Technical Paper 296

THRESHOLD OF INTELLIGIBILITY/ COMPREHENSIBILITY OF RAPID CONNECTED SPEECH: METHOD AND INSTRUMENTATION

Henry J. deHaan and John R. Schjelderup

HUMAN FACTORS IN TACTICAL OPERATIONS TECHNICAL AREA

U. S. Army
Research Institute for the Behavioral and Social Sciences

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The technology of speech compression demands new methods for measuring the intelligibility and comprehensibility of compressed speech. The present report describes a method in which repeated judgments of the comprehensibility of speech are obtained as the rate of speech is made to vary. The method is similar to the Békésy method for the determination of pure-tone thresholds but differs from it in that rate of speech is varied rather than the intensity of an auditory signal. The result is a threshold value representing the

20.

maximum rate of speech judged comprehensible by an individual listener. Instrumentation that varies speech rate, accelerating or decelerating the rate either with or without pitch changes, was developed for this determination and is described in some detail. Both the method and associated instrumentation have potential for a variety of applications.

Technical Paper 296

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HUMAN FACTORS IN TACTICAL OPERATIONS TECHNICAL AREA

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Human Performance Enhancement

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FOREWORD

The Human Factors in Tactical Operations Technical Area of the U.S. Army Research Institute for the Behavioral and Social Sciences deals with problems of human performance enhancement. To be able to exploit human capacities fully, the agency explores the limits of these capacities. Frequently, the perceptual aspects of human capacities are involved, such as visual perception during land and airborne night operations. Auditory perception was the subject of ARI Technical Paper 295, which dealt with training people to comprehend rapid speech.

This report describes a method for measuring the comprehensibility of speech as the rate of speech varies. The result is a threshold value representing the maximum rate of speech judged to be comprehensible by an individual listener.

This exploratory work was done under Army Project 2T161101A91B, and its results are relevant for a wide range of voice communication situations in the Army, especially those requiring rapid review and processing of tape-recorded verbal material.

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Technical Director (Designate)

THRESHOLD OF INTELLIGIBILITY/COMPREHENSIBILITY OF RAPID CONNECTED SPEECH: METHOD AND INSTRUMENTATION

BRIEF

Requirement:

Speech reproduction technology has made it possible to reproduce speech at rates far beyond man's capacity to understand it. Consequently, methods are needed to measure the comprehensibility of rapid speech, and specifically, the maximum rate of speech understood by an individual listener.

Procedure:

A threshold method was developed to measure the rate at which speech becomes incomprehensible as rapidity is increased. It is analogous to the Békésy method for measuring pure-tone loudness thresholds; however, the rapidity of speech is varied rather than the intensity of either a tone or speech.

Instrumentation developed for determining this threshold includes a laboratory-fabricated device for controlling the rate of speech and its acceleration or deceleration. The apparatus allows the pitch of speech either to be held constant or to vary in proportion to the speed of speech.

Findings:

The maximum rate of comprehensible speech may be determined by a threshold method involving successive judgments of the comprehensibility of speech as the rate of speech is made to accelerate and decelerate. Employed in the manner described herein, the method appears to have considerable reliability.

Utilization of Findings:

The method may be used to determine individual differences in ability to understand rapid speech and/or engage in rapid scanning of speech, to evaluate devices that produce or time-compress speech, and perhaps to evaluate the comprehensibility of recorded spoken materials. In addition, both the method and instrumentation may be considered multipurpose research tools.

THRESHOLD OF INTELLIGIBILITY/COMPREHENSIBILITY OF RAPID CONNECTED SPEECH: METHOD AND INSTRUMENTATION

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THRESHOLD OF INTELLIGIBILITY/COMPREHENSIBILITY OF RAPID CONNECTED SPEECH: METHOD AND INSTRUMENTATION

INTRODUCTION

Instruments such as the phonograph and tape recorder have made it possible to reproduce speech at rates far beyond human capacity to understand it. This process of speech reproduction is known as time-compression of speech.

Perhaps the simplest way to produce time-compressed speech is to increase the speed of a reproduction device beyond the speed of the original recording, a process known as the speed-changing method of time-compression. Speech produced in this way is frequently referred to as speeded speech: It is rapid, but has a peculiar, high-pitched quality commonly associated with the cartoon character Donald Duck because frequencies of the speech components vary directly with playback speed.

