Speech perception and phonemic restorations*

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When a speech sound in a sentence is replaced completely by an extraneous sound (such as a cough or tone), the listener restores the missing sound on the bases of both prior and subsequent context. This illusory effect, called phonemic restoration (PhR), causes the physically absent phoneme to seem as real as the speech sounds which are present. The extraneous sound seems to occur along with other phonemes without interfering with their clarity. But if a silent gap (rather than an extraneous sound) replaces the same phoneme, the interruption in the sentence is more readily localized in its true position and PhRs occurs less frequently. Quantitative measures were taken both of the incidence of PhRs and of the direction and extent of temporal mislocalizations of interruptions for several related stimuli under a variety of experimental conditions. The results were connected with other auditory illusions and temporal confusions reported in the literature, and suggestions were made concerning mechanisms employed normally for verbal organization.

We frequently listen to conversation under conditions that are less than ideal, with extraneous sound interfering with, and occasionally obliterating, individual speech sounds. Of course, speech usually contains considerable redundancy, so that it is not surprising that comprehension is possible under such noisy conditions. However, it is surprising that our mechanisms for speech comprehension are so compelling that a listener cannot distinguish between speech sounds physically present and those perceptually synthesized on the basis of context. A preliminary report by Warren (1970) described how a listener to a sentence in which a cough replaced completely a phoneme, not only heard the missing sound clearly, but mislocalized the cough, judging the extraneous sound to occur several phonemes away from its actual location. However, if a silent gap replaced the speech sound, the absence of the phoneme could be detected, together with correct localization of the gap.

Phonemic restorations (PhRs) offer promise as a method for investigating the effect of verbal context upon perception and for probing the mechanisms used for temporal integration of speech. The present study was designed to explore further the nature of PhRs and their relationship to other phenomena.

METHOD

Subjects

The 180 Ss were students from the introductory course at the University of Wisconsin-Milwaukee. Each S served in only one of the nine groups of 20 Ss. They had no known history of auditory impairment and no prior experience with experiments dealing with localization of events in sentences.

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Stimuli

A single channel of an Ampex PR 10 recorder operated at 15 ips was employed to obtain a master recording of a male voice, reading the following statement clearly and at a normal rate: "The state governors met with their respective legislatures convening in the capital city." The duration of the sentence was 4.1 sec. This recording was used for the preparation of the eight different stimulus tapes used in this study.

A tape containing a short 0.5-msec click in the middle of the phoneme /s/ (the first letter "s") in the word "legislatures" was prepared by tapping the record key for Channel 2 (the blank channel) of the master tape while the tape was held stationary against the recording head. The stimulus tape was then prepared by mixing the output from the two channels and re-recording at 7½ ips on a Sony TC-530 recorder. The intensity of the click approximated the loudest speech sound in the sentence.

A second stimulus containing a silent gap replacing the unvoiced consonant /s/ in "legislatures" was prepared as follows. The portion of the tape containing the recorded target sound was determined by drawing the tape manually over the playback head at slow speed while listening through headphones at high amplification. The limits of the target phoneme were marked on the back of the tape. This /s/ (about 70 msec) was excised from the tape along with approximately 25-msec segments from the preceding and from the following speech sounds (these portions of the adjacent phonemes were deleted in order to minimize transitional cues to the identity of the missing sound). The 120-msec gap was replaced by a spliced section of tape of the same length, which was acoustically equivalent to the "silent" portions of the recorded sentence (new tape was not used since it is noticeably different from recorded "silence"). The complete absence of the aperiodic noise corresponding to the target, /s/, was confirmed by drawing the tape slowly over the playback head, and also by examining a sound spectrogram of the sentence (prepared with a Kay Model 7029A sound spectrograph). The stimulus tape employed in the experiment was made by re-recording this spliced tape, using a Sony TC-530 recorder at 7½ ips.

