OBSERVATIONS ON SPEECH RESEARCH: OBJECTIVES, STRATEGIES, AND SOME PARTIAL ANSWERS

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Recipient of the Fletcher-Stevens Award

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Speech research, about which I should like to talk with you today, has long been my major interest. In this, I can claim a certain kinship of the son-to-father kind with Dr. Harvey Fletcher. To be sure, his research and mine dealt with different topics, used different tools, and had different goals. That was to be expected, given that speech research itself was, and still is, a dynamically changing field. Perhaps I should mention that Fletcher's book on "Speech and Hearing," published in 1929, was already a classic when I first discovered speech in the mid-40's. That holds also for the book by Stevens and Davis with its simple but comprehensive title, "Hearing." These two books[1] were my starting point; I have had the further good fortune to know both Dr. Fletcher and Dr. Stevens personally, though really only at grazing incidence.

So, for me, it is a very special and very personal honor to be asked to give the Fletcher-Stevens Lecture--and it is a challenge, too. I gather, from the general guidelines I have been given, that I am not expected to encapsulate all that has been learned about speech within a 40-minute message--rather, that I should talk about speech research as an enterprise that has both a history, which I have watched with interest, and also a burgeoning future. It is my hope that looking back to some of the earlier researches will help to highlight the continuing problems that were uncovered in the process of experimenting on spoken language. I think it is fair to say, though, that we have learned more about the problems than about the answers. I shall be content if the linguists among you, and the engineers and the psychologists, can get some sense of challenge to your own discipline, since your combined efforts will be needed if we are eventually to understand how it is that human beings are able to communicate with each other so effectively by these strange sounds we call speech.

Objectives

In turning to the objectives of research on speech, I ought logically to ask--as some linguists actually do--what does speech research have to do with, or for, linguistics? The answer to that question is my main theme, but just now I will ask your patience until I have commented briefly on the more obvious practical interests of the engineers.

What are some of the practical goals and problems in speech research? There are many situations in which face-to-face conversation would be desirable but is simply not possible. Thus, the need to talk at greater distances than the voice will carry led to the development of telephony, a field in which Dr. Fletcher made many notable contributions. Sound recording made it possible for man's voice to reach across time as well as across space. But in both recording and simple telephony, noise and distortion have always been major problems. When there is need to speak from city to city, rather than house to house, these problems become extremely severe. Initial solutions depended on putting high quality amplifiers (or repeaters) at regular intervals along the telephone line. Digital methods have made it possible to greatly simplify the design of these repeaters, and for an interesting reason: when the voice waveform itself is being transmitted, any noise that is added during transmission gets merged into the speech and cannot be sorted out later. Consequently, amplifying the signal to make it stronger only makes the noise stranger, too, and the deterioration continues to increase. But digital methods replace the speech waveform by a numerical recipe for reconstructing the speech. So when this numerical description is transmitted, the repeating station can regenerate a noise-free set of numbers, thereby avoiding cumulative deterioration.

Another problem for telephony is the comparatively large bandwidth (or the bit rate in digital transmission) that is required to transmit a voice message. In the late 1930's, Homer Dudley[2] invented the Vocoder as an ingenious way to put ten conversations over the single wire that usually carries only one. The principle deserves comment. The incoming speech is first analyzed into a number of components, these are processed for transmission, and then a speech output is synthesized from the components. Vocoders have not come into common use, in part because they are not yet cost effective in dollars even though they do save bandwidth, but by combining the vocoder principle with digital processing of the analyzed signal--for example, by adding digital noise before transmission and subtracting just the same digital noise at the receiving end--it is possible to achieve a considerable degree of message security.

SPEECH RESEARCH:

SOME PRACTICAL GOALS AND ACCOMPLISHMENTS

- - - - - - -

VOICE COMMUNICATION

- AT A DISTANCE: TELEPHONY
- AT ANOTHER TIME: RECORDING
- WITH LESS NOISE: REPEATERING & DIGITAL METHODS
- WITH LESS BANDWIDTH: VOCODER
- WITH BETTER SECURITY: PRIVACY & SECRECY SYSTEMS
- WITH COMPUTERS, FOR GREATER VERSATILITY:
  - ANSWER-BACK SYSTEMS
  - DATA RETRIEVAL
  - TEXT-TO-SPEECH CONVERSION
  - AUTOMATIC TRANSLATION
  - SPEECH UNDERSTANDING SYSTEMS

AIDS FOR THE HANDICAPPED

- FOR THE BLIND: TEXT-TO-SPEECH READING MACHINES
- FOR THE DEAF: HEARING AIDS, TACTILE VOCODERS, COCHLEAR OR NEURAL IMPLANTS
- FOR QUADRIPLEGICS: COMMUNICATIONS BOARDS

FIGURE 1

But why stop with digital processing of such a limited kind? Why not put a whole computer between analyzer and synthesizer and then program it both to recognize what was said into the microphone, and to give an appropriate answer through the synthesizer? That is to say, why shouldn't humans and computers talk to each other? It turns out in practice, as I am sure most of you know, that computers have a great deal of difficulty in understanding human speech. It is only a little less difficult to teach them to use natural language--English, for example--even when the input and output are in typewritten form.

The extreme difficulties of teaching computers to use ordinary fluent speech[3] has prompted serious questions of whether there is any real reason why computers ought to learn the use of speech. One attempt to answer this kind of question was described in a delightful article by Chapanis[4] in the Scientific American about two years ago. Chapanis asked two people to cooperate in the task of putting together a mail order device. One person had the kit; the other person, in a different room, had the instructions for putting it together. They could communicate in various ways, but only one way, or combination of ways, was permitted in any one experiment. How long it took to assemble the device depended, as you might suppose, on the kind of communication that the experimenter allowed. The gross result of experiments on many modes of communication, some with speech and some without, was that when the task had to be done without voice it took about twice as long. In one respect, this is a gross underestimate of the difference, since the communication rate (as measured in words per minute) was about ten times as high with speech as with any other words. However, the teams wasted most of this advantage by using five times as many words when they talked as when they wrote, thus leaving a net factor of only two. The moral, for speech understanding systems, seems fairly clear: not only do people prefer talking to writing, but also they are much faster at it. Given man's insistence on his own convenience, we can expect that spoken input/output to computers will eventually replace present methods, just as the telephone replaced the telegraph despite greater cost and complexity. The question of why speech can be so fast is one to which we shall return.

Strategies

We have seen that speech research has had important practical consequences and also that there are some very challenging problems still remaining. Let us now consider a few simple models to see what they can suggest to us about strategies for speech research when it is directed to human performance rather than to device development. The first of these models can serve as a general purpose schema for many communications devices (Fig.2a). Note especially the central processor: for a Vocoder, it can be as simple as a bank of low-pass filters, but for a speech understanding system the processor may need to be an entire computer.

If we repackage this device-oriented system, we have a model such as psychologists often use in talking about human behavior (Fig. 2b). Sometimes they ignore the central processor entirely and deal only with input-output relationships, though I do not suppose they would go so far as to deny the logical necessity for a certain amount of machinery between ear and mouth. Moreover, many present-day psychologists would insist on having at least the components indicated in the figure. But we can see what the problem is in using a model of this kind, whether for dealing with a speech understanding system or a human being: so many of the important components are totally inaccessible.

Perhaps two heads are better than one (Fig. 2c), since then the message is out in the open where we can capture and study it. But that is only one of the reasons for using this as a model for talking about strategies in speech research. The other reason lies in the dual nature of speech. It is this which prompts us to probe experimentally into the processes of reception (to the right) and those of production (to the left). At no other point in the total communicative process do we have such rich experimental opportunities.

