-noise ratio of -1 dB. "4 Pilot testing had determined that this signal-to-noise ratio resulted in an overall intelligibility for the uncompressed speech that was comparable to that of the 38% compressed speech. This condition was included to determine whether the adaptation is simply the result of learning how to deal with speech that is degraded in some fashion. This group is called the noise condition. Finally, a fourth group was included that had no prior experience with either compressed or uncompressed speech. This group provided a baseline level of performance on the critical sentence set without any previous context. This group is called the baseline condition.

If practice with the task is sufficient to account for improve-
ment, then the first three conditions should result in signifi-
cantly better performance on the critical sentence set over the baseline condition. However, if improvement is specific to experience with compressed speech, performance in the compressed condition only should be above baseline.

The results of this control experiment are that the recall scores in the compressed condition (26%) are higher than

### Table 2

<table>
<thead>
<tr>
<th>Set order</th>
<th>Compression rate 38%</th>
<th>Compression rate 45%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Talker</td>
<td>Set M</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>26.9</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>31.7</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>61.5</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>67.6</td>
</tr>
<tr>
<td></td>
<td>Set M</td>
<td>74.7</td>
</tr>
</tbody>
</table>

The analyses of both compression rates revealed significant interactions between Counterbalancing, Set Position, and Rate (p < .0001 for both analyses). These higher order interactions are difficult to interpret; however, they appear to reflect the fact that the different sentence sets had different recognition performance for which the counterbalancing in the experiment controlled.

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4 We thank Arthur Samuel for suggesting this control condition.
A one-way ANOVA revealed a significant difference between the compressed condition and the other three comparisons (Neuman-Keuls) revealed a significant difference between the two compression rates. One possibility is that the amount of exposure required is greater for the higher (38%) compression rate, because the tokens are more extreme examples of rapid speech. When perceivers encounter speech produced at different rates, they retune certain perceptual criteria (cf. Miller & Liberman, 1979). This retuning takes time, and the more extreme the speaking rate, the more time is required for the retuning process to be completed. Note that such a retuning process would be independent of the number of words initially recognized in the speech signal. More important, the shape of the recall function should depend on the compression rate of the speech and not on a particular participant's overall performance level. Thus, the gradient of adjustment has a steeper slope for the 45% group than for the 38% group not because participants find the sentences compressed at 45% easier to recognize than the sentences compressed to 38%. Instead, the more highly compressed sentences require more time for complete normalization to occur.

To examine this possibility, overall performance across the 38% and 45% conditions was equated to determine whether similar learning curves occur. For each participant, the two sentences on which they performed best and the two sentences on which they performed worst were identified in each of the four sentence sets. Next, the participants' best responses in the 38% compression condition and the worst responses in the 45% compression condition were extracted for further analysis. The mean percentage of content words correct in each of the four sentence sets obtained from these data are displayed in Figure 2. As shown in the figure, the performance level on these sentences in the two compression conditions is approximately equal. However, the shape of the function differs for the two compression rates. For the 38% condition, improvement is gradual over the first three sets. In contrast, a substantial improvement occurs between the first and second set in the 45% condition, with little change between the remaining sets. Analyses similar to that performed in the Results section confirm this evaluation.
at a point at which performance was already significantly above baseline. The results of Experiment 1 indicate that not much improvement occurs after 10 sentences have been presented. Therefore, in this experiment a switch in talker was made after the presentation of the first 10 sentences.

To look at the effect of a switch in talker on the adjustment to compressed speech, three analyses were performed. The first examined whether there was a drop in performance due to the switch in talker. The second set of analyses compared the performance after the switch in talker to the performance of other groups of participants that had no switch but had varying amounts of experience with compressed speech, ranging from no prior experience to three full sets of sentences. Finally, to determine whether a switch in talker had a local effect, we ran similar analyses but restricted the data to the first two sentences after the switch. Note that the counterbalancing of the experiment was done only in sets of five sentences, not in terms of single sentences or pairs of sentences. This means that the interpretation of these more local analyses is tentative.

**Method**

**Participants.** A total of 60 new undergraduate students at the University of Arizona participated in the experiment. The participants were randomly assigned to one of six experimental groups.