The groundwork for another method of producing time-compressed speech was laid some years ago by Miller and Licklider (1950). These investigators found that interruptions of speech at 10 or more times per second did not interfere seriously with the intelligibility of a speech signal until relatively large proportions of the signal were discarded. Subsequently, Garvey (1953) manually cut out short segments of a tape recording and physically rejoined the remaining parts. This resulted in time-compressed speech without the previously described distortion in pitch. Shortly thereafter, Fairbanks, Everitt, and Jaeger (1954) developed a rotating-head tape recorder-reproducer to compress speech without the cumbersome manual manipulations used by Garvey. Since that time, a number of devices using more sophisticated electronic technology have been developed to achieve the same result. The process, in which devices sample speech at very frequent intervals and discard a portion of each sample, is known as the sampling method of time-compressing speech.

METHOD

Devices such as these need methods for evaluating the perception of the speech they produce. Methods currently used for this purpose were reviewed by Foulke and Sticht (1969). In general, they are extensions or applications of methods used for the evaluation of normal speech, although some interesting innovations have been made. The methods fall into two classes: comprehension measurement and the measurement of intelligibility.

Comprehension measurement usually is applied to materials of some length, such as connected discourse. The measurement is obtained by asking questions concerning content of the materials. Questions are frequently the multiple-choice type, assembled in comprehension tests, and standardized according to conventional methods of test construction.

Despite the amount of work done on comprehension measurement, the results of its application to time-compressed speech can be summarized briefly. Usually, comprehension declines as the rate of speech increases. Moreover, Foulke (1971) and Foulke and Sticht (1969) found that a rapid decline in comprehension occurs when the speech rate exceeds approximately 250 to 275 words per minute (wpm) regardless of the word rate of the original passage.

Other methods of evaluating the perception of speech can be classified as intelligibility measurement. Such methods derive from investigations of the quality of speech transmitted over the telephone system (Fletcher, 1929). The methods often deal with the sound-intensive aspects of audition. In one version of the so-called articulation test, listeners are presented with words or other brief materials at various intensities and asked to repeat them. The intensity at which half the words can be repeated is referred to as the threshold of intelligibility. Several such techniques were used to determine the intelligibility of compressed speech. Calearo and Lazzaroni (1957) determined the threshold intensity required for compressed word identification; Garvey (1953) used the percentage of compressed words correctly identified; and Foulke (1969) used reaction time required to identify single compressed words as an index of intelligibility.

Although most intelligibility methods dealt with single words or other brief materials, a number of attempts were made to measure the intelligibility of connected, running speech (Chaiklin, 1959; Dahle, Hume, & Haspiel, 1968; Falconer & Davis, 1947; Haspiel & Havens, 1966; Hawkins & Stevens, 1950; LeZak, Siegenthaler, & Davis, 1964; Speaks, Parker, Harris, & Kuhl, 1972). In these studies, the listener was asked to adjust the intensity of speech to the lowest point at which he could understand it or understand some given percentage of it. In many studies, a modified Békésy technique was used to determine the intensity of the auditory signal, the so-called speech reception threshold.

Consideration of the foregoing methods revealed that no threshold method was available for evaluating the understanding of connected speech based on variations in the rate of speech rather than variations in intensity. Consequently, a simple, direct, psychophysical method was developed by the present authors for this purpose.

The method is analogous to the Békésy (1947) method for determining pure-tone loudness thresholds. The rapidity of the speech signal is varied instead of the intensity of a tone. Rapidity of speech is made to increase automatically at a constant rate of acceleration until the listener indicates, by pressing a button, that he can no longer understand it. Rapidity of speech then decreases automatically at a constant rate of deceleration until the listener indicates, by releasing the button, that he can understand it again. A repetition of this process, whereby the listener responds to and controls the changing rate of speech, effectively brackets the point at which understanding fails as rapidity increases.

The method assumes that the perception of rapid speech is a variable that obeys the same psychophysical laws as do other perceptual variables, and that the listener can perceive the point at which he no longer understands speech as it becomes progressively more rapid. Although there is little direct evidence for this assumption, Hutton (1955) found that perceived word rate was a logarithmic function of measured rate, even though his stimulus materials were quite brief (ranging from 8.0 to 42.6 seconds in duration).

