Received 21 August 1967 9.7, 9.6

Metamorphosis of a Critical Interval: Age-Linked Changes in the Delay in Auditory Feedback that Produces Maximal Disruption of Speech

DONALD G. MACKAY*

Massachusetts Institute of Technology, Cambridge, Massachusetts 90024

A developmental study of delayed auditory feedback (DAF) indicated that: (1) DAF disrupts the speech of children more than adults, for all delays in feedback; (2) The delay for maximal interference varies with age. The older a subject, the shorter the delay producing maximal interference with his speech; (3) The peak interference delay remains at 0.2 sec, when adults reduce their rate of speech by drawing out speech sounds. This finding suggested that the critical DAF interval is independent of the duration of speech sounds in the returning auditory signal; (4) Slowing down the rate of speech as described above, reduced the amount of stuttering under DAF; (5) However, a subject's maximum rate of speech was significantly correlated with the duration of the delay producing maximal interference with his speech. The slower the subject's maximum rate of speech, the longer the peak interference delay. A correlation of maximum speech rate and frequency of DAF stuttering was also significant. The slower a subject's maximum speech rate, the more he tended to stutter under DAF. Since voluntary prolongation of speech sounds had the opposite effect, decreasing rather than increasing stuttering, it was suggested that: (1) Mechanisms determining the maximum speech rate are to some extent different from those governing the prolongation of speech sounds; (2) both the amount of stuttering under DAF and the peak interference delay are related to some as yet unknown factor or set of factors determining the maximum rate of speech, and, (3) this factor is age-linked since the maximum rate of speech varies inversely with age.

INTRODUCTION

WHEN an adult speaker hears what he says delayed for approximately $\frac{1}{5}$ sec, his speech will become disorganized.[1] He will stutter, prolong speech sounds, and even produce phonemes that are not part of any language he has ever learned.[2] However, delays in feedback longer or shorter than the critical 0.2 sec disrupt his speech output less.[3]

Several years ago, Chase *et al.*[4] reported that delayed auditory feedback (DAF) impairs the speech of young children (age 4 to 6) less than the speech of older children (age 7 to 9). Chase and his collaborators[4] and Smith[5] considered this developmental difference to reflect an increasing tendency for children to pay attention to their own speech as they grow older. If the precision in auditory monitoring of speech is assumed to develop with age, it seemed logical that a disturbance due to altered auditory feedback should become correspondingly more severe with age.

However, studies of DAF, since 1961, have demonstrated the importance of several uncontrolled parameters in Chase's study, which might allow alternative explanations of his results. The present study was designed to investigate the hypotheses outlined below.

A. Critical-Interval Hypothesis

Chase and his co-workers[4] employed only a single feedback delay (0.2 sec) in their study of DAF in children. However, it is conceivable that the critical feedback delay for younger children might differ from that for older children and adults. This being the case,

* Present address: Psychology Department, University of California at Los Angeles, Los Angeles, California 90024.

[1] B. S. Lee, "Effects of Delayed Speech Feedback," J. Acoust. Soc. Am. 22, 824–826 (1950).

[2] G. Fairbanks and N. Guttman, "Effects of Delayed Auditory Feedback upon Articulation, J. Speech and Hearing Res. 1, 12–22 (1958).

[3] G. Fairbanks, "Selective Vocal Effects of Delayed Auditory Feedback," J. Speech Hearing Disorders 20, 333–346 (1955).

[4] R. A. Chase, S. Sutton, D. First, and J. Zubin, "A Developmental Study of Changes in Behavior under Delayed Auditory Feedback," J. Genetic Psychol. 99, 101–112 (1961).

[5] K. U. Smith, *Delayed Sensory Feedback and Behavior* (Saunders, Philadelphia, Pa., 1962), pp. 35–58.

Chase's single delay may have been closer to the critical value for his older children (age 7 to 9) than for his younger ones (age 4 to 6). As a result, the speech disruption might have been maximal for his older children, but less than maximal for his younger children. At some other delay in feedback, the speech of very young children might be greatly disrupted, possibly as much as adult speech, with a delay of 0.2 sec. In the present study, the delay in feedback was systematically varied from 0.1 to 0.75 sec in order to determine whether the critical interference delay varies with age.

B. Rate-of-Speech Hypothesis

Another interpretation of the findings of Chase and his co-workers (1961) focuses on the increasing rate of speech during childhood. Younger children usually speak more slowly than older children and adults.[4]

Beaumont and Foss[6] and Fillenbaum and Wiessen[7] suggested that reducing the rate of speech of adults may diminish the severity of DAF speech disruption. Thus, younger children may be less severely affected by DAF because of their slower rate of speech.

However, there are theoretical grounds for suspecting that reducing the rate of speech may lengthen the delay for maximal interference under DAF. Several investigators have suggested that the most disruptive DAF interval (0.2 sec) may be related to the modal duration of some segment of the speech signal such as the syllable.[3,8] All speech units in the auditory signal would tend to be lengthened when the rate of speech is reduced by prolonging speech sounds.[9] Thus, a "peak-shift" hypothesis suggests that the optimal delay for interference might be longer than 0.2 sec when speech units are lengthened in this way.

We therefore attempted to determine whether the DAF interval producing the most stuttering would change, when adults slow down their speech under DAF. If the critical delay depends on the speech rate in this way, and the rate of speech is the only factor differentiating in the DAF disturbance in children and adults, then a longer critical interval might be expected for maximal disruption of the slower speech of children.