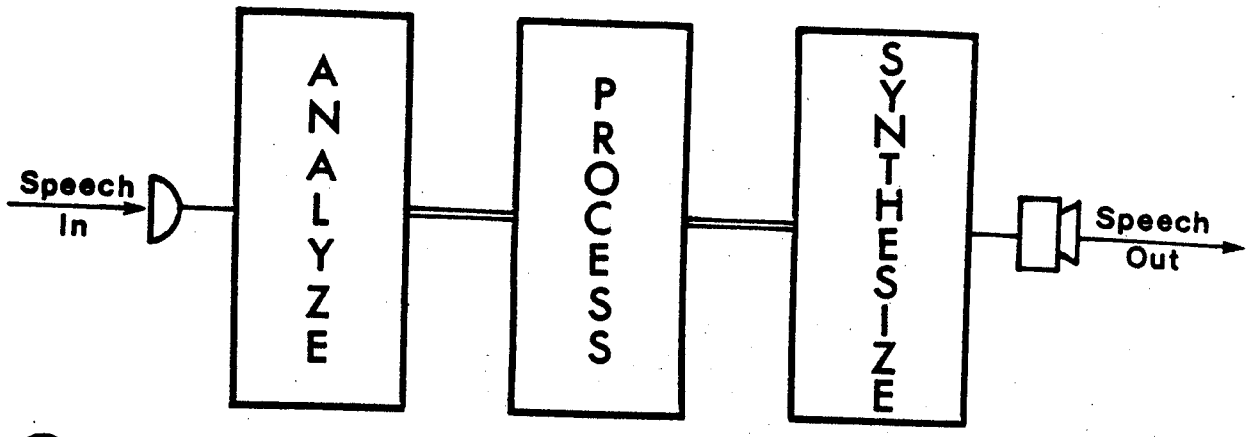
Dual Nature of Speech

But why attribute a dual nature to speech in justification of these more or less obvious ways to approach perception and production? Do I mean to imply that the speech signal is unusual, i.e., that it is special in some important sense, in the degree of its dependence on the mechanisms by which it is produced and by which it is perceived? That is exactly what I do wish to imply, namely, that speech is not just a set of acoustic signals, but rather that it is an encoding of the message, in the cryptographic sense of the term. Moreover, the nature of the code is dependent on two sets of properties and characteristics: those of the processes that produce the signal and also those of the processes that receive and decode it. It follows from these considerations that our best hope for finding the message within the acoustic signal lies not in studying the signal itself but in trying to find out how it was encoded in production and how it is decoded in perception.[5]

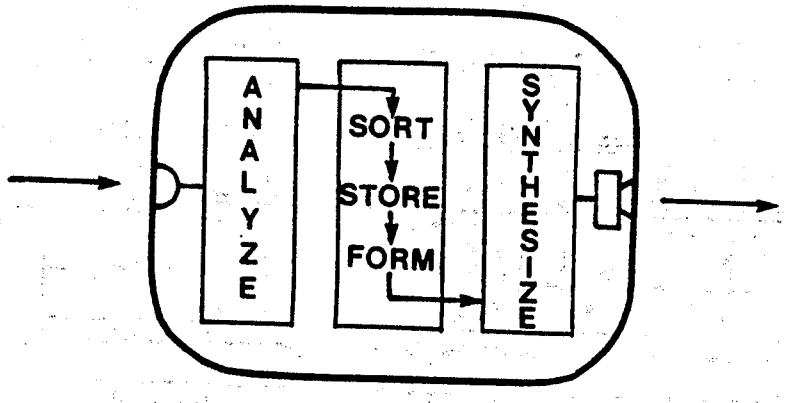
This is a point of view that has evolved in consequence of research on speech; certainly, it was not how speech was viewed as of the late '40's and early '50's. Then, the emphasis was on the acoustic signal. The objective was to locate acoustic invariants that could characterize phonemes and/or distinctive features. Much of this interest was sparked by the sound spectograph, which emerged in the mid-'40's from war-time research at the Bell Telephone Laboratories. The spectograms revealed in full detail the complex patterning of speech sounds.

You might enjoy seeing what is, so far as I know, the very first spectogram ever made (Fig.3). It was published by John Steinberg[6] in 1934. One of the reasons the method did not