**Materials.** The materials were the same four sets of five sentences spoken by the male and female talkers of Experiment 1. The sentences were compressed to 38% of their original duration.

**Procedure.** The participants in this experiment heard two sets of five sentences from one talker, and then a third set of sentences from the second talker. Despite the attempts to make the sentences comparable, there was some variability in their "recognizability" after compression. Therefore, it was necessary to counterbalance for the set of sentences presented as the third set. This was accomplished by comparing across four groups of participants. The first two groups (Groups A and B) were presented with Sets 1 and 2, with the switch in talker occurring between Sets 1 and 2. The other two groups (Groups C and D) were presented with Sets 2 and 3, with the switch in talker occurring between Sets 2 and 3.

**Experiment 2**

The results of the first experiment support the claim that overall performance level. Even when performance levels are equated, the same difference in the slope of the adjustment function occurs. This finding is inconsistent with the view that high-level guessing strategies account for the differences between the two compression rates. However, the results are also consistent with the idea that at least some of the improvement in the ability to recognize compressed speech is due to perceptual mechanisms involved in the normalization for speaking rate.
The table below shows the average percentage of content words correctly recalled for two different sentence sets as a function of the change in talker and the presence of a complete context. The data were analyzed using a four-way ANOVA with Change Condition, Talker, and Group as between-subject factors. The analysis revealed a significant effect of Change Condition, indicating that a change in talker resulted in a decrease in performance compared to the same talker condition.

<table>
<thead>
<tr>
<th>Talker</th>
<th>First Set</th>
<th>Second Set</th>
<th>Third Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>27.2%</td>
<td>33.1%</td>
<td>30.1%</td>
</tr>
<tr>
<td>Female</td>
<td>25.9%</td>
<td>31.6%</td>
<td>28.7%</td>
</tr>
</tbody>
</table>

The performance on the third set of sentences is lower for the different talker condition. Furthermore, there was a significant difference between the performance on the first two sentences presented in the set and the average performance on the set just before the change in talker. These results suggest that participants struggle to adjust to compressed speech immediately after a change in talker, which then shows a rapid improvement over the next sentences in the set.
Fact that there is considerable savings from one talker to mechanisms that are not tapped by these other tasks. The adjustment to compressed speech is accomplished by perceptual and memory tasks (Goldinger, Pisoni, & Logan, 1993; Martin, Mullennix, Pisoni, & Summers, 1989; Pisoni & Mullennix, 1989, 1990). This difference may mean that the adjustment to compressed speech is accomplished by mechanisms that are not tapped by these other tasks. The fact that there is considerable savings from one talker to another might indicate that adjustment to compressed speech is performed at a rather abstract level, that is, a level at which detailed acoustic characteristics of the signal no longer play a role. An alternative account, which we favor, is that at least some of the adjustment to compressed speech does involve perceptual mechanisms involved in rate normalization. Moreover, switching talkers does produce an immediate decline in performance, but the effect is compensated for very rapidly by the perceivers. However, further investigation of the time course of adjustment on a sentence-by-sentence basis may be necessary to show such immediate effects.

**Discussion**

The results of this experiment found support for the idea that there are considerable savings on recall over a shift in talker when dealing with highly compressed speech. After a change in talker, participants' performances do not return to baseline. Indeed, the overall performance of groups experiencing talker change did not differ significantly from those of groups experiencing the same talker. Finally, a marginal decline in performance was seen in the first two sentences after a change in talker, indicating that changing talkers may have an immediate impact on the adjustment to compressed speech. However, the perceiver is able to recover from this within a couple of sentences and performance at the end of the set is comparable to that of the group of participants presented with just a single talker.

The results of this experiment contrast with others showing that changing talkers has a detrimental effect on many perceptual and memory tasks (Goldinger, Pisoni, & Logan, 1993; Martin, Mullennix, Pisoni, & Summers, 1989; Pisoni & Mullennix, 1989, 1990). This difference may mean that the adjustment to compressed speech is accomplished by mechanisms that are not tapped by these other tasks. The fact that there is considerable savings from one talker to another might indicate that adjustment to compressed speech is performed at a rather abstract level, that is, a level at which detailed acoustic characteristics of the signal no longer play a role. An alternative account, which we favor, is that at least some of the adjustment to compressed speech does involve perceptual mechanisms involved in rate normalization. Moreover, switching talkers does produce an immediate decline in performance, but the effect is compensated for very rapidly by the perceivers. However, further investigation of the time course of adjustment on a sentence-by-sentence basis may be necessary to show such immediate effects.