The null hypotheses of the present study can now be summarized as follows:

(1) DAF disrupts the speech of children less than that of adults for all delays in feedback.

(2) The delay producing maximal disruption of a subject's speech does not vary with age.

(3) When adults reduce their rate of speech under DAF, their stuttering will diminish, without changing the delay in feedback that produces maximal disruption of their speech (0.2 sec).

I. APPARATUS

The method of delaying feedback is quite simple. A subject's speech is recorded on tape and then returned to his ears after the appropriate interval. Two Ampex PR 10 tape recorders (each with three heads) were used for this purpose in the present study. Varying the tape speed and the distance between the heads achieved delays in feedback of 0.100, 0.150, 0.200, 0.263, 0.375, 0.524, and 0.750 sec. A zero delay or synchronous feedback condition made eight values on this dimension. For all feedback conditions, the subject was wearing Layfayette stereo headphones (model F-767). An Astatic Electrovoice micorphone was adjusted to about 6 in. from his lips. The microphone was connected to a Dynaco Amplifier and magnetic playback preamplifier. This amplification system transmitted signals to the earphones with a gain of approximately 45 dB. Thus, the subject heard his speech amplified by 45 dB for both delayed- and synchronous-feedback conditions.

II. PILOT STUDIES

Since many of the younger children were unable to read, our choice of experimental procedure was limited to either spontaneous speech or sentence repetition. These two techniques were compared in a pilot study with two subjects in each of the following age classes: 4–6, 7–9, and 20–26.

A. Spontaneous Speech

In this procedure, S was presented with a picture from Carroll,[10] mounted on an adjustable stand above the microphone. The subject was simply asked to describe the picture spontaneously, in his own words, and at his own rate of speech. He was warned that he might make mistakes, but that he was not to worry about them. A different picture was presented for each of six delay conditions, 0 (for synchronous feedback) 0.1; 0.2; 0.375; 0.524; and 0.750-sec delays. Examples of the types of utterances the children produced in this condition are: *a girl holding an umbrella; a rabbit drinking a bottle of wine, sorry about that, chief.*

The time to produce at least 25 syllables was then determined, excluding all pasuses longer than 1.0 sec. Dividing the output time by the number of correctly produced syllables gave us a measure of the correct syllable interval (in seconds per syllable). This measure of speech rate was then plotted for each group of pilot

[6] J. T. Beaumont and B. M. Foss, "Individual Differences in Reacting to Delayed Auditory Feedback," Brit. J. Psychol. 48, 85–89 (1957).

[7] S. Fillenbaum and R. Wiessen, "Contextual Constraints and Disruptions in Reading with Delayed Auditory Feedback," J. Acoust. Soc. Am. 33, 1800–1801 (1961).

[8] J. W. Black, "The Effect of Delayed Side-Tone upon Vocal Rate and Intensity," J. Speech and Hearing Disorder 16, 56–60 (1951).

[9] V. A. Kozhevnikov and Luidmila A. Chistovich, "Speech: Articulation and Perception," (U. S. Government Printing Office, Washington, D. C., 1966), pp. 1–250.

[10] L. Carroll, *Alice's Adventures under Ground* (General Publishing, Toronto, Ont., Canada, 1965) (a facsimile of the 1864 manuscript), pp. 1–3.

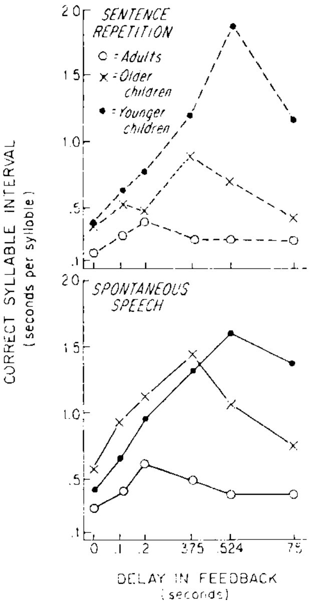

FIG. 1. The CSI (in seconds per syllable) as a function of feedback delay for (a) sentence repetition, and (b) spontaneous speech.

subjects as a function of feedback delay [see Fig. 1(b)]. Prominent peaks in the correct syllable interval can be seen in Fig. 1(b) for all three age groups. The peak for the younger children occurred at the 0.524-sec delay, that for the older children at the 0.375-sec delay, and that for adults at the 0.2-sec delay. One curious finding of this pilot study was that the older children spontaneously spoke more slowly than the younger children for delays up to 0.375 sec. However, the data (described below) for these same subjects using a sentence-repetition task led us to suspect that the subjective criterion of "normal spontaneous speech rate" adopted by the older children might have been slower than that adopted by the younger ones.

B. Sentence Repetition

The same pilot subjects were presented with sentences to repeat at their maximum rate of speech.

The correct syllable interval for the three groups of subjects is shown in Fig. 1(a). Here, it can be seen that the optimal delay for interference varied with age in the same manner as for spontaneous speech. In contrast to the results for the spontaneous speech procedure, the speech rate of the older children was faster than that of the younger children for all delays in feedback.

In the zero-delay condition, the speaking rate of the adults was about 240 words/min (300 syllables/min). Since the average rate of speech (reading) has been estimated at 158 words/min,[11] this rate is indeed quite rapid. As might be expected, the maximum rate [see Fig. 1(a)] was greater than the spontaneous rate [see Fig. 1(b)] in the zero-delay condition, for all three groups of subjects.