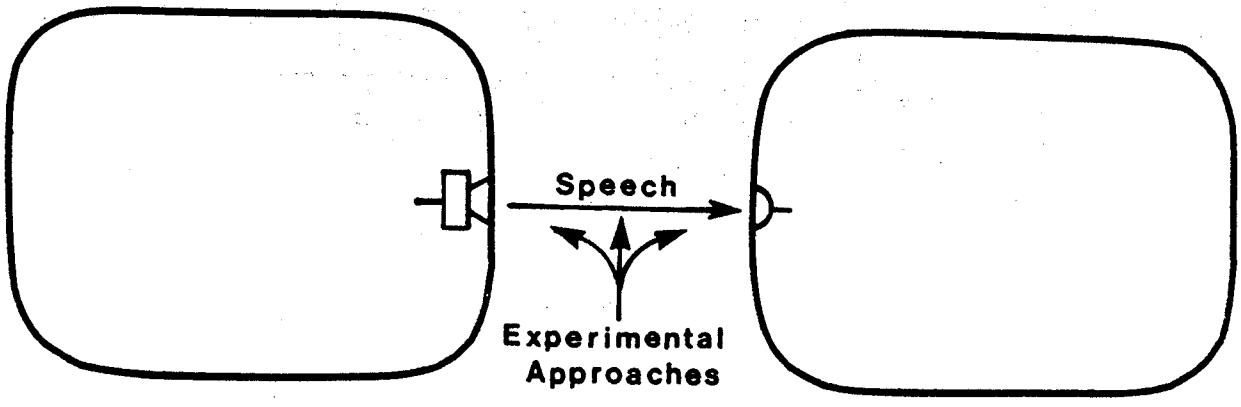
MODELS



(A) Speech Processors



(B) Speech Behavior



(C) Speech Research

FIGURE 2

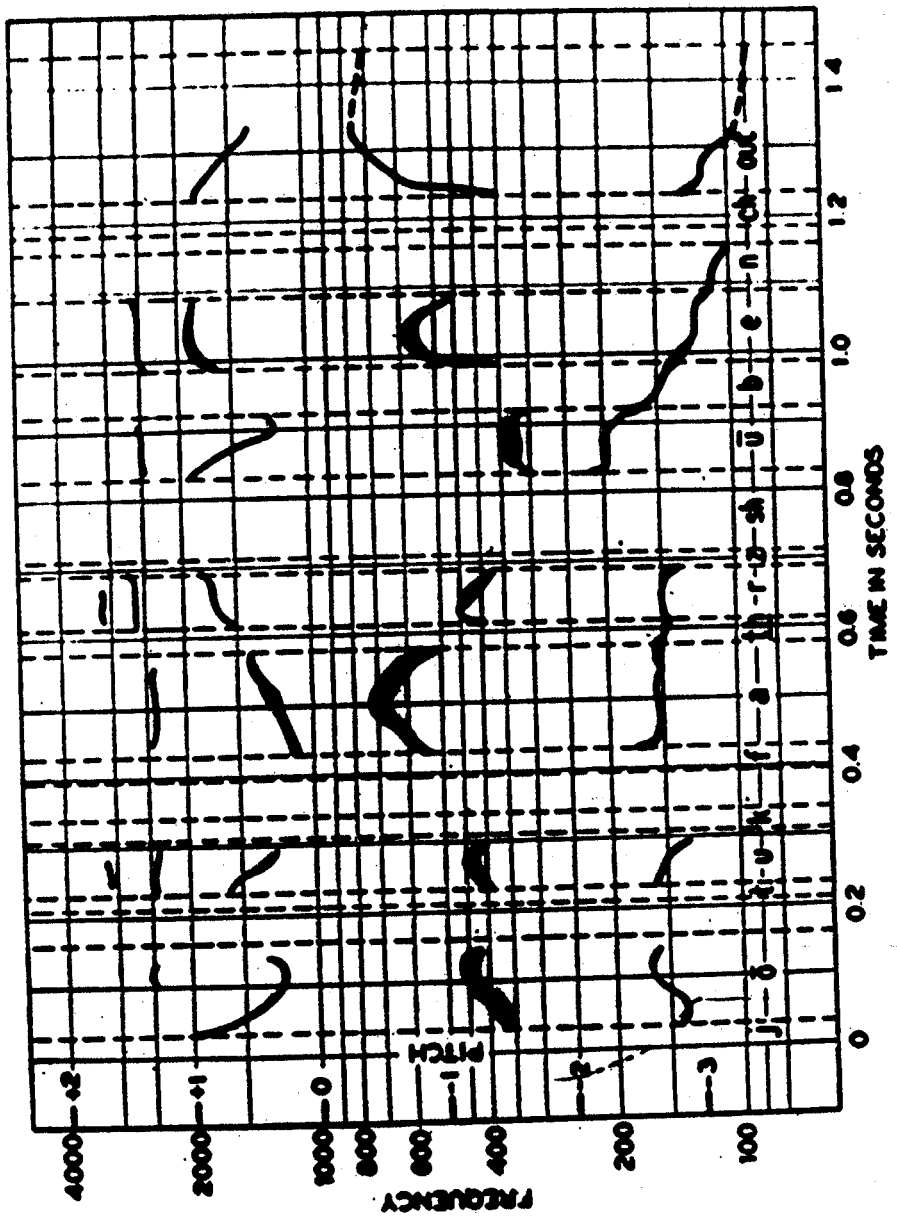

FREQUENCY
4000
2000
1000
800
600
400
200
100
PITCH
+2
+1
0
-1
-2
-3
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
TIME IN SECONDS

FIGURE 3

catch on then was that the Fourier analyses for this one sentence required several hundred hours of hand measurement and computation.

Early Research on Speech Perception

My own discovery of the wonders of speech had a different origin more nearly related to the remarkable speed with which speech sounds are perceived. My colleagues and I had been trying to build a reading machine for the blind.[7] We used photocells to convert the shapes of letters (on the printed page) into distinctive acoustic shapes, but no matter how hard we tried to find an optimal set of sounds or how long our subjects worked to learn them, about the best they could do was ten to twenty words per minute. That is barely a tenth of normal rates for speaking and listening. It took us a long time to understand that the real problem was not why our signals were so slow, but why speech was so fast.

We built the Pattern Playback[8] as a way to find the acoustic cues in the speech signal, since it seemed obvious that there must be some underlying pattern in the sound spectrogram that served to carry most of the information. The basic idea of the method was quite simple: one used a paint brush to draw a simplification--almost a caricature--of the real spectrographic patterns. Then, by playing back these patterns, that is, by reconverting them into dynamically changing sounds, one could judge by ear whether the visual simplification had in fact caught the phonetic content. In spite of crudities, this proved to be a powerful research method. Initially, we worked with sentences. The original spectrogram of such a sentence, and a simplified pattern of the kind we often used, are shown in Figure 4. (Recordings were played of the speech synthesized from these patterns.)

The playback itself is, as I have said, a rather simple-minded device. The diagram in Figure 5 shows how it works: a line of light is modulated by a tone wheel and is imaged on a painted spectrogram. As the spectrogram moves past the scanning point, some of the light is scattered (or transmitted) into a photocell that is connected with an amplifier and loudspeaker. The modulation frequencies that are selected for conversion into sound depend on where the painted areas are along the modulated line image from the tone wheel; the low frequencies are at the bottom of this line, the high at the top. The tone wheel is a motor-driven disc about 20 inches in diameter with the harmonics of 120 Hz, from 120 to 6000 Hz, recorded photographically in variable-density mode on fifty tenth-inch bands. The entire device is mounted on three lathe beds bolted to a heavy table, and deserves characterization as American Gothic for the stark simplicity of its construction.

I would like to draw your attention to some interesting characteristics of speech that are implicit in the fact that the playback is so crude, and yet talks intelligibly.[9] Obviously, naturalness and good voice quality are not essential to intelligibility, though maybe they would help. Likewise, pitch inflections are non-essential, since playback speech is a flat monotone. This is entirely consistent with the underlying principle of Homer Dudley's Vocoder, namely, that the voice carrier, including its pitch, serves one function, while the modulations imposed on it by articulation serve another. Linguists and phoneticians make a corresponding distinction, though they may not attach as much significance as they might to the near-independence of the segmental and suprasegmental aspects of speech. A third point, and perhaps the most interesting of all, is the ability of these highly simplified patterns to carry <u>all</u> of the message, or, more accurately, as much of it as we expect to find on a printed page.

Let me review for you, very briefly, some early experiments we made with the playback.[10] Figure 6 summarizes several series of studies of the acoustic cues for stop and nasal consonants. In the experiments, we used a wide variety of second-formant transitions, nasal resonances, and first formant transitions and "cutbacks". The nine patterns shown in the figure are the best we could find for the nine consonants when paired with the vowel [a], and they are here arranged in rows and columns according to distinctive acoustic characteristics. You can see that the same 3 x 3 arrangement would have resulted if we had used the familiar phonetic dimensions of place and manner. But you should not assume that the acoustic characteristics I have mentioned are acoustic <u>invariants</u> for these consonants because, if they were, then one should find them intact when the same consonants are paired with different vowels. This is not so, as you can see in Figure 7, where the transitions are quite different from vowel to vowel, most notably those of the second-formant for [d].

In working with these acoustic cues we often observed a striking perceptual characteristic of consonants that one might not have expected. Thus, when we listened to a series of patterns that progressed in small steps along one acoustic dimension--for example, the <u>extent</u> of the second-formant transition--what we noticed was that the perception remained the same for several sounds, then changed abruptly to a different perception, and again to a third. This impression was well founded because, when we asked our subjects how well they could tell the difference between two adjacent patterns, the answer was that they could hardly do it at all (as between patterns that were in the same category, that is, patterns that had the same label), although they were quite aware of an equal stimulus difference at the boundary between categories. George Miller once characterized categorical perception of this kind by saying that phones, like coins, rarely land on edge.

In describing the Pattern Playback, you may have noticed without my mentioning it the resemblance to the device-type model of Figure 2a. For the Pattern Playback, the central processor was a paint brush operating on a spectrogram and the synthesizer was a tone wheel plus an electro-optical system. At a later stage in our work, we built and used an exact counterpart of a