Figure 1 is a block diagram of the instrumentation used for determination of the threshold. The instrumentation provides for the presentation of either speeded speech (speed-changing method) or compressed speech (sampling method). Speeded speech is obtained by means of a Crown variable-speed tape recorder (Model CX822) together with a Crown speed control device (Model VSD-5).[1] Compressed speech is obtained by an AmBiChron pitch compensator (Koch, 1974) in conjunction with the above equipment. The AmBiChron samples speech, writes the signal into a temporary memory, and reads the signal from memory at a rate that may be different from the writing rate. The rate of writing into memory is proportional to the tape transport speed, which here refers to the speed of the Crown recorder. The read-out rate is constant. Depending on the relative rates of writing and reading, brief segments of the speech signal are either discarded (compression) or repeated (expansion). Consequently, the AmBiChron produces speech with constant pitch despite changing speeds.

Both the speed of the tape recorder and the pitch compensation of the AmBiChron are controlled remotely by a laboratory-fabricated device that provides for a constant starting speed and constant rates of acceleration and deceleration selected by the adjustment of three potentiometers.

The potentiometer settings are calibrated in units of time required for the rate of speech to double (accelerate from normal to twice normal) or halve (decelerate from twice normal to normal). The circuitry of this device will be described later.

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[1] Commercial designations are given only in the interest of precision of reporting. Their use does not constitute endorsement by the U.S. Army Research Institute or the U.S. Army.