[11] Franks, in N. Guttman, "Measurement of Articulatory Merit," J. Speech Hearing Res. 9, 323–339 (1966).

In another procedure, the pilot subjects were asked to repeat sentences at their normal rate of speech. Again, the peak interference delay for younger children was longer than for older children and adults.

Finally, the same sentences that the pilot subjects had previously produced spontaneously, in describing the *Alice in Wonderland* pictures, were presented for repetition. Again, the optimal delays for interference were 0.2, 0.375, and 0.524 sec for the respective age groups.

The pilot study indicated that the spontaneous-speech and sentence-repetition techniques are probably equivalent for determining the delay for maximal interference. Thus, we felt free to choose either one or the other technique for the main experiment.

The pilot study also led us to introduce new controls (described below) to determine whether DAF actually impairs the speech of children *more* than adults, rather than *less* as suggested by Chase *et al.*[4]

III. MAIN EXPERIMENT

We decided to use sentence repetition in the main study, since the spontaneous-speech technique seemed to give S control of both the dependent and independent variables. For example, S determines the material by what he says in the spontaneous-speech procedure. This makes comparison of age groups difficult since one group could be producing easier sentences than the other.

Even more serious, S controls the dependent variables, such as the rate of speech, in the spontaneous-speech procedure. By pausing or drawing out sounds, S could speak at any rate he wished. Further, one group of subjects may be differentially capable of developing strategies to overcome DAF interference in the spontaneous speech procedure. For example, an adult might be able to say a five syllable sentence so fast that, with a 0.75-sec delay, the feedback from his voice would not arrive until after he had completed the sentence. The child, on the other hand, whose rate of speech is characteristically slower, would be unable to complete even such short sentences without concurrent interference from feedback.

However, the sentence-repetition technique allowed us to overcome these difficulties. First, we were able to instruct all subjects to repeat the sentences at their maximum rate, thus reducing the possibility of differences in subjective criteria for the "normal rate" of speech for different groups of subjects.

The strategy of pausing was also ruled out by having subjects repeat trials on which they paused.

Finally, the sentence-repetition technique allowed us to compare our three groups with identical materials, and to ensure that all subjects were hearing feedback while producing a sentence, regardless of the delay condition or their natural rate of speech. This was achieved by adding an extra clause to the beginning of a core sentence, which was identical for all subjects. However, the length of the appended clause varied for the three age groups. For the younger children, the extra clause was two syllables long, making a seven-syllable sentence such as *I think Smokey is a bear*. For the older children, another two-syllable clause, such as *He said*, was added to the sentences of the younger children. For the adults, an eight-syllable preface, such as *Regardless of what the man said*, was added to the sentences of the younger children. We could thus be certain that the adults would be hearing feedback during their production of the core sentence, even with a 0.7-sec delay in feedback.

Because of the possibility that the contextual constraints of the appended clause might influence the amount of stuttering in the core sentence (Fillenbaum and Wiessen[7]), we tried to make the meaning of all three sets of added clauses irrelevant to that of the core sentence. The materials for all three groups are shown in Appendix A.

Data analysis for all three age groups was limited to the core sentence. In this way, all subjects would hear feedback while producing the analyzed sentences, which were identical for all subjects.

Since the pilot study indicated that the amount of articulatory disturbance for the first five sentences of a delay condition was about the same as for any later set of five sentences up to 25, the materials in the main experiment consisted of five sentences for each delay condition.

A. Subjects

In the main experiment, there were 11 younger children (age 4 to 6, with a median age of 5 yr, 4 mo). They were selected from a population of subjects participating in other experiments in language development at MIT. Their mothers were present during the experiment.

There were eight older children (age 7 to 9, with a median age 8 yr, 5 mo). The majority of the children in this group were older siblings of the 4- to 6-yr-old children.

The adults were 13 graduate and undergraduate students at the Massachusetts Institute of Technology.

B. Instructions

The general procedure consisted of two phases: the delay conditions and an "irrelevant-voice" procedure.

1. Irrelevant-Voice Procedure

The pilot study suggested that DAF disrupts the speech of younger children *more* than that of adults. One possible explanation of this result is that younger children are simply less able to concentrate on their speech output while simultaneously hearing another amplified voice.

In order to test this hypothesis, we had our subjects repeat a set of five sentences while hearing an amplified recording of a passage from Lewis Carroll's *Alice's Adventures under Ground*[10] played into the earphones. This particular story was chosen because it seemed equally capable of distracting both adults and children.

The instructions to all groups in this condition were as follows:

> *This time you will hear a different voice when you are saying the sentence. Do not pay any attention to this voice or let it bother you. I will tell you the sentence and you will say it as fast as you can even though you are hearing a different voice in the earphones.*

Prior to the five experimental sentences, the subject was given two practice sentences to repeat while the *Alice in Wonderland* tape was turned on (amplified to the same degree as for the delay conditions). There was no playback of the subject's voice as he attempted to repeat the sentence. As soon as he completed each sentence, the recording was turned off.

Subjects in all groups sometimes blocked or forgot their sentence in this condition. When this happened, the trial was simply repeated.