**Experiment 3**

The previous two experiments examined adjustment as a function of exposure to highly compressed speech and explored whether the adjustment transfers from one talker to a new talker. However, they did not address the durability of the adjustment, that is, once a plateau in performance is attained, whether it is maintained despite the need to adjust to other rates of speech. This question is of interest because it relates to the nature of the underlying mechanism. If the phenomenon is due to local rate normalization, then the adjustment should be affected by abrupt changes in the compression rates of the sentences. For example, the normalization might reset after the presentation of uncompressed materials. Alternatively, there may be some savings across different rates, in which case part of the adjustment process may be related to more permanent learning.

Consider an analogy from the visual modality, the perception of contrast with respect to dark adaptation. The perception of contrast is directly influenced by the sensitivity of the visual system to the ambient light level. However, we often experience large changes in the overall levels of ambient light in the course of a normal day. Therefore, our visual systems have to be able to operate over a wide range of lighting conditions with extreme sensitivity. The visual system meets these two requirements by adopting a narrow operating range for intensity with good contrast sensitivity, and then adjusting that operating range to match the level of illumination in the environment, through an adaptation mechanism (Goldstein, 1989; Hood & Finkelstein, 1986). When an observer moves from a dark environment to a light environment (or vice versa), adaptation takes place over a 5–10 min period of time. During that time, the visual system adjusts its operating range to the new light level, and the perception of contrast can be impaired. Once a state of adaptation has been attained, the perceptual system can quickly adjust to smaller amounts of illumination changes within a particular scene.

If adjustment to compressed speech is analogous, then after adjustment has occurred, presentation of uncompressed speech should cause the perceptual system to reset to the normal range of speech rates. A switch back to compressed speech should then trigger a readjustment. Alternatively, normalization to compressed speech may involve some kind of perceptual learning (e.g., Pisoni & McClaskey, 1983; Schwab et al., 1985) in which the phonetic parameters adequate for dealing with new or degraded stimuli are extracted and stored for later use. If so, some savings may be maintained through intervening uncompressed materials.

This last experiment asked whether normalization, once attained, can be affected by intervening speech that is either uncompressed or less compressed. Participants first heard 10 sentences compressed to 38% of their original duration. Next, five new uncompressed or less compressed sentences were presented, followed by five new sentences at the original 38% compression rate. As in Experiment 2, the participants were assigned to either of two groups, with the sentence material before and after the change in compression rates counterbalanced across the two groups. Three conditions were compared. In the first, all sentences, compressed and uncompressed, were produced by one talker. In the second, the talker changed during the uncompressed

<table>
<thead>
<tr>
<th>Preceding context</th>
<th>Before change</th>
<th>After change</th>
<th>First 2 sentences</th>
<th>All 5 sentences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different talker</td>
<td>29.7</td>
<td>31.4</td>
<td>23.9</td>
<td>31.1</td>
</tr>
<tr>
<td>Same talker</td>
<td>31.1</td>
<td>34.2</td>
<td>29.8</td>
<td>34.2</td>
</tr>
<tr>
<td>No preceding</td>
<td>24.3</td>
<td>17.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(no normalization)</td>
<td>Complete context</td>
<td>35.5</td>
<td>29.8</td>
<td></td>
</tr>
<tr>
<td>Same talker</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(full normalization)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
sentences. This condition was added as an alternative way of examining the generalizability of the compression adjustment. In the third condition, listeners heard just one speaker, and the shift was from less compressed (50%) to compressed speech rather than from uncompressed to compressed speech. This condition was added to see whether any influences due to an abrupt change in compression rates would also be found with a less dramatic change in rate. Each of these groups was compared to a group of participants who heard the same sentences with no intervening uncompressed or 50% compressed sentences. This group was drawn from Experiment 1.

As in Experiment 2, three sets of analyses were conducted. In the first set, a potential drop in performance was tested by comparing scores before the change in compression rate to scores after the change. In the second set of analyses, the performance after the change was compared to conditions with no change in compression rate across the four sets and various amounts of prior exposure to compressed materials. Finally, we again looked for evidence of an immediate drop in performance on the first two sentences right after the change in compression rates.