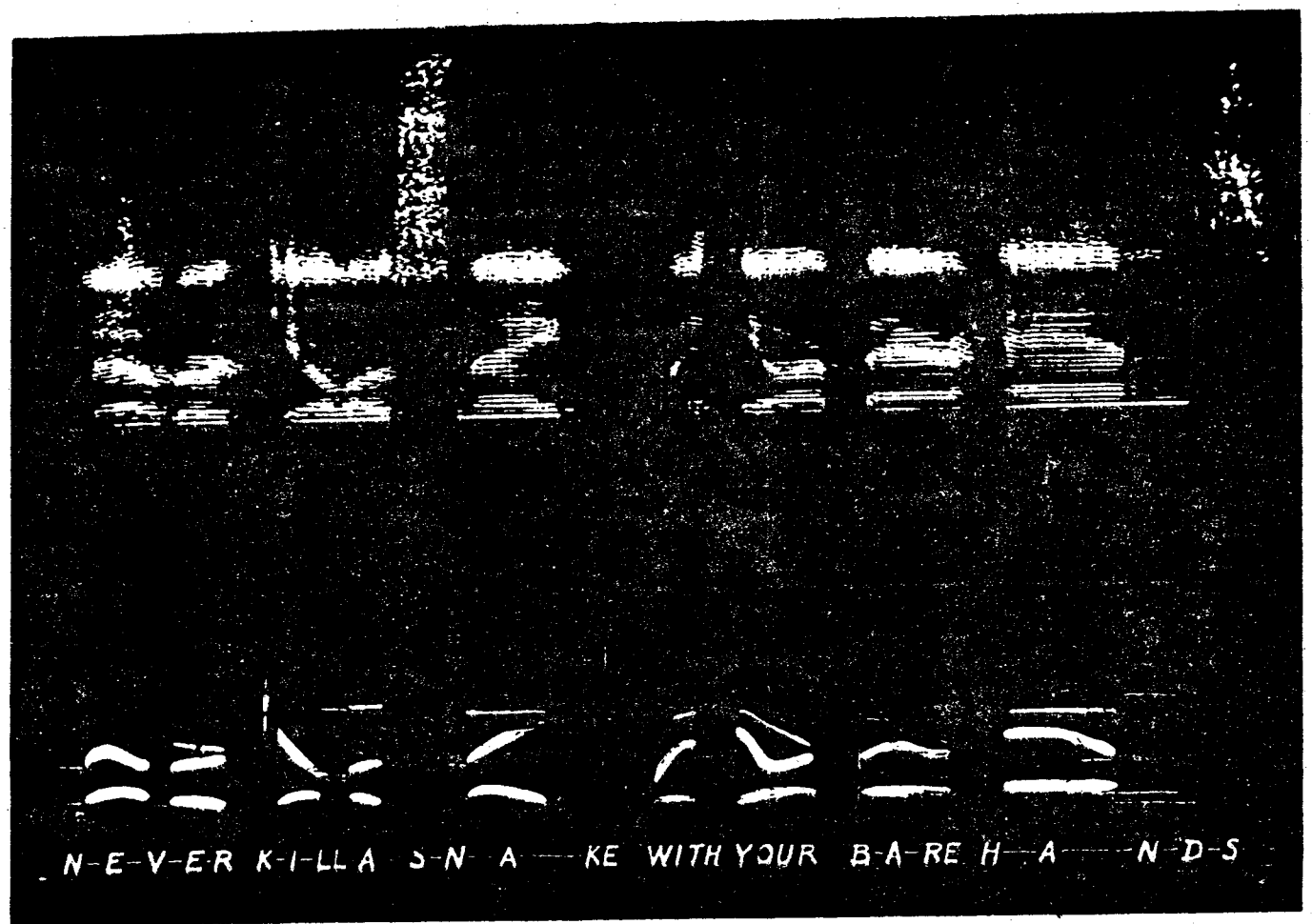
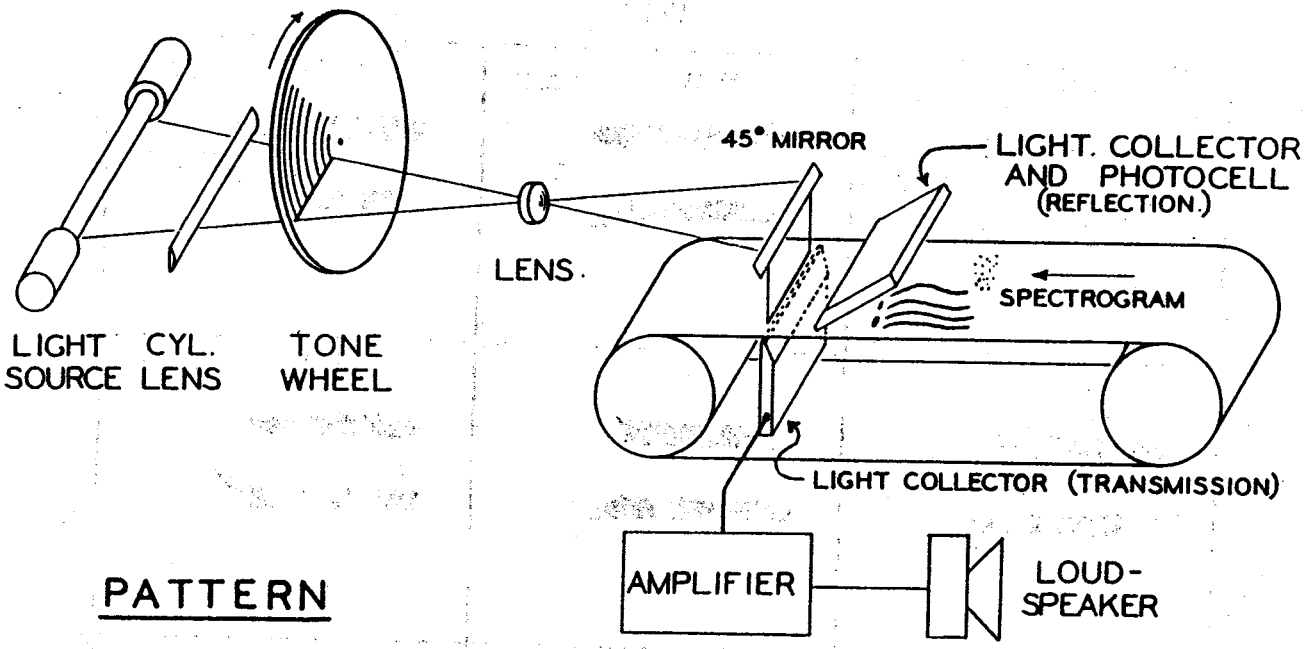