2. Delay Conditions

The instructions for the delay conditions differed slightly for adults and children. The adults were read the following instructions:

> *This is an experiment on the rate of speech. Your task will be to repeat sentences which I read to you. I will instruct you to speak either as rapidly as you can, slightly more slowly or very slowly. In all cases you are to say the sentence continuously, without pausing. Do not speak in stacatto bursts, or word by word as for example* Foxes–live–in the–woods. *Later, it may become difficult to say the sentence without making errors, but the important thing is to maintain a continuous rate of speech. If your rate of speech does not fall within certain limits or if you pause during a sentence, you will have to repeat it.*

Sentences containing pauses longer than 1.0 sec were repeated. This was necessary for only four trials out of 520. For each set of sentences, S was told to speak at his maximum rate, at the medium slow rate or the very slow rate; E demonstrated the appropriate rate of speech, and manner of slowing down (by prolonging speech sounds without pausing). For the medium and very slow rates the materials were the seven-syllable sentences of the younger children rather than 15-syllable sentences. The shorter sentences were used here because the 15-syllable sentences caused the adults to run out of breath at these reduced rates of speech; and it was considered desirable to have the sentence spoken continuously, without breathing pauses. Up to three practice sentences were given to the subjects in order to stabilize their speech at the desired rate. Limits on the sentence duration were 3.5 (± 1) sec for the medium-slow rate and 6.0 (± 1) sec for the very slow rate. E determined the sentence duration by means of a standard stop watch. When the rate of speech was

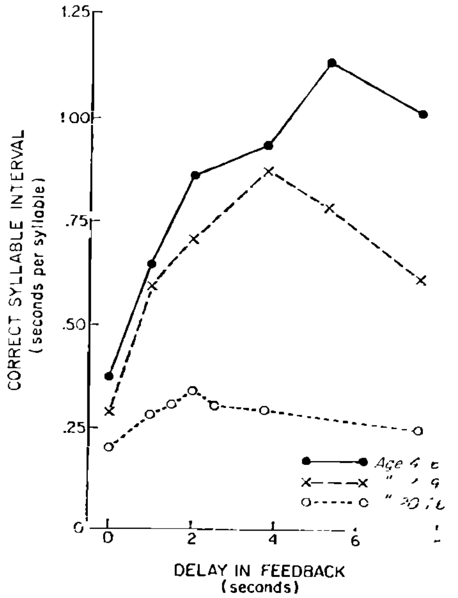

FIG. 2. The CSI (in seconds per syllable) as a function of feedback delay for adults (age 20–26), older children (age 7–9), and younger children (age 4–6).

too fast or too slow, E informed S of the direction of the error and the trial was rerun.

3. Children

The instructions for the children in this phase were as follows:

> *This is an experiment, which means that we have to do everything by the rules. We want to find out how fast you car speak. I am going to say a sentence and you are to say it after me as fast as you can, and without stopping or pausing. Ready...* Foxes live in the woods. (*The child repeats the sentence without delay in feedback.*) *Later it may become more difficult to get the sentence right without making mistakes, but that does not matter. Do not worry about mistakes. Just say the sentence as fast as you can without stopping as in* Foxes–live–in the–woods. *If you stop like that during the sentence we will have to repeat it.*

E then read the sentences to the children in the same manner as for the adults.

C. Procedure

Each adult was given 12 sets of five sentences to repeat in a session lasting about 45 min. There were eight apparatus settings: the 0-, 0.1-, 0.2-, 0.263-, 0.375-, and 0.75-sec delay conditions and the irrelevant-voice procedure. The order of presentations of the eight conditions was randomized across subjects in order to control for the possibility of interaction between conditions.

The adults repeated three sets of sentences for the 0.2- and 0.263-sec delays at the three rates of speech described above. The order of these three speech rates was randomized within the 0.2- and 0.263-delay conditions.

The procedure for the children was identical to that for the adults, except that the children always spoke as fast as they could and their delay conditions were 0, 0.1, 0.2, 0.375, 0.524, and 0.750 sec.

D. Measures

All trials were recorded on tape, and the following measures were taken from the recording:

1. Correct Syllable Interval

This measure of speech rate is an adaptation of Fairbanks'[13] correct-word rate. The correct syllable interval is essentially the time required to produce a syllable correctly in a sentence. It was defined as follows: $CSI = T/CS$, where T is the time to repeat the core sentence, CS is the number of correctly produced syllables in this sentence, and CSI is the correct syllable interval. The CSI is shown in Fig. 2 as a function of feedback delay. Butler and Galloway[12] report that loudness of feedback *per se* does not affect the rate of speech with synchronous feedback. Thus, the rate of speech in the zero-delay condition in Fig. 2 can probably be considered the maximal rate for these subjects, even though they were hearing their voice amplified.

Prominent peaks can be seen in this function for all three groups of subjects. The usual peak for adults was found with a delay of 0.2 sec. A peak for the older children occurred at the 0.375-sec delay, and that for the younger children at the 0.524-sec delay.

The three groups of subjects also differed in their absolute speech rates, independent of the delay in feedback. The younger children spoke slowest (or had the longest CSI) for all delay conditions (see Fig. 2). The older children spoke slightly faster, even at their point of peak disturbance (0.375 sec). Adults spoke very much faster than the children for all delay conditions.

2. Syllable Interval

In general, the slower rate of speech under DAF could reflect either the prolongation of syllables, the insertion of pauses, or the occurrence of extra stuttered syllables. Pauses were ruled out in the present study by repeating trials on which they occurred. However, we wanted to determine whether the reduced rate of speech under DAF was due to extra time taken up by stuttering or syllable prolongation, or both.