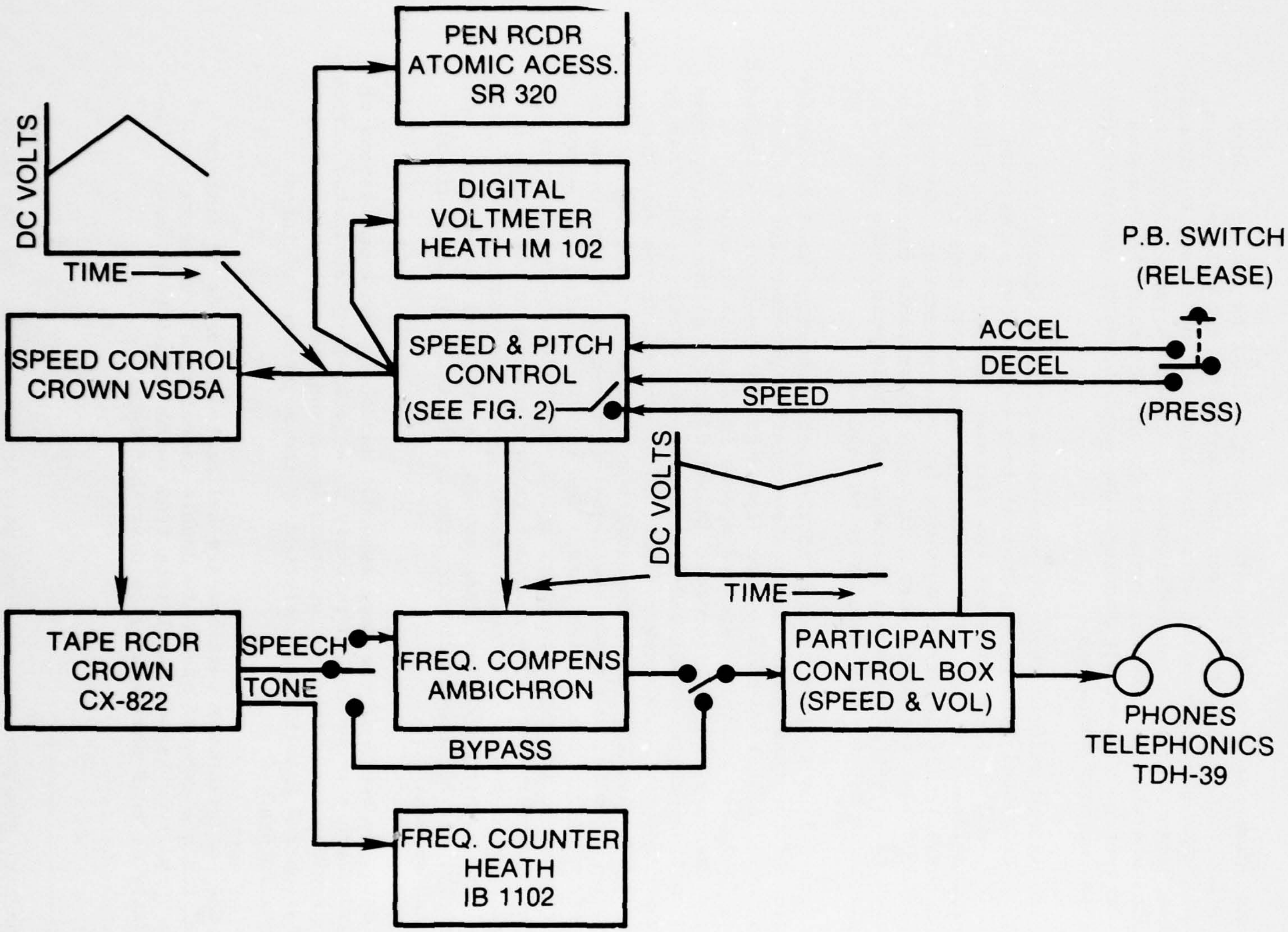

Figure 1. Block diagram of major instrumentation components.

The voltages applied by the control circuits determine the speed of the tape recorder and pitch compensation of the AmBiChron. The former is displayed on a digital voltmeter and recorded in analog fashion by a strip chart recorder (Atomic Accessories Model SR320) on 6-in. (15.24 cm) wide paper at 2 in./min (5.08 cm/min). In addition, all speech tapes have a 1,000 Hz tone recorded on another channel at 3.75 in./sec (9.525 cm/sec). As tape speed varies, the frequency, which is indicative of the momentary speed of speech, changes proportionately and can be read on a digital frequency counter (Heath Model 1B-1102).

Additional equipment includes a small control box that enables the listener to set the intensity and rate of speech by multiple-turn potentiometers (the rate control is inactivated for automatic threshold determination), a pair of Grason-Stadler headphones (Telephonics Model TDH39), and a Grason-Stadler audiometer switch used to select either acceleration or deceleration. During threshold determinations, rates of acceleration and deceleration are preselected by potentiometer settings.

The circuitry of the Tape Speed and Pitch Control Unit is shown in Figure 2, and a list of parts is given. The unit is basically a voltage ramp generator (A1 and associated components) and an adder which combines the ramp voltage with a preset voltage to set the starting level of the ramp (IC1 and components). The output of IC1 connects to the Crown VSD-5A speed control with +2.5 volts d.c. corresponding to 3 3/4 in./sec and +10.0 volts d.c. corresponding to 15 in./sec. Because the input to the AmBiChron voltage controlled oscillator (VCO) required a simultaneous but different ramp with the range +13.46 to +12.41 volts to maintain the voice pitch at normal for the corresponding speed range of 3 3/4 in./sec to 7 1/2 in./sec, it was necessary to modify the ramp obtained at IC1 to have an opposite slope, smaller range, and shifted level. This is effected by IC2 and components, and the output of this stage connects to the VCO of the AmBiChron.

A1 is the basic ramp generator and is configured as an integrator where C1, C2 combination is charged through R6, R7 or R8, R9 (selected by S4) by a positive or negative voltage (selected by S1). S2 allows either the experimenter (by S1) or the participant (by S7) to select a positive or negative going ramp. C1 and C2 are wired back to back so that approximately 10 microfarads of capacitance are available for either positive or negative outputs from A1. These capacitors were selected from a group of 10 and tested for least leakage by applying 15 volts d.c. and measuring the ensuing steady-state current. This was less than 100 picoamperes for the two selected capacitors and minimized output voltage drift at A1 when the integrator was in the stop mode (S5 set to STOP).

When S5 is set to STOP, both the inverting and noninverting inputs of A1 are at the same potential (common) through R10 and R11, integration ceases, and the ramp voltage at A1 output holds a steady