Method

Participants. Sixty undergraduate students at the University of Arizona participated in the experiment. These participants were randomly assigned to one of six groups of 10 participants. They had not participated in Experiments 1 or 2.

Materials. Three of the four sets of sentences spoken by the right after the change in compression rates. This condition was added to see whether any influences due to an abrupt change in compression rates would also be found with a less dramatic change in rate. Each of these groups was compared to a group of participants who heard the same sentences with no intervening uncompressed or 50% compressed sentences. This group was drawn from Experiment 1.

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Table 5
Average Percentage of Content Words Correct for the Sentence Sets Immediately Before and After the Intervening Alternate Rate Set and the Means for the Same Sentence Set for the Control Groups With No Preceding or Intervening Alternate Context

<table>
<thead>
<tr>
<th>Condition no.</th>
<th>Preceding context</th>
<th>Before change</th>
<th>After change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>All 5 sentences</td>
<td>First 2 sentences</td>
</tr>
<tr>
<td>Change conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Uncompressed same talker</td>
<td>25.9</td>
<td>29.6</td>
</tr>
<tr>
<td>2</td>
<td>Uncompressed different talker</td>
<td>27.4</td>
<td>27.1</td>
</tr>
<tr>
<td>3</td>
<td>50% compressed same talker</td>
<td>27.2</td>
<td>32.4</td>
</tr>
<tr>
<td>No change conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>38% compressed same talker</td>
<td>25.7</td>
<td>31.7</td>
</tr>
<tr>
<td>5</td>
<td>No preceding context</td>
<td>20.4</td>
<td>12.9</td>
</tr>
<tr>
<td>6</td>
<td>Complete context same talker</td>
<td>32.8</td>
<td>23.9</td>
</tr>
</tbody>
</table>

Note. Also included are the means for the first sentence, the first two sentences in the set following the alternate rate context.

Further, paired t tests were calculated between the sentence set before a change in compression rate and the average of the first two sentences in the set immediately after a change in rate for the three change conditions and the 38% compression no-change condition (using a corrected alpha of .013). These tests indicated that a change to uncompressed speech produced a significant decline over the first two sentences of the set after a switch back to 38% compression, t(19) = 2.74, p < .013, and t(19) = 2.87, p < .01, for the same talker and different talker conditions, respectively. However, switching to only 50% compressed speech did not result in a significant decrease in performance, t(19) = 1.32, p > .20. Finally, the no-change condition also failed to show a decrease in performance over the same sentences, t(19) = .62, p > .54. Thus, a change in rate to normal speech also seems to have an immediate impact on the adjustment to compressed speech.

Discussion

Overall, these results indicated that adjustment to compressed speech did not cause a return to baseline performance when intervening uncompressed sentences were presented to the listener in either the same voice or a different voice. The presentation of compressed speech at an intermediate rate had a similar effect. However, there were indications of a small drop in performance due to the intervention of the uncompressed speech: The mean recall scores for the compressed sentences immediately following the uncompressed tokens were numerically lower than those of a comparable group of participants who did experience a change in compression rate. This small drop was due to lower performance on the first two sentences after the change, suggesting that a change in rate has a small and immediate impact on the adjustment process. However, this impact does not cause a complete resetting of adjustment parameters to baseline. This suggests that some kind of perceptual learning must be occurring. Finally, these results support the findings from Experiment 2 by again demonstrating that a change in talker has little effect on the adjustment to compressed speech even when that change is combined with a change in compression rates. Apparently, the perceptual mechanism that is responsible for compression adjustment, although influenced by large changes in compression rates, is not influenced by a change in talker characteristics.

General Discussion

The results of the first experiment established that performance improves with increased exposure to compressed speech. In addition, this improvement is specific to compressed speech in that prior exposure to uncompressed or noise degraded speech did not produce improved performance with compressed speech. The adjustment is not immediate, requiring experience with five or more sentences before full adjustment is obtained. Moreover, the time to reach a plateau in performance depends on the rate of compression: Highly compressed stimuli require more time for improvement than less compressed tokens. The second and third experiments extended this research by exploring how an abrupt change in either talker or compression rate or both influences improvement.