We thus calculated the syllable interval, defined as the time to produce the core sentence divided by the actual number of syllables produced, including stuttered and incorrect syllables. That is: $SI = T/Scs$, where SI is the syllable interval; T, the time to produce the core sentence, and Scs is the number of syllables in the core sentence.

---

[12] R. A. Butler and F. T. Galloway, "Factoral Analysis of the Delayed Speech Feedback Phenomenon," J. Acoust. Soc. Am. 29, 632–635 (1957).

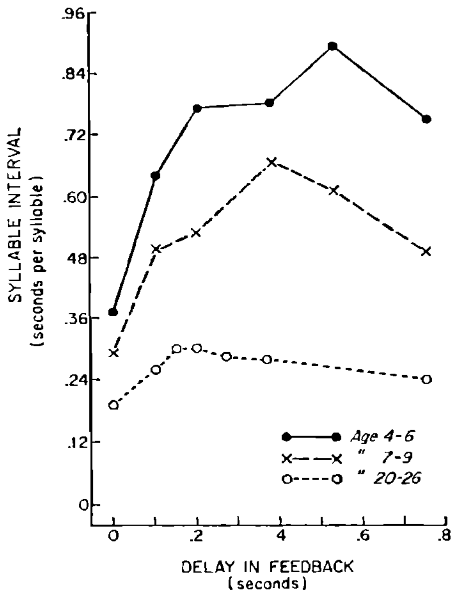

FIG. 3. SI as a function of feedback delay for adults, older children, and younger children.

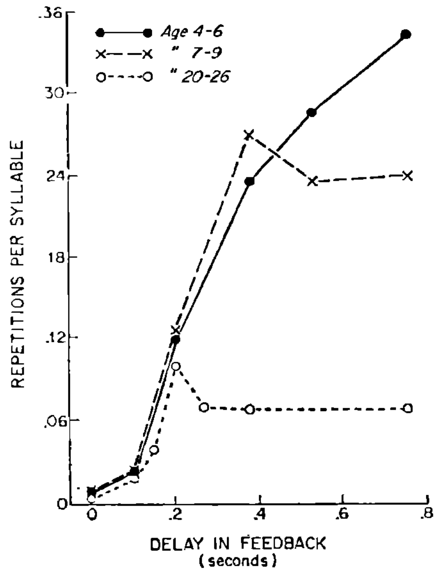

FIG. 4. The frequency of repetitions (stutters) per syllable as a function of feedback delay for the three groups of subjects.

The mean SI for each of the three groups of subjects is shown, in Fig. 3, as a function of feedback delay. The critical interval for the three groups of subjects remained constant, whether measured by CSI or by SI (see Fig. 3). For the younger children, the delay producing the longest SI was 0.524 sec; for the older children, 0.375 sec; and for adults, 0.20 sec. Clearly, the time taken up by stuttering cannot be the sole determinant of the peaks in reduction of the rate of speech under DAF.

Inspection of Fig. 3 also shows that the SI of younger children was relatively longer than that of older children and adults for all delays in feedback. Consequently, the slower over-all rate of speech of the younger children cannot be entirely attributed to a greater tendency for them to stutter under DAF.

Finally, in reconciling the present findings with those of Chase and his collaborators,[4] it might be pointed out that their measure of speech rate was an estimate of the percent of syllables prolonged. That is, the younger children in Chase's study were judged to prolong fewer syllables than older children—a measure not incorporated in the present study.

3. *Articulatory Errors*

Substitution of speech sounds such as *pork* for *fork* sometimes occurs under DAF.[2] Such errors are very difficult to define and discriminate in DAF speech, however. The repetition of speech sounds is much more frequent, and very easily recognized. We therefore decided on repetitions or stutters as our major unit of analysis in comparing the articulatory disturbance of our three age groups. We defined a stutter as the repetition of a syllable or part of a syllable. The frequency of stutters per syllable is shown as a function of the feedback delay in Fig. 4. Again, the delay producing the highest frequency of stuttering was found to vary with age. Adults stuttered most frequently with a 0.2-sec delay in feedback, and older children with a 0.375-sec delay. For the younger children, our longest delay (0.75 sec) produced the most stuttering. This was the only case in which one measure suggested a different peak-interference delay from other measures.

The total amount of stuttering (averaged over all delay conditions) was found to vary in the same fashion as other measures of interference. Younger children stuttered more than older children and adults for all delays in feedback.

In summary, these measures force us to reject Chase's conclusion that younger children are less severely affected by delayed speech than older children.[4] We are similarly forced to reject an interpretation of the effect of DAF in terms of egocentric speech[3]—an assumed inability of younger children to monitor their own speech or to assume simultaneously the rôle of speaker and listener.[13]

It is also clear that future studies of DAF, using different subject groups, must incorporate more than one delay in feedback. In fact, previous investigations of DAF, using a single feedback delay, might profitably be reopened. For example, Goldfarb and Braunstein[14] reported differences in the response of normal and schizophrenic children to DAF. The basis of this finding is ambiguous, however, since only a single feedback delay was used.

[13] J. Piaget, *The Language and Thought of the Child* (Harcourt, Brace and Company, Inc., New York, 1926), pp. 239–282.

[14] W. Goldfarb and J. A. Braunstein, "Reactions to Delayed Auditory Feedback in Schizophrenic Children," in P. H. Hoch and J. Zubin Eds., *Psychopathology of Communication* (Grune and Stratton, New York, 1958), pp. 49–63.