The master tape with the 120-msec silent gap was employed for the preparation of six additional stimuli containing specified extraneous sounds rather than a silent gap. The procedures used for preparing five of these tapes were equivalent: The splice was opened, and a 120-msec portion of prerecorded tape containing the desired signal was spliced in its place. After rerecording from the master tape as described above, the splice was opened, and another segment of tape of the same duration and different acoustic signal was spliced in its place. The tapes prepared in this fashion contained the following extraneous sounds, replacing the original /s/ in "legislatures": (1) cough (peak level 8 dB above peak intensity of sentence); (2) loud 1,000-Hz tone (level 8 dB above peak intensity of sentence); (3) soft 1,000-Hz tone (level equivalent to peak level of sentence); (4) loud buzz (40-Hz square wave, level 8 dB above peak level of sentence); (5) soft buzz (40-Hz square wave, level equivalent to peak level of sentence). A final tape was prepared in which a cough replaced the sounds corresponding to the syllable "gis" in "legislatures." For this last tape, the deleted portion of the sentence was extended by removing an additional 90-msec segment of the tape, starting with the silent interval preceding the plosive release corresponding to the onset of the syllable "gis." The end of the deleted portion was the same as for the stimuli with the missing /s/, so that a total of 210 msec was removed from the sentence. The complete absence of the syllable "gis" was confirmed by sound spectrographs. In place of "gis" a cough of the same duration (210 msec), with an intensity 11 dB above the peak level of the sentence, was spliced into the master tape, and the stimulus tape was prepared by rerecording in the standard fashion described above.

Procedure

Ss were tested singly in an audiometric room. All Ss read the instructions appropriate to their group before hearing

Table 1
Median Error Magnitudes for Temporal Localization by Groups of 20 Listeners, Each Making Four Successive Judgments (The First and Third Quartiles are Given in Parentheses)

Target	Medians and Quartiles in Phonemic Units			
	First Judgment	Second Judgment	Third Judgment	Fourth Judgment
1. Cough replacing phoneme	5.5 (3.5, 10.7)	5.0 (2.2, 5.7)	3.5 (1.8, 5.2)	2.6 (1.3, 4.7)
2. As 1, but partial disclosure*	5.2 (2.2, 9.0)	2.0 (1.0, 5.7)	1.5 (1.0, 5.0)	1.5 (1.0, 4.5)
3. Loud tone replacing phoneme	3.2 (2.8, 8.5)	2.8 (1.0, 4.0)	1.2 (1.0, 2.8)	2.8 (1.3, 4.5)
4. Loud buzz replacing phoneme	3.2 (2.8, 7.5)	2.4 (1.0, 3.7)	1.6 (0.8, 3.2)	1.0 (0.5, 2.1)
5. Soft tone replacing phoneme	4.5 (2.6, 15.7)	2.4 (1.4, 3.2)	2.8 (0.5, 3.7)	1.5 (1.0, 2.8)
6. Soft buzz replacing phoneme	4.2 (1.5, 11.5)	3.5 (1.5, 5.0)	2.2 (1.2, 4.2)	1.5 (1.0, 4.2)
7. Silent gap replacing phoneme	1.7 (1.5, 7.0)	0.5 (0.0, 2.5)	0.5 (0.0, 1.4)	0.5 (0.0, 1.7)
8. Click within phoneme	6.4 (2.9, 11.2)	3.7 (2.0, 6.0)	3.2 (1.5, 6.0)	3.0 (2.5, 4.7)
9. Cough replacing three phonemes	2.0 (0.6, 5.7)	2.0 (0.3, 6.0)	0.8 (0.1, 2.0)	0.8 (0.0, 2.0)

***Listeners were informed that the cough completely replaced one or more speech sounds.**

any stimulus or seeing the answer sheet with the typewritten stimulus sentence. The group informed about the physical nature of the stimulus (i.e., substitution of a portion of the sentence by an extraneous sound) read the following instructions: "You will hear a sentence spoken clearly. A portion of the sentence has been cut out of the tape recording and replaced by a recorded cough. You are to indicate the missing sound(s) by placing a circle around the *exact* place in a typewritten statement of the sentence." The other eight groups read the following instructions, except that the word describing the stimulus was changed from "cough," as given below, to "tone," "buzz," "click," or "silent gap" when appropriate: "You will hear a sentence spoken clearly. A cough will occur at some time during the sentence. You are to indicate where you think the cough occurred by placing a circle around the *exact* place in a typewritten statement of the sentence. You are to indicate also whether the cough completely replaced the sound(s) which you circle."