Experiment 2 demonstrated that, once listeners have adapted to the compressed speech of one talker, an abrupt switch to a different talker causes a small decline in performance immediately after the switch. Performance does not, however, drop to the level of participants having no prior experience with compressed speech. Moreover, the drop in performance is made up in the next few sentences, indicating that there are considerable savings across talkers. Experiment 3 investigated whether an abrupt shift in compression rates from highly compressed speech to uncompressed speech would influence the adjustment process. The results of the experiment revealed that an interruption by uncom-
pressed speech had little overall impact on the recall scores for compressed speech. There was some evidence of a decrement in performance in the first two sentences after the switch back to compressed speech. However, the decrement was small and by the end of the set, performance had fully recovered. Thus, the adjustment after a change in compression rate or a change in talker is much more rapid than observed on the first exposure to these compressed sentences. These two findings indicate that there are savings from an earlier exposure to compressed speech, although further experiments are necessary to determine the exact nature of such savings and how long it might last.

The results of this study raise the question of the level of speech processing that is responsible for the improvement in the recall scores with highly compressed speech. Speech compressed at high rates presents a challenge to the listener’s processing system at a number of different levels. First, the robustness of various acoustic cues in the signal is severely reduced due to their brief durations. Some cues that are extremely short to begin with (such as release bursts) may be too brief for the perceptual system to detect. In addition, the underlying temporal characteristics of cues such as VOT or transition duration are also dramatically altered. Because the compression algorithm compresses all parts of the speech signal equally, the temporal relationship between cues such as VOT or closure duration to vowel duration are also distorted. Therefore, extraction of phonetic information from compressed speech is severely jeopardized, and it is remarkable that listeners can recognize anything at all. Second, once phonetic representations are determined, whether correct or not, lexical access must then operate with an unusually high rate of phonetic-phonological input. After lexical access has occurred, and barring errors, syntactic integration and semantic interpretation have to cope with the unusually high rate of syntactic-semantic input. Therefore, difficulties are created for the entire speech processing system and adjustments may take place at any of these levels, resulting in an improvement in the recall score of compressed speech over time. In the following discussion, several of these possibilities are addressed.

The present research ruled out the possibility that the improvement in performance reflects the operation of certain task-specific strategies such as the ability to recall the sentences or write down the items on the response sheet. Participants presented with uncompressed training sentences on which they performed the transcription task had no better performance on subsequently presented compressed sentences than participants with no prior exposure to the compressed tokens (see also Mehler et al., 1993). Moreover, no effect of these training sentences was observed even when the sentences were partially masked by white noise, making them as difficult to understand as the compressed versions. Improvement occurred only when the training sentences were compressed.

We also judge it unlikely that the improvement reflects improved guessing of unperceived words based on the words that were accurately perceived. Participants initially recalled fewer than 30% of the words at the 38% compression rate, which does not provide much of a context in which guessing strategies can operate. In addition, the results of Experiment 1 indicate that the compression rate influences the gradient of adjustment. The higher the compression rate, the more exposure is required before performance reaches a plateau. Importantly, this difference in gradient is maintained even when the number of recalled words is globally equated between the two rates. This indicates that it is compression rate, and not the amount of recalled words, that determines the gradient of adjustment. This finding is consistent with those of Mehler et al. (1993), who reported that monolingual Spanish speakers can benefit from hearing compressed sentences in Catalan, a language they do not know (and for which they can hardly understand anything). In other words, comprehension of the message may not be necessary for adaptation to compressed speech to occur (for a similar finding, see Altmann & Young, 1993). Therefore, although the possibility of improvement at late levels of processing cannot be ruled out, it is unlikely that they are the only factors in the adjustment to highly compressed speech.

Another possibility is that the improvement reflects adjustments occurring at early levels of speech processing in which the acoustic signal is mapped onto underlying phonetic representations. As described previously, past studies have demonstrated that certain perceptual criteria at the acoustic-phonetic level can be modified by variations in speaking rate. Given that compressing speech dramatically alters the physical and perceived rate of the sentences, it is plausible that some portion of the adjustment to compressed speech was the result of low-level tuning of the perceptual system such as occurs during rate normalization. Some of the results from the current study do seem to reflect rate adjustments in phonetic perception. For example, there was a small and immediate drop in performance as a result of changing talker, compression rate, or both, which is reminiscent of similar effects in rate normalization studies.