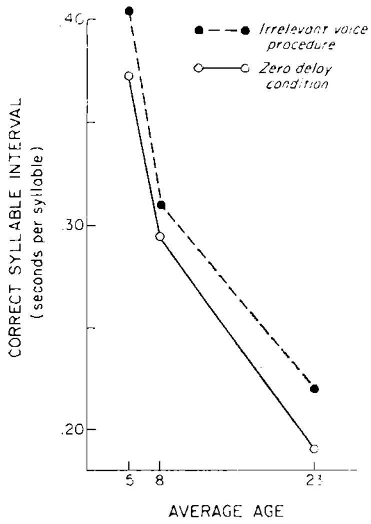

FIG. 5. The CSI as a function of age group under two conditions: (1) While hearing their own voice undelayed, but amplified, and (2) while hearing another voice amplified to the same extent.

E. Irrelevant-Voice Procedure

The purpose of the irrelevant-voice procedure was to determine whether any concurrent speech input would be relatively more distracting for children than for adults. The frequency of errors for this procedure and the synchronous feedback condition was so low that the CSI and actual SI were almost identical for these two conditions. A comparison of the CSI for these two conditions is showin in Fig. 5 for the three groups of subjects. Examination of Fig. 5 indicates that hearing another voice reduced the maximum rate of speech for all three groups. However, the children slowed down about as much as adults, relative to their rate of speech in the synchronous (zero-delay) condition. The ratio of the CSI in the irrelevant-voice condition to that in the zero-delay condition was 0.22/0.19 for adults and 0.41/0.38 for the younger children. That is, the CSI for adults was 1.15 times as slow in the irrelevant-voice condition as in the synchronous-delay condition, and, for younger children, it was 1.08 times as slow. Since the CSI for the younger children was over three times as slow at the peak interference delay, it is clear that interference from hearing *any* concurrent, amplified voice can contribute little to reducing the rate of speech under DAF.

IV. SPEECH RATE OF ADULTS: THE DRAWING OUT OF SPEECH SOUNDS

One of the main reasons for including the adult group in the present study was to determine the effect of varying the rate of talking on the amount and locus of DAF speech disruption. Adults were chosen for this task because they seemed better able to control their speech rate with precision and more willing to repeat trials on which their rate fell outside the specified limits.

The adults spoke at three different rates of speech under two delay conditions. The rates of speech were: (1) Maximal, which, averaged for the 0.2- and 0.263-delay conditions, was 0.32 sec.

(2) Slow, which was 0.50 sec/syllable. This rate was chosen to correspond to the rate of the 7 to 9 yr olds in the 0.2 sec delay condition. There was virtually no difference in the average syllable interval for the two delay conditions.

(3) Very slow, which was 0.86 sec/syllable, roughly the rate of the 4 to 6 yr olds under the 0.2-sec delay.

The feedback delays were 0.200 and 0.263 sec. These delays were chosen in order to determine whether slowing down the rate of speech would lengthen the DAF interval producing the peak in stuttering. By choosing a delay value only slightly longer than 0.2 sec, we hoped to detect even a very small shift in the locus of peak

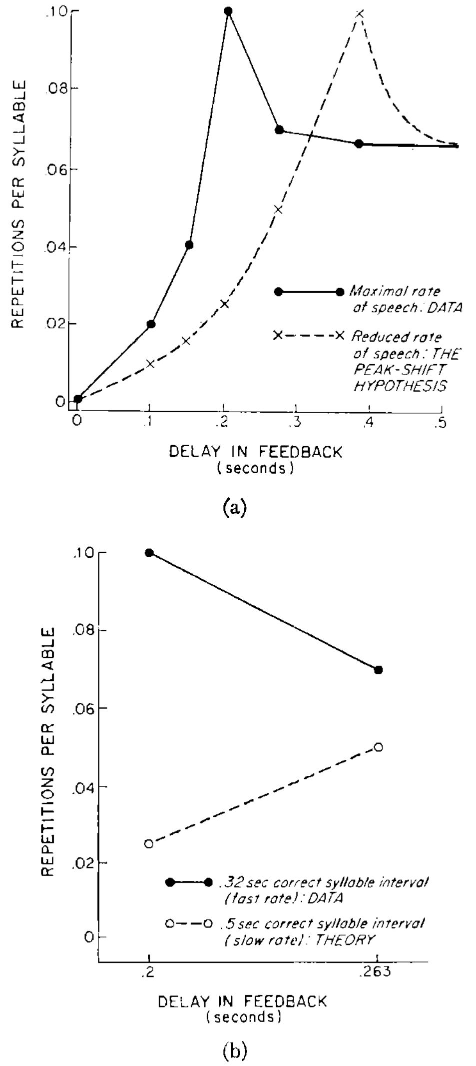

FIG. 6. (a) The actual frequency of stuttering for the maximal rate of speech is shown with the solid line. The peak-shift hypothesis (see text) predicts that slowing down the rate of speech will lengthen the delay for maximal interference. Hypothetical data predicted from this hypothesis are shown with the dotted line. (b) The frequency of stuttering for the 0.2- and 0.263-sec delay conditions from 6(a), plotted as a function of two rates of speech.