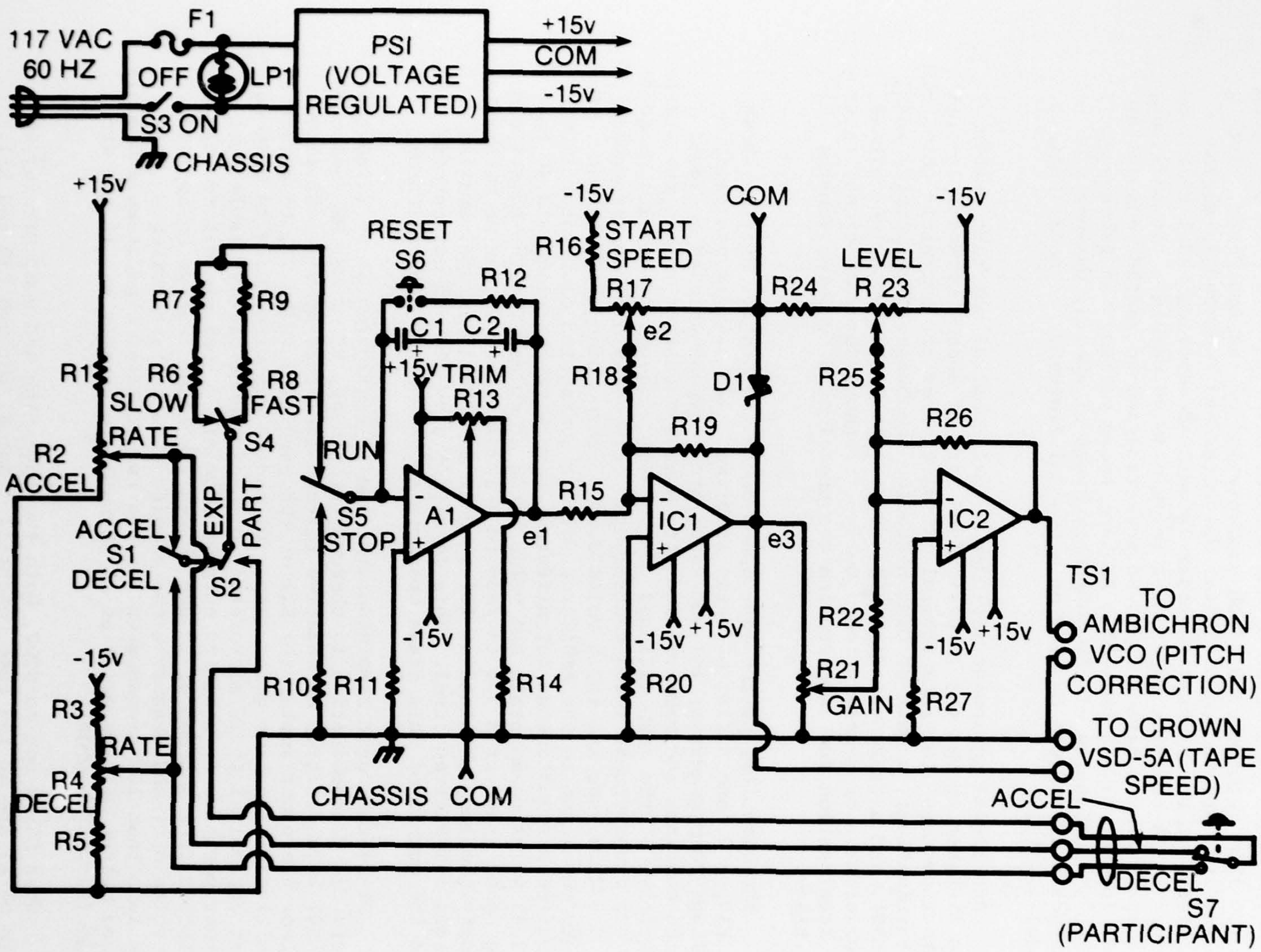

Figure 2. Electrical schematic of Tape Speed and Pitch Control Unit.

Table 1

Parts List for Tape Speed and Pitch Control Unit

Location code	Part
A1	Discrete operational amplifier, Analog Devices 118A[a]
C1, C2	Capacitor, 10uF/25WVDC, Sprague TE-1204
D1	Diode, 1N5856A, 10V Zener, 500 mW
F1	Fuse, Littelfuse 3AG 1/4A 250V
IC1, IC2	Integrated circuit, operational amplifier Calectro K4-590 (equiv 741)
LP1	Lamp, neon, Industrial Devices 2150A
PS1	Power Supply, +15V, Com, -15V, 25 mA, Semiconductor Circuits SQ2-15.30[b]
R1, R3	Resistor, 10K ohms[c]
R2, R4, R17	Resistor, 10K ohms, 1-turn potentiometer, Centralab F2-10K
R5	Resistor, 120 ohms
R6	Resistor, 10 megohms
R7	Resistor, 3.3 megohms
R8, R11	Resistor, 220K ohms
R9	Resistor, 18K ohms
R10	Resistor, 12 megohms
R12	Resistor, 100 ohms
R13, R21, R23	Resistor, 10K ohms, multiturn trimming potentiometer, Allen-Bradley RP103U or Bourns 3006
R14	Resistor, 100K ohms
R15, R18, R19, R22, R25, R26	Resistor, 1 megohm
R16	Resistor, 12K ohms
R20, R27	Resistor, 330K ohms
R24	Resistor, 22K ohms
S1, S2, S4, S5	Switch, SPDT, ALCO MST-105
S3	Switch, SPST, 125VAC 3A, Cutler-Hammer 8280
S6	Switch, N/O push button, Grayhill 10-9
S7	Switch, push button, nonlocking, Switchcraft EP 903, or audiometer switch, Grason-Stadler E800-6

[a]Analog Devices Inc., PO Box 280, Norwood, Mass. 02062.