However, the results of the current study reveal some important differences between compression adjustment and rate normalization. First, the adjustment to compressed speech occurs over a number of sentences whereas rate normalization operates over a fairly small, local context. Most studies on rate normalization randomize their test trials such that the rate of either the precursor phrase or the syllable itself varies from trial to trial. If the system did not respond within a single trial, there would be little difference in the phoneme boundaries across the entire experiment. Second, although there was evidence for a drop due to a change in talker and compression rate, this drop was small and did not reset performance to baseline. In other words, unlike in rate normalization studies, compression adjustment shows considerable savings through changes in talker characteristics. Moreover, once stable performance has been reached for compressed speech, the level of performance is

\[7\text{However, we cannot rule out the possibility that the nonlocal character of our effects are due to the extreme range of compression rates that we are using.}\]
roughly maintained despite the presentation of intervening materials spoken at a very different rate.

We speculate that adjustment to compressed speech may be the result of two processes operating simultaneously: a short-term adjustment to local speech rate parameters (that would be related to rate normalization in phonetic processing) and a longer term adjustment reflecting a more permanent perceptual learning process. This long-term adjustment would operate on a level of representation abstract enough that the acoustic differences between talkers no longer matters. As in other cases of perceptual learning (e.g., Schwab et al., 1985), it would involve a long-term memory component.

What could be the purpose of such a long-term adjustment? One possibility is that it is used to compensate for the fact that talkers vary in their overall articulation rates (Miller, Grosjean, & Lomanto, 1984) and in the way in which they realize their articulatory targets according to speech rate, phonological context, and dialect. To operate under optimal conditions for all talkers, the perceptual system may extract a set of phonetic–phonological parameters that work best in a given situation and store them for later use.

In perception of compressed speech, some of the cues for a phonetic segment might be lost in the compression process or misapplied to another segment. Alternatively, even when phonetic information is recovered correctly, it could be inappropriate to the current speech rate. For example, the compression algorithm does not flap or spread nasality. However, the phonological–lexical system might expect these phonetic changes to be present at these speaking rates and attempt to overcorrect for them. Therefore, it may be that the phonological–lexical component has to adjust for what is essentially a new speech style, perhaps in the same way that it handles foreign accents or dialects. This hypothesis would account for the fact that, once the adjustment to fast speech has been learned for a given talker, there will be (a) considerable savings for a different talker (at least, of the same dialect) and (b) savings that persist over an extended period of time (the only cost being in retrieving the phonetic–phonological mapping rules appropriate for that particular input on later occasions).

In summary, adaptation to compressed speech is an interesting phenomenon that raises many questions related to speech perception and spoken language processing. The purpose of the current study was to establish the phenomenon and suggest some directions for future research. We expect that examining how listeners adjust to highly compressed speech will provide further insight into the mechanisms involved in spoken language processing.

References


APPENDIX

MATERIALS

The 20 sentences used in the experiment:
1. Mother yelled at Billy because he never eats fresh fruit.
2. During home football games we drink lemonade and eat peanuts.
3. Sally wanted fresh fish but could only buy it frozen.
4. Every girl who phoned Mary heard exactly the same story.
5. After a hard day's work William goes directly to bed.
6. A man who loved fresh vegetables wanted to grow cucumbers.
7. Behind the wooden fence Sam watched the construction crew working.
8. The oranges that grow in Nancy's yard taste very bitter.
9. Randy has never left the country or even the state.
10. A painting that cost a million dollars was stolen yesterday.
11. Above Susan's head large black spiders crawled on the ceiling.
12. From disease and rot the large oak timbers finally collapsed.
13. The woman who won the lottery last week quit working.
14. An apple that is baked without cinnamon tastes very bland.
15. The famous author who opened the program told clever jokes.
16. Linda called home shortly after she got her big promotion.
17. The angry teacher made Tommy write sentences on the board.
18. Many passengers saw the cruise ship strike the fishing boat.
19. Mark only makes mistakes when the supervisor checks his work.
20. Near the old red building many different desert plants grow.

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