FIGURE 4



PATTERN

PLAYBACK

FIGURE 5

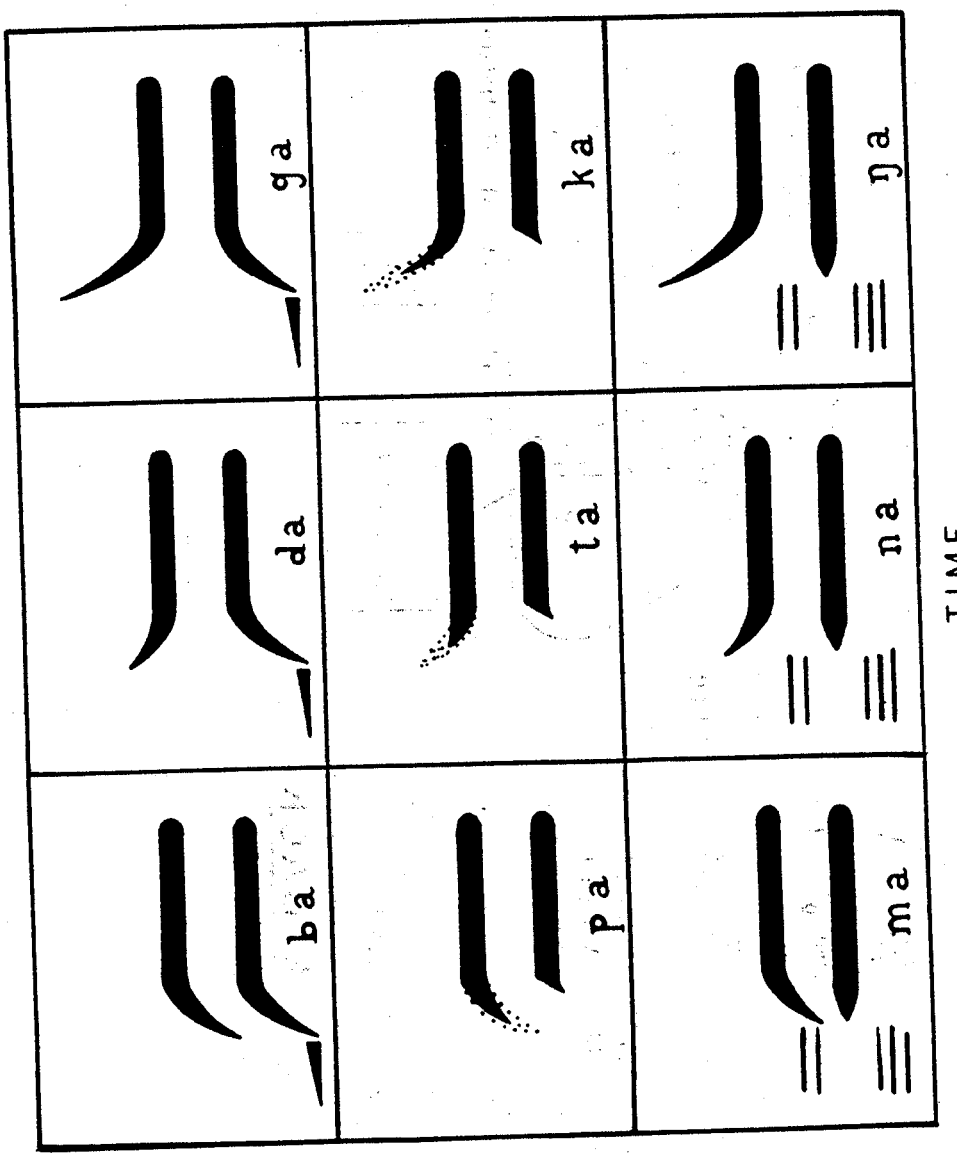


FIGURE 6

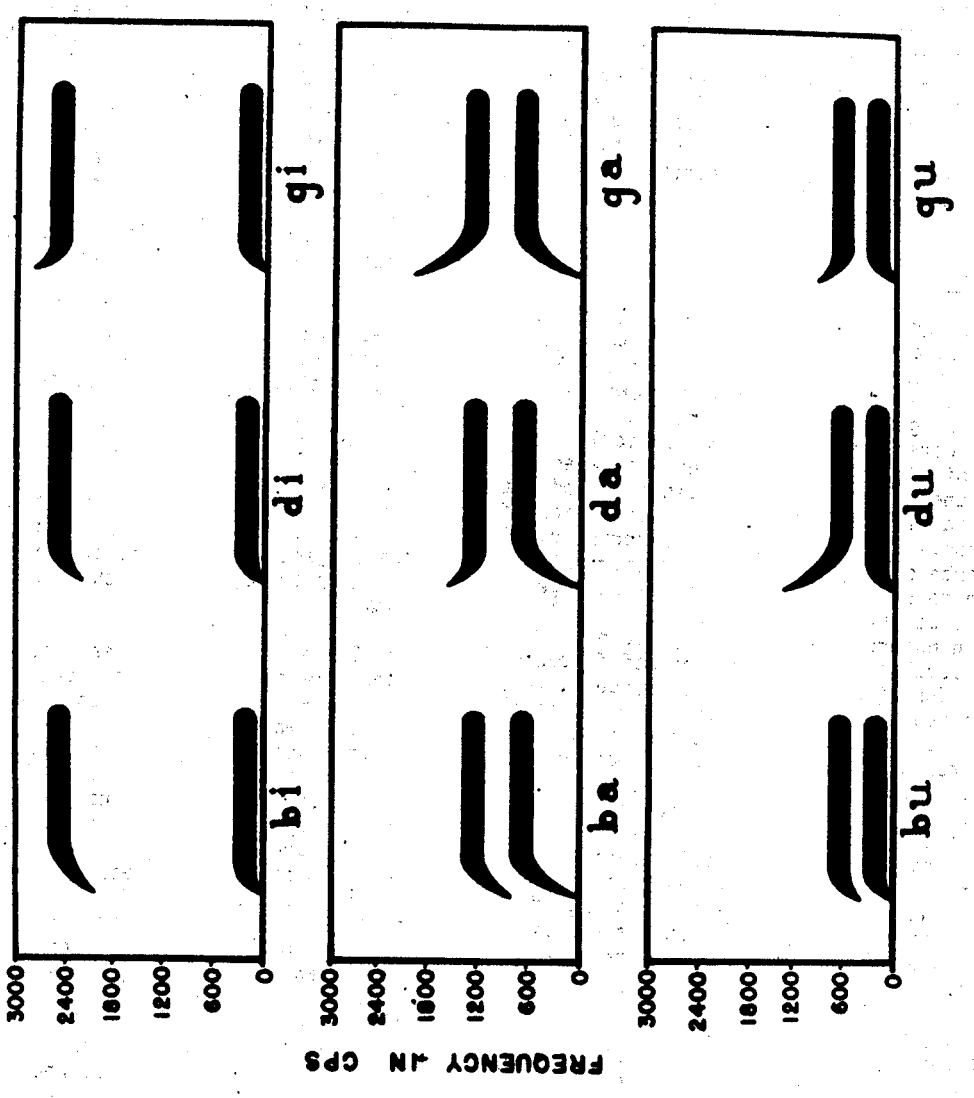

3000
2400
1800
1200
600
0
FREQUENCY IN CPS
bi
di
gi
ba
da
ga
bu
du
gu

FIGURE 7

vocoder and called it a Voback.[11] Figure 8 shows the Voback's own kind of spectrogram between analyzer and synthesizer. The principal virtues of this device were that it gave better quality speech and it let us manipulate pitch as well as spectrum. More recently, we have put together a computerized version of this vocoder-type playback. Figure 9 shows how it works and why we built it: neither the Pattern Playback nor Voback made it possible to work with real speech with any degree of facility, but this Digital Playback does. We have tried to retain the simplicity and immediacy of the original playback, insofar as the operator is concerned, though at some considerable cost in terms of instrumental complexity, as you can see in Figure 10, which shows the major components of the system.[12]

I have mentioned only a few of the ways in which speech perception can be studied by manipulating the speech signal and then trying to infer from the perceptual consequences what the perceptual processes might have been. This is a lively area of current research, as many of you know.

Speech Production

Let me turn now to research on speech production. You can understand what motivated us to look in this direction by recalling the 3 x 3 array of stop and nasal consonants shown in Figure 6. Originally, the patterns for the nine consonants were arranged that way strictly on the basis of acoustic regularities but, when this was done, the row and column headings turned out to be the familiar names for manner and place of articulation. This is not really surprising, of course, since one would expect production and perception to be compatible. What is strange, is that the acoustic features were not really acoustic in nature--at least, they did not differ along the usual acoustic dimensions of frequency, intensity, duration, and the like. Indeed, very few of the acoustic cues we found as we studied the various sounds of English seemed to have any intuitive relationship to acoustic dimensions or, indeed, to be perceived as acoustic events that happened to have phonetic names; rather, they were phonetic events in the first instant. On the other hand, all the cues could readily be rationalized along articulatory dimensions. This set us to wondering if perceptual decoding of the speech signal might best be understood by studying the encoding operations of speech production.

We thought this approach might also help us to understand why speech can go so fast. You will remember that this was what lured us into speech research in the first place. If one looks with a fresh eye at the articulatory system, his first impression would have to be that even Rube Goldberg wouldn't have built a plumbing system like this: the airway to the lungs and the foodway to the stomach actually cross each other and, because they do but must be kept functionally separate, there is a whole array of valves to control the traffic. But notice what this implies for speech. If these valves--more generally, these articulators--are controllable independently then the individual components do not have to move rapidly in order that the state of the system (as determined by all of them collectively) can change many times per second. Thus, corresponding events in the acoustic signal can also change rapidly, and we have the miracle of rapid speech produced by slowly moving articulators, simply because there are several of them and they can operate in parallel. One could make the same point about touch typing as compared with the single-finger hunt-and-peck method. An even better analogy is stenotyping.