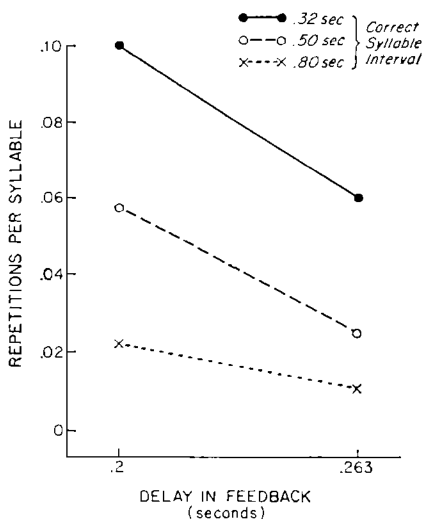

FIG. 7. The frequency of stuttering per syllable under two delay conditions 0.200 and 0.263 sec) as a function of three rates of speech for adults.

interference for different rates of speech. This "peak-shift" hypothesis is outlined in Fig. 6(a). The assumption of the peak-shift hypothesis is that slower rates of speech lengthen the peak interference delay [see Fig. 6(a)]. This would mean that a delay slightly longer than 0.2 sec should produce the highest frequency of stuttering, as shown in Fig. 6(b). This did not occur.

The relative frequency of stuttering is shown, in Fig. 7, as a function of rate of speech for the two delay conditions. Inspection of Fig. 7 shows that the frequency of stuttering decreased about equally for both delays in feedback as the rate of speech was diminished. The probability of stuttering remained greater for the 0.2-sec delay for all three speech rates. A one-tailed t test of the difference at the medium slow rate (0.5 syllables/sec) was significant at the 0.01 level. Thus, the obtained difference was opposite to that predicted from the peak-shift hypothesis. We can, therefore, conclude that there was no shift in the delay producing the most stuttering for these delays and at these rates of speech, achieved by prolongation of speech sounds.

V. MAXIMUM RATE OF SPEECH: CHILDREN AND ADULTS

Returning to the developmental data, we originally postulated that the slower speech rate of children might lengthen the delay producing maximum interference with their speech. The data just described do not support this hypothesis. When the rate of talking was reduced by voluntarily prolonging speech sounds, we found no shift in the peak delay for interference.

It is clear that the duration of speech sounds in the acoustic signal cannot be the basis of the critical DAF interval for adults. It might also be argued that the longer critical interval for younger children under DAF cannot be due to the longer duration of their speech sounds.

However, the factors limiting the maximum rate of speech of children may not be identical to those involved in slowing down speech by prolonging speech sounds. We still considered it possible that some factor underlying a subject's *potential* speech rate could determine the critical delay for interference.

We therefore correlated each subject's maximum rate of speech (i.e., the correct syllable interval in the zero-delay condition) with the delay time producing maximal interference with his speech. The rate of speech of our subjects under synchronous feedback varied considerably both within and between groups. The mean SI for the younger children was 0.36 sec (with a range from 0.21 to 0.51 sec). For the older children, it was 0.28 sec (with a range from 0.18 to 0.38 sec); and for adults it was 0.19 sec (with a range from 0.14 to 0.30 sec).

The peak interference delay also varied considerably for different subjects. Within each group, only about half the subjects had the same peak; a quarter of them had a peak at a longer delay and a quarter at a shorter one.

The Spearman coefficient for the correlation between the maximum speech rate (the CSI in the zero-delay condition) and the peak interference delay was +0.52. This correlation is significant at the 0.001 level. Thus, the *slower* a subject's maximum rate of speech without delay in feedback, the longer the delay producing maximal interference with his speech. This positive correlation also held within subject groups. For the adults, the Spearman coefficient was 0.33; for the older children, 0.03; and for the younger children, 0.30.

The correlation of peak interference delay and maximum speech rate for the sentence-repetition task in the pilot study was also positive and significant at the 0.01 level. However, the correlation between the peak interference delay and the *spontaneous* rate of speech for these same subjects was nonsignificant at the 0.10 level.

Our next step was to compare the maximum rate of speech of our subjects with their frequency of stuttering under DAF. The correlation of amount of stuttering (for all delay conditions) and CSI (in the zero-delay condition) was +0.34. This correlation was also significant at the 0.001 level. Thus, the slower a subject's maximum rate of speech, without feedback delay, the greater the tendency to stutter.

This correlation also held within the three age groups. For the adults, the Spearman coefficient was 0.39; for the older children, 0.29; and, for the younger children, 0.16.

Thus, slower maximum rates of speech were associated with increased DAF stuttering, and a longer delay for maximal interference. Clearly, some factor or set of factors limiting a subject's maximum rate of speech must determine both the amount and locus of DAF interference. However, the factors limiting the maximum rate of speech cannot be identical to those for prolonging speech sounds since DAF interference was *reduced* rather than *increased* when speech was slowed down in this way. Further, specification of factors determining the maximum speech rate would appear to be an important goal for the future studies of DAF.

Age and rate of speech were not significantly correlated within any of the three age groups, although the correlation for the total group was significant at the 0.01 level (Spearman's product-moment correlation). That is, the older a subject, the faster his maximum rate of speech. Thus, the as yet unknown factor(s) determining the maximum rate of speech appear to be age-linked.

VI. SUMMARY

Three claims were investigated in the present study: (1) That delayed auditory feedback (DAF) would disrupt the speech of children less than that of adults; (2) that 0.2 sec is the most disruptive delay in feedback, regardless of a subject's age; and, (3) that reducing the rate of speech of adults would lengthen the delay producing maximal interference with their speech. None of these claims was substantiated.