After reading the appropriate instructions, the stimulus sentence was heard binaurally through matched TDH 49 headphones, at a peak speech level of 80 dB (re 0.0002 microbars).

With all groups, immediately after hearing the auditory stimulus, Ss were given the answer sheet described in the instructions, which contained a typewritten statement of the intact stimulus sentence ("The state governors met with their respective legislatures convening in the capital city"). After they marked the location in the sentence where they thought the interruption occurred and (except for the group informed about the deletion from the sentence) indicated whether they thought the interruption replaced completely a speech sound or sounds, the answer sheet was removed, and the same stimulus was presented again. S was then presented with a fresh answer sheet (identical with the first) for marking his responses to the second presentation. After removing this answer sheet, the process was repeated for a third presentation of the stimulus, followed by a new answer sheet. The fourth and last presentation differed from the others in that the fresh answer sheet was presented *before* the auditory stimulus, so that S could read the sentence as he listened.

RESULTS

In scoring errors in the positions marked by Ss for the locations of extraneous sounds or phonemic gaps, the letter or letters corresponding to single phonemes and the spaces between individual printed words on the answer sheets each were counted as one position, and the total number of positions separating the circled portion of the printed sentence from the true location was calculated. When more than one position was circled, then the score for each of these positions was calculated separately and averaged to give a single score for the response. Because of occasional extreme scores, medians were used rather than means. In Table 1 for error magnitudes, the direction of error (i.e., whether the reported position preceded or followed the actual position) was ignored, and all deviations were given the same sign. In Table 2 for temporal direction of errors, responses were scored as positive if they followed the actual position and negative if they preceded this position. Hence, it is possible for scores for a particular group to be high in Table 1 and low in Table 2, if the errors were distributed fairly symmetrically on both sides of the correct position (as was the case with clicks).

The cough may be considered as a familiar phonemic masking sound encountered frequently outside the laboratory, and for the first judgments (Ss with no prior knowledge of the stimulus) the magnitude of error shown in Table 1 for the cough replacing /s/ was not significantly different from that observed with the less familiar tones or buzzes (Mann-Whitney U tests). However, the same statistical test showed that the error for first judgments with this cough was significantly greater than the corresponding error for the silent gap ($p < .05$) and for the cough replacing "gis" ($p < .05$).

It might be anticipated that the magnitude of errors would decrease with knowledge of the stimulus. Table 1 shows that such changes did occur, with a tendency for the error magnitude to decrease for the second judgment and to decrease further with subsequent judgments. Comparing the first with subsequent responses within each group, the decrease in error magnitude reached

Table 2
Median Temporal Direction Errors by Separate Groups of 20 Listeners, Each Making Four Successive Judgments (The First and Third Quartiles are Given in Parentheses)

Target	Medians and Quartiles in Phonemic Units			
	First Judgment	Second Judgment	Third Judgment	Fourth Judgment
1. Cough replacing phoneme	−2.0 (−10.7, +5.0)	+3.7 (−1.0, +5.2)	+2.7 (+0.7, +4.5)	+2.0 (+0.5, +4.0)
2. As 1, but partial disclosure*	−4.0 (−8.5, +0.5)	−0.2 (−1.0, +2.7)	+1.5 (−0.2, +5.0)	+1.5 (+0.5, +5.2)
3. Loud tone replacing phoneme	−1.8 (−5.2, +1.0)	−1.0 (−3.3, +1.0)	−0.5 (−1.0, +1.0)	+1.0 (−0.5, +2.5)
4. Loud buzz replacing phoneme	−2.5 (−6.0, +1.0)	+0.5 (−2.2, +1.5)	−0.5 (−2.5, +0.7)	−0.5 (−1.0, +0.2)
5. Soft tone replacing phoneme	−4.5 (−15.7, −0.7)	−1.5 (−3.0, +1.0)	+0.2 (−2.2, +1.0)	0.0 (−1.5, +1.0)
6. Soft buzz replacing phoneme	−3.2 (−11.5, −1.0)	−0.5 (−3.2, +3.7)	−0.2 (−3.0, +1.5)	−0.5 (−3.5, +1.2)
7. Silent gap replacing phoneme	+1.2 (−0.5, +2.2)	0.0 (0.0, +0.7)	0.0 (0.0, +1.0)	0.0 (0.0, +0.7)
8. Click within phoneme	+1.2 (−3.0, +7.0)	+3.0 (+0.7, +5.7)	+2.7 (−0.2, +5.5)	+2.5 (−0.2, +4.2)
9. Cough replacing three phonemes	−0.1 (−1.8, +1.3)	+0.3 (−0.3, +2.0)	0.0 (−0.1, +1.5)	+0.2 (0.0, +1.5)