As to speech perception, we have seen already in the 3 x 3 array that the acoustic cues are describable in terms of a set of more-or-less independent features that are used in combination. Thus, the speed with which perception operates can also be understood in terms of the parallel processing of slowly changing features encoded into the sound signal. In short, if perception somehow tracks production, then we can readily understand several things about speech: why it is so fast, why the encoding operations do not place an intolerable burden on perception, and why the acoustic cues for speech seem so strangely unacoustic in their makeup.

But I started to consider strategies for research on speech production. Here is a diagram of some of the stages in the process (Fig. 11). We know that the speech that comes out of the articulatory process is encoded, though we do not know the size or nature of the units that are involved in that operation. We can guess, from linguistic theory as well as from research on speech, that segments of something like syllabic length are near the upper limit for unitary speech gestures and also approximate a lower bound on the operations that belong in the domain of linguistics.

Since we wished to learn as much as we could about the organization of speech gestures, and how and where speech blends into phonology, we chose to work with electromyography[13] because it provides information about stages that lie as high in the production chain as we can reasonably expect to reach experimentally, and because it lets us by-pass two low-level stages where we can be sure there is much encoding. This encoding comes about because the movements of the articulators depend in a complex way on the pattern of muscle contractions, and this is true not only on a moment-by-moment basis but across some span of time so that the phonetic segments are, in effect, merged into each other. Likewise, the shape of the vocal tract at any instant depends not only on how the articulators are moving at that moment, but where they have been and where they are going. These effects are commonly "explained" as coarticulation, though the emphasis this puts on phone-sized segments may actually complicate the task of accounting for the ongoing parallel operations of articulation. But coarticulation can offer little by way of explanation for components of a gesture that anticipate their segmental roles in it--for example, lip rounding of all the consonants in an initial cluster before [u], though not

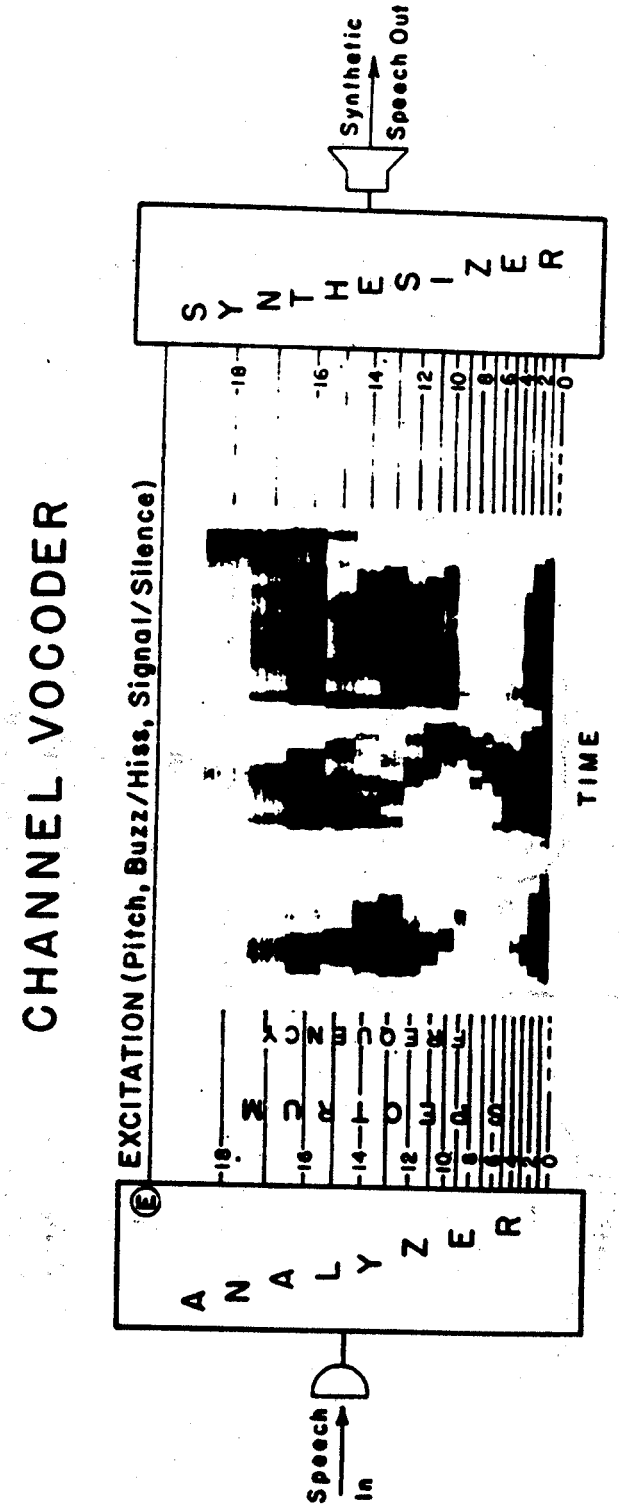

CHANNEL VOCODER
Speech In
ANALYZER
EXCITATION (Pitch, Buzz/Hiss, Signal/Silence)
CHANNEL
TIME
SYNTHESIZER
Synthetic Speech Out

FIGURE 8

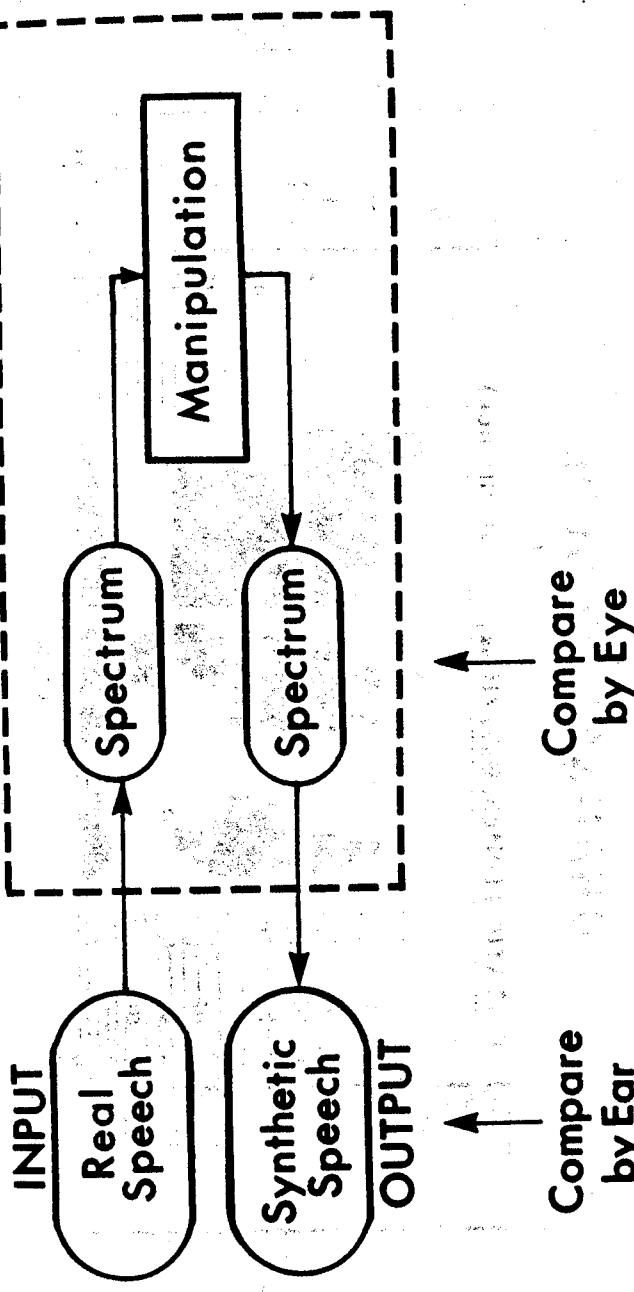

DIGITAL PLAYBACK
Manipulation
Spectrum
Spectrum
INPUT
Real Speech
Synthetic Speech
OUTPUT
Compare by Eye
Compare by Ear