First, The DAF speech disturbance for very young children (age 4 to 6) was greater than for older children (age 7 to 9) and adults (age 20 to 26) regardless of the delay in feedback. It was also shown that children are no more distracted by hearing an "irrelevant," amplified voice while talking than adults. Thus, distraction or shifting of attention to the auditory feedback is probably not the basis for the greater speech disruption in children under DAF.

Second, the delay producing the peak disruption of speech under DAF varied with age. The optimal delay for interference was much longer for children than adults. A feedback delay of roughly 0.5 sec produced the peak disturbance for the younger children, a 0.4-sec delay for the older children, and a 0.2-sec delay for the adults.

Third, when the adults reduced their rate of talking by drawing out speech sounds, their stuttering under DAF decreased. However, slowing down the rate of speech in this way did not shift their peak interference delay (0.2 sec). On the other hand, a significant correlation was found between a subject's maximum rate of speech and the duration of the delay producing maximal disruption of his speech. The slower a subject's maximum rate of speech, the longer his critical DAF interval.

A subject's maximum speech rate also correlated highly with his over-all tendency to stutter under DAF. The slower a subject's maximum speech rate, the higher his frequency of stuttering under DAF.

Since the voluntary prolongation of speech sounds had the opposite effect, decreasing rather than increasing stuttering, it was suggested that: (1) Mechanisms determining the maximum speech rate are to some extent different from those governing the prolongation of speech sounds; (2) both the amount of stuttering under DAF and the peak interference delay are related to some as yet unknown factor or set of factors determining the maximum rate of speech; and (3) this set of factors is aged-linked since the maximum rate of speech varies inversely with age.

ACKNOWLEDGMENTS

I am indebted to Dr. H.-L. Teuber, T. Bever, J. Fodor, and M. Garrett, whose advice and constructive criticism have been of great value in all stages of this work. I am especially grateful to Dr. Teuber, who suggested the study.

This work was supported by an M.I.T. intramural fellowship, a NASA grant to Dr. H.-L. Teuber and a John A. Hartford Foundation grant also to Dr. Teuber.

Appendix A.

Materials for Adults, Older Children, and Younger Children

The materials for all groups included the five syllable core sentence. A two-syllable clause was appended to the core sentence for the 4- to 6-yr old children. The heading—Younger children—indicates this clause. Under the heading—Older children—is the two-syllable clause for the 7- to 9-yr olds, which was attached to the sentences of the younger children. An eight-syllable clause, under the heading—Adults—plus the seven-syllable sentences of the younger children, made up the adult sentences.

Adults	Older children (7–9)	Younger children (4–6)	Core sentence
1. Regardless of what the man said	Sometimes	I think	we can help Mommy.
2. Although he did not say so	Today	I think	Patsy is a doll.
3. Although it was not mentioned	Sometimes	I think	fire engines are red.
4. Although he should have known about it	He knew	Sometimes	pilots go to Mars.
5. Regardless of what the man said	Sometimes	I think	rabbits live in holes.
6. Even in the hottest weather	Oh yes	I know	Santa Claus has a beard.
7. Although this is unconfirmed	Sometimes	I think	horses can run fast.
8. During certain months of the year	Often	I think	birds sing pretty songs.
9. Although I knew about that	At lunch	Today	I saw funny clowns.
10. Having heard him mention the fact	Today	I know	Jack climbed the beanstalk.
11. There seems to be little doubt that	He said	Sometimes	good cowboys shoot guns.
12. Regardless of what the men said	Today	I think	hunters shot the wolf.
13. Regardless of what the broker said	He said	I think	it is almost lunchtime.
14. Their neighbor insisted that	Sometimes	I think	robbins can not fly.
15. Not knowing what else could be done	Today	I think	the pigs ran home.
16. Regardless of what the man said	He said	Sometimes	bears sit in chairs.
17. Despite what the teacher claimed	Oh yes	I think	most cows eat grass.
18. Even though nobody said as much	He said	Sometimes	the captain sails ships.
19. Although I didn't see this myself	Often	He said	the king blew the trumpet.
20. No matter what time of year it is	He said	I think	monkeys live in trees.
21. Even though I've never seen it	At least	Sometimes	hens get up early.
22. Because of what the people said	I think	They knew	firemen brought the pails.
23. Although he didn't see it	He knew	Sometimes	airplanes can fly fast.
24. Despite the professor's warning	I think	He said	Bambi was a deer.
25. Although you spoke well today	He said	I think	Dumbo is a clown.
26. Although he did not say so	Today	I think	Smokey is a bear.

Adults	Older children (7–9)	Younger children (4–6)	Core sentence
27. During two seasons of the year	Often	I think	Joe drives a tractor.
28. Having heard him mention the fact	Oh yes	I think	snakes live in jungles.
29. Regardless of what the man said	Oh yes	I know	milk comes from cows.
30. The man next door insisted that	He said	Sometimes	babies cry at night.
31. Despite what the people said	Oh yes	Today	I ate a cookie.
32. He carefully explained that	Oh yes	Sometimes	it rains at night.
33. Although they didn't know yesterday	Today	I think	the car is broken.
34. Regardless of what he answered	Oh yes	I know	turtles have a shell.
35. Despite what the teacher mentioned	I think	Sometimes	fish swim upside down.