**Listeners were informed that the cough completely replaced one or more speech sounds.*

Table 3
Percentage of Separate Groups of 20 Listeners Judging that the Auditory Target Did Not Replace Any Speech Sound

	First Judgment	Second Judgment	Third Judgment	Fourth Judgment
1. Cough replacing phoneme	95	70	80	95
2. As 1, but partial disclosure*	--	--	--	--
3. Loud tone replacing phoneme	100	95	85	95
4. Loud buzz replacing phoneme	75	85	95	100
5. Soft tone replacing phoneme	90	70	70	70
6. Soft buzz replacing phoneme	90	80	95	85
7. Silent gap replacing phoneme	65	35	35	30
8. Click within phoneme	100	100	95	100
9. Cough replacing three phonemes	90	85	90	95

**Listeners were informed that the cough completely replaced one or more speech sounds.*

significance for each of the nine groups at the .05 level by the third judgment (Wilcoxon signed-ranks test, one-tailed).

Table 2 shows that for the first presentation, all seven groups presented with an extraneous sound replacing the /s/ judged that sound to occur earlier than its actual position. The probability of all seven groups in this category having the errors in the same direction by chance is $(\frac{1}{2})^6$, or $p = 1/64$. When these seven stimuli were presented for a second time (so that Ss then knew the sentence), the extraneous sound seemed to come later for all seven groups (the probability of seven values changing the same direction by chance is again 1/64).

When heard for the first time, the click seemed to occur after its actual position in the sentence and, hence, differed in direction of error from all the first judgments with the longer extraneous sounds which completely replaced the /s/ (see Table 2). This table shows that the median for directional errors for first judgments with clicks was relatively small (+1.2 units), while the corresponding click error magnitude shown in Table 1 was large (6.4 units, the greatest error in the table), indicating that, while Ss were badly confused concerning the location of the click, little systematic bias existed toward early or late localization.

Table 3 shows that, for first judgments, most Ss in each of the groups which were uninformed concerning the deletion of a portion of the sentence thought that the target did not replace any speech sound. The group with the lowest percentage of Ss having this belief had a silent gap as their target. Fisher's exact-probability test showed that the differences for gap vs loud tone and gap vs click were both significant at $p < .005$, and gap vs cough replacing /s/ was significant at $p < .05$. By the second judgment most Ss presented with the silent gap judged that it completely replaced one or more speech sounds, and most of these Ss who believed that complete replacement occurred identified correctly the missing phoneme. It is interesting to consider the numbers of totally correct responses, that is, responses in which the target sound was both correctly localized and recognized as replacing (rather than coexisting with) speech sound(s). This information is not available from the tables. Out of a total of 80 responses by the group presented with the silent gap, 24 were correct, while there was only 1 correct response out of the total of 560 responses by the seven groups hearing complete replacement by extraneous sounds. The performance of the group hearing the cough with the disclosure that a portion of the sentence was completely replaced by a cough was noteworthy, in that knowledge of the nature of the stimulus did not permit any of the 20 Ss to correctly localize the position of the extraneous sound.

DISCUSSION

The present study confirms and extends the preliminary report by Warren (1970). Our observations can be described in terms of two separate but related effects. First, the missing phonemes seem to be present. This has been called the phonemic restoration effect. The speech sounds synthesized through phonemic restorations (PhRs) cannot be distinguished by the listener from those physically present. Even prior disclosure that one or more of the sounds were replaced completely by an extraneous sound did not enable S to detect which sound was missing. Second, the extraneous sound (such as a cough) could not be located at its true position in the sentence. This nonspeech sound is perceived as coexisting with, but not interfering with, the intelligibility of phonemes actually present.