FIGURE 9

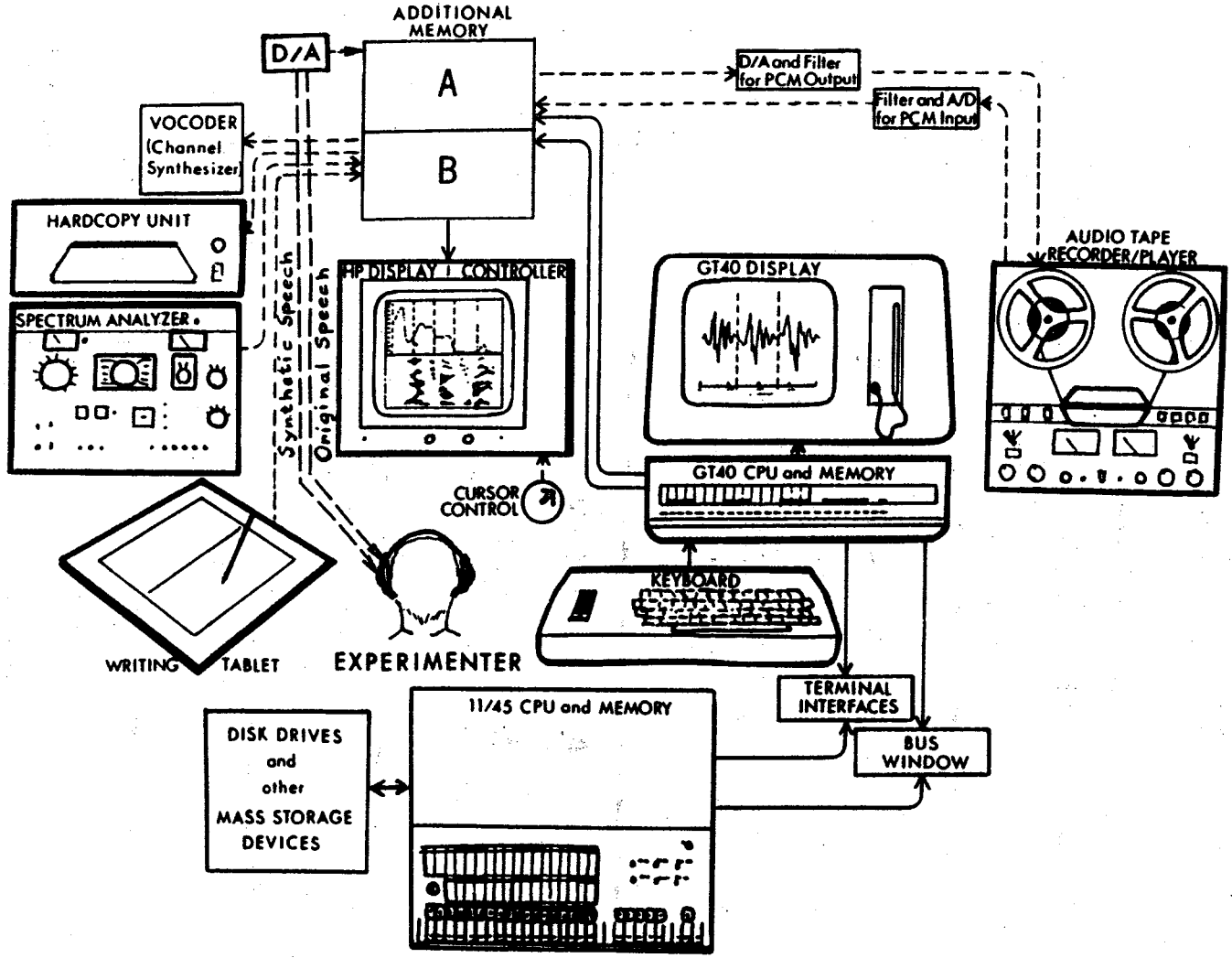
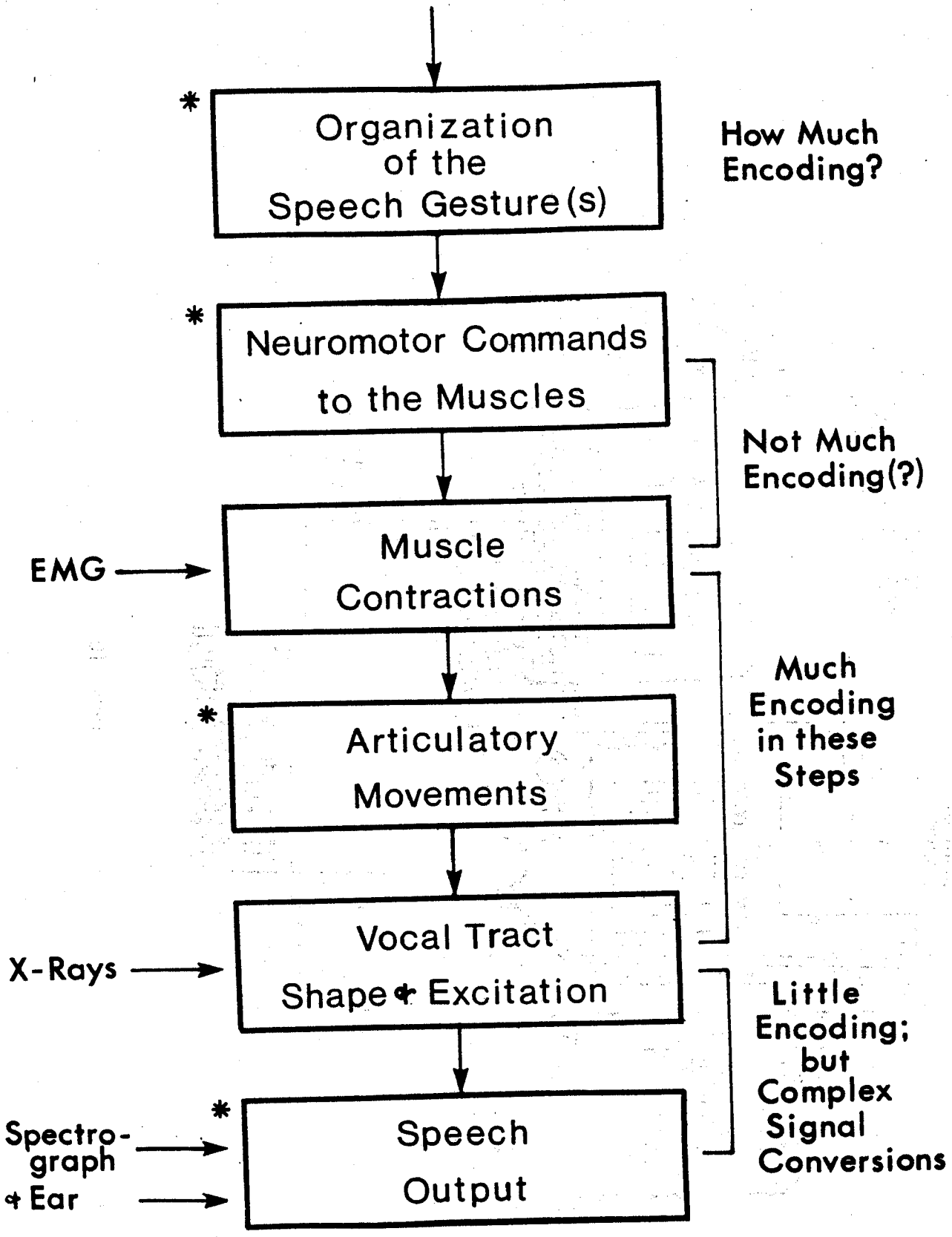

ADDITIONAL MEMORY
D/A
A
B
D/A and Filter for PCM Output
Filter and A/D for PCM Input
VOCODER (Channel Synthesizer)
HARDCOPY UNIT
SPECTRUM ANALYZER
Synthetic Speech
Original Speech
HP DISPLAY / CONTROLLER
GT40 DISPLAY
AUDIO TAPE RECORDER/PLAYER
CURSOR CONTROL
GT40 CPU and MEMORY
KEYBOARD
WRITING TABLET
EXPERIMENTER
TERMINAL INTERFACES
BUS WINDOW
11/45 CPU and MEMORY
DISK DRIVES and other MASS STORAGE DEVICES

FIGURE 10



Note: *Levels at which description is most desired.