[b]Semiconductor Circuits, Inc., 306G River St., Haverhill, Mass. 01830.

[c]All fixed resistors 1/2 watt 5% tolerance.

value. To set up initial ramp conditions, the experimenter presses RESET pushbutton switch S6 which rapidly discharges C1 or C2, and A1 output voltage goes very nearly to zero. R12 limits the initial discharge current to a value safe for S6. TRIM potentiometer R13 is set once so that A1 has as little output drift as possible when the integrator is in the STOP mode. If, at the same time, RESET switch S6 has been operated, A1 output will not be exactly at zero. This error, however, is compensated for automatically when the experimenter sets START SPEED potentiometer R17 which is never set to obtain a starting speed near zero. A1 is Analog Devices type 118A, which was on hand and has a lower rated input bias current than the common 741 IC. The drift performance of the two was not compared, and it may be that the 741, which is much cheaper, would function as satisfactorily here.

IC1 is configured as an inverting adder that combines the ramp voltage from A1 output through R15 with the adjustable starting speed voltage through R18. Because feedback resistor R19 and adding resistors R15 and R18 all have the same nominal value and connect to the inverting input of IC1, e3 = -(e1 + e2). D1 limits IC1 output to +10 volts, corresponding to a speed factor of 4:1, beyond which the AmBiChron did not function properly. R20 is 1/3 megohm to match the combined parallel effective resistance of R15, R18, R19 in order to equalize bias currents in both the inverting and noninverting inputs of IC1, thereby minimizing spurious shifts in its d.c. output at high output levels. Such shifts would cause slow, wide-range ramps to be nonlinear with time.

IC2 is also configured as an inverting adder. By means of GAIN potentiometer R21, a 2.5 volt change in the output of IC1 is converted to a 1.05 volt change and fed to the inverting input of IC2 through R22. By means of LEVEL potentiometer R23, the appropriate voltage can be fed through R25 to the inverting input of IC2, so that the output of IC2 can be set to +13.46 volts when the output of IC1 is +2.5 volts. R27 has a function similar to that of R20 discussed above. Thus, when IC1 output ramp goes from +2.5 to +5.0 volts, the Crown tape transport goes from 3 3/4 to 7 1/2 in./sec and speech frequencies go from normal to twice normal at the Crown recorder playback output. Simultaneously, the IC2 output ramp goes from +13.46 to +12.41 volts, which effects a frequency division in the AmBiChron in the range 1.0 to 2.0. Hence, speech has normal pitch regardless of tape speed.

The following calibration procedure is necessary to adjust speed and pitch ramps for coordinate operation:

1. Lift R25 where it joins potentiometer R23 LEVEL control and connect lifted terminal to common.

2. Set S5 to STOP, press S6 RESET, set R17 START SPEED so that e3 is +2.50 volts, and adjust R21 GAIN control so that IC2 output is approximately -1.05 volts.

3. Set R17 START SPEED so that e3 is +5.00 volts and note output of IC2. This should be close to -2.10 volts.

4. If difference in output between steps 2 and 3 is not exactly 1.05 volts, it will be necessary to make a minor adjustment of R21 GAIN control and repeat steps 2 and 3.

5. Restore R25 to original connection.

6. Set R17 START SPEED so that e3 is +5.00 volts. Adjust R23 LEVEL control so that IC2 output is +12.41 volts. Now set R17 START SPEED so that e3 is +2.50 volts; IC2 output should be +13.46 volts.