These two effects of substitution are not limited to any special sort of extraneous sounds, since the three different types of sound employed in the present study (tones, buzzes, and coughs) all produced similar results. Changing the intensity of the extraneous sounds from approximately that of the peak speech level to a level about 10 dB higher did not appear to have any appreciable influence upon responses. At these intensities, the extraneous sounds would be expected to at least partially mask the phoneme were it present rather than completely deleted. When a silent gap rather than an extraneous sound replaced the phoneme, correct localization of the interruption in the sentence and recognition of the complete absence of the phoneme were both accomplished more readily. With presentation of the stimulus with the silent gap again to the same Ss, still fewer PhRs occurred, and more Ss localized the gap correctly. This is in contrast with the effect of repeated presentation of stimuli with extraneous sounds; with these sentences there were no decreases in the initially high proportion of PhRs, nor was there any increase in the numbers of Ss correctly localizing the interruption.

Some insight into mechanisms is afforded by the following observations. When heard for the first time, the extraneous sounds replacing the phoneme were all located at positions earlier in the sentence than their actual occurrence. When heard again by the same S, localization of the nonspeech sound shifted to a later position. The short click (which did not replace a phoneme), when heard for the first time, was judged to occur later in the sentence than the longer extraneous sounds, and hearing the sentence with the click more than once caused little change in judgments. These quantitative data suggest that, with an unfamiliar sentence, the speech sounds in the neighborhood of the replaced phoneme (which furnish the context necessary for PhRs) were unavailable for perceptual identification while the missing phoneme was being synthesized. This delay in processing the phonemes would have caused the perceptually isolated marker furnished by the extraneous sound to be identified with an earlier portion of the sentence. Prior knowledge of the sentence, or presentation of a short extraneous sound along with a phoneme (the short click), would be expected to eliminate the delay associated with the initial phonemic synthesis, and, indeed, it was found that there was no consistent direction of temporal bias under these conditions. However, accurate identification of location was still not possible. Even after three prior presentations of the stimulus and with a printed version of the sentence in view during the fourth auditory presentation, Ss could not identify accurately the position of any of the extraneous sounds.

The inability to identify the position of an extraneous sound in a sentence was first reported by Ladefoged and Broadbent (1960). They used short clicks and hisses and, since care was taken not to delete any phoneme, only mislocalizations were discovered, and not PhRs. They found that most judgments of the position of the short extraneous sound preceded the actual position and suggested that this mislocalization might be related to the classical concept of "prior entry" (i.e., a predisposition to react to a particular stimulus reduces the time necessary for this stimulus to reach consciousness). A rather different view concerning the mislocalization of short extraneous sounds in sentences has been put forward by others (Garrett, 1965; Garrett, Bever, & Fodor, 1966; Fodor & Bever, 1965; Bever, Lackner, & Kirk, 1969; Bever, Lackner, & Stolz, 1969). In these studies, as in the Ladefoged and Broadbent work, the extraneous sound did not replace or mask any phoneme. The general conclusions of these investigators were that the direction and magnitude of the displacement of the click reflected aspects of sentence deep structure, sentence surface structure, and transitional probabilities within clauses, as well as interactions between these variables in a rather complex fashion. Some of the assumptions underlying these conclusions have been questioned by Ladefoged (1967).

There is an important point which should be noted concerning the nature of mislocalization of extraneous sounds (whether clicks or longer sounds replace phonemes): they represent a confusion rather than an illusion in the classical sense.

Listeners do not believe that they can localize the extraneous sound accurately, and when required to give a definite response, they guess. A recent report from our laboratory indicated that gross confusion and errors may occur generally for temporal localization within auditory sequences other than speech and music–for example, series consisting solely of successive hisses, buzzes, and tones (Warren, Obusek, Farmer, & Warren, 1969).

We suggested that extraneous sounds in sentences are not special in being subject to a confusion of temporal localization. Rather it may be that sequences of those sounds employed in speech and music are special in being subject to accurate temporal ordering.