FIGURE 11

before [i]. Such things point to the need for a neural organization of the speech gesture that occurs above the level of muscle contractions and also above the neuromotor commands that these contractions reflect. A major question for research on production is, then, to discover what span of attention to attribute to the operation labeled "Organization of the Speech Gesture," and also to learn how much, or how little, reorganizing goes on there.

If a schema of this kind really does describe how we produce a spoken sentence, then linguistics has the problem of providing speech production with the kinds of input signals it can use. Whatever we can learn about such units by direct experimentation can serve as guide and constraint to linguistic theorizing; also, it can help to provide a model of sorts for the linguistic operations required to assemble lexical items according to semantic needs and then put them into linear form so the sentence can be spoken.[14] If, alternatively, the sentence is to be written, the requirements are somewhat different and so is the linguistic product.

At the left of the schema, I have indicated how different research methods can help us to understand the successive stages in articulation. These are not the only available methods by any means, though they are the most versatile. Constant efforts are being made to develop new methods; also comparatively new is the use, in combination, of EMG, X-rays, and speech analysis. The first two, in particular, need to be used together because muscle activity at any instant will depend on where the articulators already are at that instant and, conversely, the effects of muscle contractions are really not predictable from EMG signals but must actually be observed. Several laboratories across the country are tooling up to do just this kind of research.

As a final instance of research strategy, may I remind you of the rationale for the Pattern Playback: you control the synthesis and then observe the perceptual result. If we use an articulatory synthesizer in this way--moving the individual articulators in ways that test various theories about articulatory targets--we may be able to conduct a search for the articulatory cues that are effective in perception.[15] This would be strictly analogous with the earlier search for the acoustic cues. It seems to us an exciting prospect.

Some Current Concerns

I have touched on some of the current concerns of speech research, though undoubtedly I have omitted many more. Let me comment briefly on three major questions. First, what is the nature of the relationship between perception and production? There is a great deal of evidence and general agreement about the existence of a significant relationship of some kind. The question is, what kind? I have tended here to emphasize the articulatory aspects of speech, and have at least implied that perceptual operations somehow make use of knowledge about how speech is encoded in order to decode it. I am sure you know that there are other highly respected points of view. Kenneth Stevens, for example, sees a relationship between quantal states of production and the feature recognizing capabilities of perception and proprioception[16]. In his view, these cooperate to localize the interpretation of speech signals within the sensory domain without need to involve the motor domain. It may, of course, turn out in the end that it is meaningless to ask whether the special perceptual mechanisms needed for speech are primarily sensory or primarily motor. For the moment, though, a lively exploration of differing points of view is underway.

A second question, closely related, has to do with the units in which the speech signal is organized in production and dealt with in perception. Put another way, it is a question of how much preplanning--and how much carryover--"belongs" in the speech component of language, and where the boundary is between the domains of speech, narrowly defined, and the rest of linguistics. A third question to which I have not so far alluded has to do with how language is acquired in the first instance. Are there operations and mechanisms that are important in language acquisition, though they may no longer be needed by adults for the everyday use of spoken language?

Summary

Let me recapitulate the main points that I have tried to make. The most general one is that speech is an integral part of language and therefore a proper concern of linguists as well as of people who call themselves speech scientists or speech researchers. Remember, please, that speech is a continuous process from sentence formulation through production and perception to comprehension by the listener. There are, at each stage in passing a message down this chain, encoding operations that have much in common, if indeed they do not have a common pattern. The efficiency of spoken language, as well as the challenge it offers to us as scientists, follows from the fact that we are dealing at every level with coded messages.

At the level of the speech signal, this code can best be understood in terms of the processes that have shaped it in production and that, in perception, must recover the message. This is the basis for an overall strategy that uses speech as a target of opportunity. From this vantage point, research can proceed downstream toward perception, making good use of the kind of analysis-synthesis methods typified by the Pattern Playback; also, research can be carried upstream quite some distance, mainly by psychological methods.

The goal of all these strategies and tactics is to understand the nature of the message in its spoken form and how this relates to the overall linguistic processes within which speech

is embedded. It is an exciting field for cooperative research. So let me end by inviting you to share in it.

May you have as good luck in the future as Dr.Fletcher and Dr.Stevens--and I, too--have had in the past.

Figure Captions

Figure 1: Some engineering aspects of speech research.

Figure 2: Models and strategies. (A) A general-purpose model for communications devices. (B) Adaptation of (A) to the human as a communications entity. (C) Communication between two humans and research strategies such a model suggests.

Figure 3: The first spectrogram of the sentence "Joe took father's shoe bench out," as published by John Steinberg in 1934.

Figure 4: Spectrograms used with the Pattern Playback, about 1950. At top, an original photographic spectrogram; at bottom, a hand-painted simplification for the same sentence.

Figure 5: Functional diagram of the Pattern Playback. The Light Collector, connected to an amplifier and loudspeaker, could be positioned either below the belt carrying a spectrogram (as shown) for use with transmission spectrograms, or above the belt for use with the hand-painted reflection-type spectrograms that were used in most of the research. The tone wheel, driven by a synchronous motor, provided fifty light beams modulated at harmonics of 120 Hz to 6000 Hz.

Figure 6: Nine two-formant patterns found to be optimal for the stop and nasal consonants when paired with the vowel [a]. The arrangement by rows and columns is according to similarities in the formant transitions; the individual patterns have the usual spectrographic dimensions of time and frequency.

Figure 7: Two-formant patterns for the voiced stops with each of three vowels, showing how the transitions of the second formant differ for the same consonant when paired with different vowels.

Figure 8: A channel vocoder, showing how the information flowing from analyzer to synthesizer is representable as a spectrogram and therefore modifiable for experimental purposes, just as with the Pattern Playback. A device called Voback implemented this approach, using photocells to "read" hand-painted spectrograms into the vocoder synthesizer; separate control channels carried information about pitch and buzz/hiss switching.

Figure 9: The Digital Playback is designed to serve the same experimental functions as the original Pattern Playback, but to do it conveniently for real speech.

Figure 10: Components and control facilities for the Digital Playback. Real-time analysis equipment stores a few seconds of speech spectrum and waveform in computer core, whence it can be called for faster display as a spectrogram or to recreate the speech by synthesis. Easy modifications can be made to the contents of core memory, and the results can be seen in a comparison spectrogram or heard as speech synthesized from that spectrogram.

Figure 11: Schema for speech production, with notations (on the right) about the extent to which successive transformations encode the message, and (on the left) about major experimental approaches to the speech process.

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[The demonstration recording played at the end of the talk was excerpted from a soundsheet that was bound into IEEE Transactions on Audio and Electroacoustics, Vol. AU-21, No.3, (June 1973)].