RESULTS

Two experiments, that used the above instrumentation, were conducted to determine whether the threshold is related to the comprehension of speech or to speech intelligibility (deHaan, 1977). The first experiment compared thresholds of two types of time-compressed speech reportedly different in intelligibility--simple speeded speech and speech compressed by the sampling method. In this experiment, higher thresholds were found for speech compressed by the sampling method than by the speed-changing method. These results supported the hypothesis that the threshold reflects intelligibility because similar results for the intelligibility of single compressed words had been found earlier by Garvey (1953). The effects of various rates of acceleration and deceleration were also studied in this experiment. Rate of acceleration-deceleration was shown to have little effect on absolute thresholds, although it did have a pronounced effect on the difference thresholds (which correspond to the amplitude of the rate-swings as the subject tracks his threshold). An example may be seen in Figure 3, which shows an individual performance record of threshold determinations for both speeded and compressed speech at each of four rates of acceleration-deceleration. (In Fig. 3, a relative acceleration-deceleration rate of 1 indicates that the rate of speech changes from normal to twice normal, and vice versa, in 60 seconds. Other values represent proportionately faster rates.)

The second experiment sought to determine the relationship of the threshold to traditional comprehension measures. Correlation was generally low between threshold values and comprehension test scores for passages at several rates of speech (from 1.5 to 3.0 times normal rate). Thus, the hypothesis that the threshold is a measure of comprehension per se was not supported. Taken together, these two investigations suggest the possibility that the threshold may be a measure of comprehensibility as used by Deese and his students (Deese, 1969; Schwartz, Sparkman, & Deese, 1970), that is, the perception of the feasibility of comprehension.