Auditory perception in our daily lives does not involve localization of extraneous sounds in sentences or identification of the order of a series of arbitrary and normally unrelated sounds. However, we do encounter conditions that may require PhRs. Consider a "dinner party problem" in which the listener is faced with the task of understanding what an after-dinner speaker is saying, despite transient sounds (coughs, clattering dishes, laughter, crunching sounds of the listener's own chewing, etc.) which mask entire phonemes and groups of phonemes. Comprehension requires that the listener clarify disrupted speech sounds and replace obliterated (masked) phonemes. While such an occasion might represent an extreme example of difficult listening conditions, extraneous sounds capable of masking phonemes are probably encountered quite frequently. It is well known that listeners with mastery of a language can comprehend speech when portions are obliterated, presumably using the redundancy provided by the intact context to maintain intelligibility. PhR may represent an essential mechanism leading to such comprehension–so that PhR is not only an illusion, but a well-practiced skill aiding in extraction of meaning from discourse heard under the noisy conditions of everyday life. Evidence supporting this view of PhR as an aid to speech comprehension is afforded by an experiment by Cherry and Wiley (1967) dealing with a comparison of the effect of silent gaps vs noise upon speech intelligibility, which will be discussed shortly.

It is of interest that our study has shown that we can both locate the silent gap and recognize that it replaces the phoneme, yet we can do neither when an extraneous noise is used rather than silence. Our perceptual reactions to the silent gap are not surprising; it is the existence of PhRs for extraneous sounds that raises questions concerning the special status of silence. It is as if an erasure of a letter in a printed text could be detected, while an opaque blot over the same symbol would result in illusory perception of the obliterated letter, with the blot appearing as a transparent smear over another portion of the text. Clearly, mechanisms of perceptual "closure" applicable to both vision and hearing do not hold here, and the basis for the differences in response to a silent gap and an extraneous sound is to be sought in special features of auditory perception. Nonspeech sounds occurring during speech are interfering stimuli extrinsic to the discourse which are to be discounted to maximize comprehension, while silent intervals must be intrinsic and due directly to the speaker. Further, silent pauses have significance in speech and can function as "suprasegmental phonemes" designated by appropriate phonetic symbols. Hence, accurate perception of the silent gap in our experiments may reflect the listeners' skill in locating silent intervals as a part of normal speech perception.

In our experiments, intelligibility of the sentence is not influenced by the presence or absence of PhRs. The context is quite adequate to ensure that the word with the deleted speech sound is understood as "legislatures," regardless of PhR. Cherry and Wiley (1967) reported an interesting experiment involving the intelligibility of speech having many gaps. These gaps were either left silent or filled with white noise. They were concerned with how well selections read from literature were understood, rather than with recognition of phonemes or even single words. Intelligibility was increased markedly when white noise rather than silence filled the intervals between the fragments of speech sounds. These results were confirmed by Holloway (1970). Our study suggests that this increase in intelligibility might have involved PhRs for gaps filled with noise. Unfilled gaps might inhibit PhRs, as in our study, and lead to the paradoxical function of silence as a masking agent with regard to intelligibility. Noise, then, furnishes a release from this masking by silence.

In the discussion thus far we have not distinguished past from subsequent context in relation to PhRs. In our stimulus sentence, the context prior to the missing /s/ in "legislatures" was sufficient to identify the missing phoneme. However, it is possible to arrange the information so that *subsequent* context is necessary to identify the missing sound. As one example, if a cough is followed directly by the word fragment "ave" in the sentence beginning "There was time to (?)ave . . .," the missing fragment, on the basis of prior context, could be shave, save, wave, rave, etc. If a subsequent portion of the sentence refers to activity directed toward departing friends, the appropriate PhR would be /w/. Some preliminary experiments in this laboratory by Gary Sherman have shown that listeners can indeed store the auditory information until subsequent context identifies the phoneme obliterated by an extraneous sound and then "hear" the missing phoneme as a PhR. Further study is under way to determine, among other factors, the limit of temporal separation between the ambiguous stimulus fragment and the resolving context which will still permit PhRs.

PhRs seem to involve skilled storage of auditory information, with final perceptual synthesis dependent upon both prior and subsequent context. Such a mechanism has been proposed and described in some detail in connection with the verbal transformation effect (Warren, 1968).

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