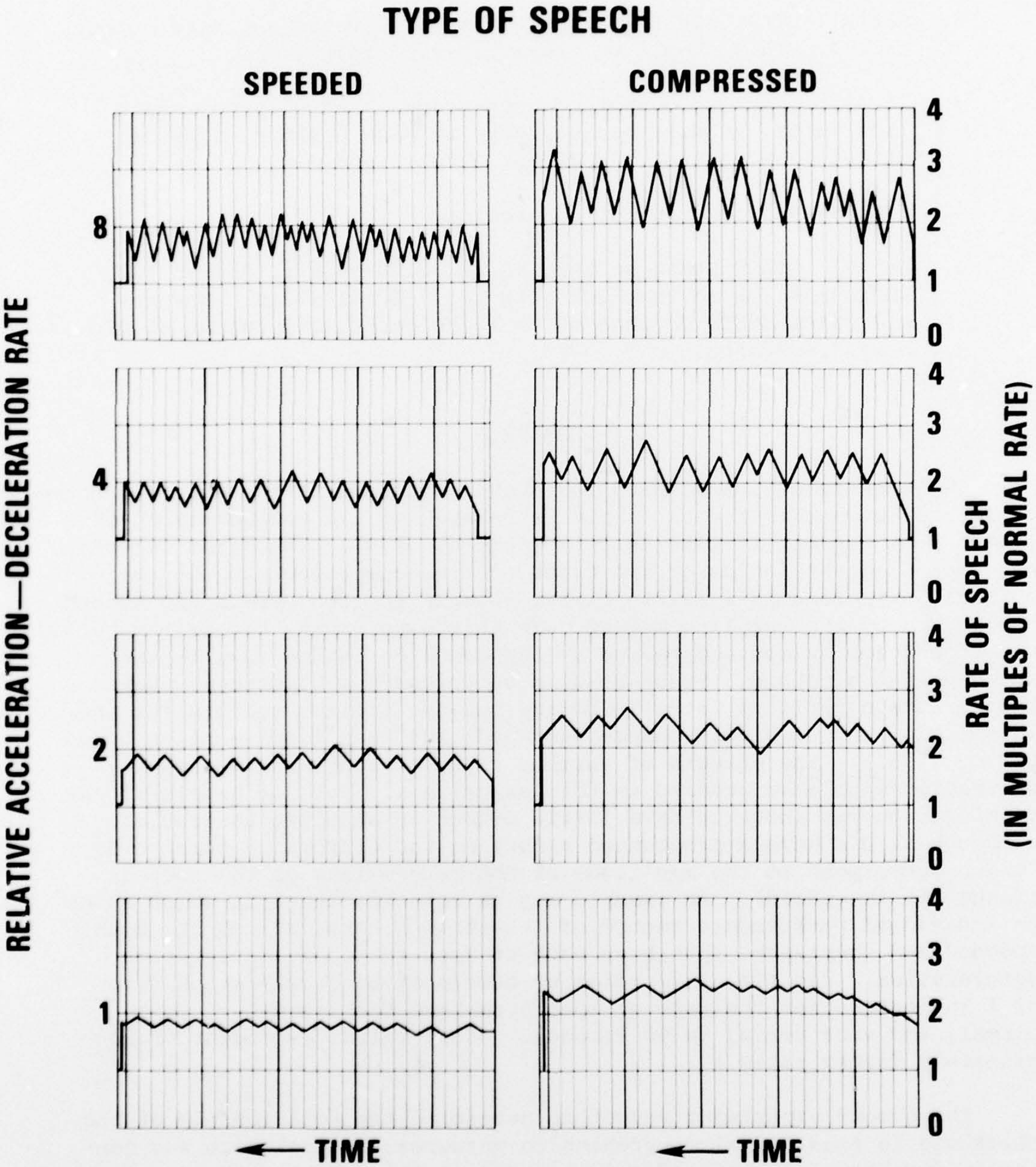

Figure 3. Record of eight threshold determinations on a single individual.

Thresholds were determined for 3-minute periods in these studies. Longer periods have been used and may increase reliability when fewer thresholds per listener are determined. An estimate of the reliability of the threshold was obtained from intercorrelations of the various conditions in the first experiment. Correlations between the two types of time-compressed speech at each of the four rates of acceleration-deceleration yielded the following coefficients: .77, .72, .84, and .75. An average value of .77 was obtained for the 3-minute trials by means of Fisher's r-to-z transformation. Four thresholds for each type of speech were determined. Thus, an estimate of reliability for 12 minutes of data collection may be obtained by applying the Spearman-Brown formula for quadruple length. This yields a correlation coefficient of .93.

After the two experiments had been completed, a more automated version of the above instrumentation was developed, including an ADS (Automated Data Systems) 1800E computer for experimental control and digital recording. This version controls the sequencing and timing of a group of relays with the following functions: (a) select acceleration rate (1 of 4), (b) select deceleration rate (1 of 4), (c) reset to initial rate, (d) audio "blanking," (e) start/stop tape recorder and pen recorder. These functions were obtained by adding a bank of relays above the original Tape Speed and Pitch Control Unit, with all coils operated under control of the ADS 1800E Input/Output buffers. Contacts of two relays are wired as a "tree" to select one of four preset acceleration potentiometers instead of R1 and R2 of Figure 2.

Similarly, two other relays cause selection of preset deceleration potentiometers instead of R3, R4, R5 of Figure 2. The contacts of a fifth relay are connected to an existing relay which has a set of N.O. contacts wired to the RESET push button S6 of Figure 2, another set wired in series with the paper drive power of the pen recorder, and a third set wired in series with the ramp voltage to the recorder variable speed control unit (Crown VSD-5A). A sixth relay opens the line to the subject's earphones during high-speed tape search periods.

A very desirable feature of this version is the use of the computer as a frequency counter. The computer is programed to detect and measure the frequencies of the sine wave (recorded on the second tape channel) during transitions from rising to falling or from falling to rising, and to store these values. At the end of an experimental run, the typewriter prints out the value of each peak and valley in terms of speed factors (that is, 2.00 represents twice the normal rate) and also gives the average of all peaks and valleys taken together. This average speed factor, when multiplied by words per minute on the tape (at normal speed), yields the threshold value. This frequency printout eliminates the need for laborious hand measurement of peaks and valleys on the chart; the pen recorder is used mainly as a graphic aid to the experimenter.

CONCLUSIONS

Several applications of the method may be suggested: determination of individual differences in speech perception rate; evaluation of the quality of speech from devices which compress and produce speech, such as speech compressors and speech synthesizers; and perhaps the evaluation of recorded spoken materials, considering aspects such as difficulty of the materials and their syntactic and semantic variables. The method's possible use for evaluation of central speech processing disorders has also been suggested (deHaan, 1977). The instrumentation can also be used without the automatic acceleration-deceleration function (integral to the method) in investigations requiring the listener to control the rate of speech by means of a multiturn control knob.

Future research should be directed toward the variables to which the method may be sensitive. These variables include the effect of instructions and cognitive set on performance, the effect of variation of the various parameters of the method, and the relationship of individual differences to other psychological variables. The relationship of the threshold to single-word intelligibility measures and to the Békésy speech-loudness thresholds discussed earlier might also warrant further investigation.

Both the method and instrumentation have possibilities for a variety of applications by other investigators. In fact, the method may make its greatest contribution in basic investigations of the temporal limit of information processing, especially in the comparison of language processing by auditory and visual modalities.

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