NONLINEARITY IN THE RATE OF SPEECH PRODUCTION

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It is the mark of an Instructed mind to not be satisfied,,
with that degree of precision
which the nature of subject admits;
and not to seek exactness,
where only an appraximation of truth is possible.

\- *Aristatle*

Certificate

This is to certify that the dissertation entitled **"NONLINEARITY IN THE RATE OF SPEECH PRODUCTION"** ***is the*** *bonafide work in part fulfilment for the degree of Master of Science (Speech and Hearing) of the student with Register No. M.9716.*

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This is to certify that the dissertation entitled **"NONLINEARITY IN THE RATE OF SPEECH PRODUCTION"** *has been prepared under my supervision and guidance.*

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Declaration

This dissertation entitled **"NONLINEARITY IN THE RATE OF SPEECH PRODUCTION"** *is the result of my own study under the guidance of Dr. N.R Nataraja, Professor and Head, Department of Speech Sciences, All India Institute of Speech and Hearing, Mysore and has not been submitted earlier at any University for any other diploma or degree.*

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TABLE OF CONTENTS

	Page No.
INTRODUCTION	1
REVIEW OF LITERATURE	7
METHODOLOGY	41
RESULTS AND DISCUSSION	49
SUMMARY AND CONCLUSION	65
REFERENCES	71

LIST OF FIGURES

Page No.

Figure A : Representation of the schema of a simple neural network. 38

Figure B : Waveform display and cursor placements for the analysis of durational measures in the speech production sample of normal subject using the DSP sonagraph. 47

Figure C : Waveform display and cursor placements for the analysis of durational measure in the speech production sample of dysfluent speaker using the DSP sonagraph. 48

Figure 1 : Accumulated time series plot for the rate of speech production in normal subject 1. 55

Figure 2 : Accumulated time series plot for the rate of speech production in normal subject 2. 56

Figure 3 : Accumulated time series plot for the rate of speech production in dysfluent subject 3. 57

LIST OF TABLES

Page No.

Table 1a : Represents the maximum, minimum, range and mean values of the durational variability in every fifth set of speech production for normal subject 1. 52

Table 1b : Represents the maximum, minimum, range and mean values of the durational variability in all twenty sets of speech production for normal subject 2. 53

Table 1c : Represents the maximum, minimum, range and mean values of the durational variability in all twenty sets of speech production for dysfluent subject 3. 54

I . INTRODUCTION

Speech is a complex motor act brought about by sophisticated and fine movements of the components of vocal tract and their complex interaction with vocal cord vibration. The speech results by the fine organisation, coordination and modulation between the respiratory, phonatory, articulatory and resonatory systems. All biological systems, including speech are complex and nonlinear in their response - greater stimulus does not simply increase the magnitude of the response, but may bring about a qualitative change in its nature. Nonlinear dynamics includes the study of these systems that respond disproportionately to stimuli.

Under some circumstances, deterministic nonlinear systems behave erratically, a state called CHAOS. Any system is potentially chaotic if :

a) It is deterministic and nonlinear

b) It shows sudden qualitative changes in its output. That is it demonstrates "bifurcations" (the system may exhibit at certain parameter values, non periodic behaviour that appears as intermittent bursts or irregularity, or the output may be exquisitely dependent on initial condition and tiny parameter changes.

c) Its repesentation in phase space shows fractal properties (Titze, 1993).

Principles of nonlinear dynamics are being increasingly applied to the study of human physiology, including, cardiovascular, pulmonary, nervous and vocal systems. Regular behaviour of the different physiological systems sometimes accompany ageing and disease while irregular and unpredictable behaviour is an important feature of health (Goldberger et al, 1990, 1992).

The results of research on aspects of the nonlinear, dynamical systems aspects of speech production and perception, lead to a conclusion that nonlinear, dynamical system's behaviour and principles are represented in speech production and perception at several levels of system behaviour. Examples are provided from studies of phonation, speech respiration, vocal tract acoustics, speech gestures and auditory - phonetic perception. In the case of human vocal system, nonlinearity is encountered in the vocal fold vibrations themselves, in the aerodynamics of the flow through the vocal fold opening and the interaction between these two quantities (Fletcher, 1996). The nonlinearity of the system is responsible for the richness of vocal sounds, and it is also responsible for the fact that these sounds generally have regularly repeating waveforms and thus harmonic spectra. The nonlinearity locks the behaviour of the system into one of a number of regimes of autonomous oscillations which can then be controlled as stable entities. At the same time, the nonlinearity allows the possibility of more complex and even chaotic behaviour, and it is generally the objective of neural control system to avoid these (Fletcher, 1992)

The results suggest, that communicative distinctions in speech are presented in task relevant, "order parameters", which are preserved over a wide range of sets of task irrelevant, "control parameters". The control parameters, in turn, define the domains of behaviour of each of the relevant acoustic, biological or psychological systems. More specifically, it is proposed that speech parameters may be understood in terms of collective variables defined in production, over the degrees of and opening/closing rates of, the vocal tract and in perception, over the rates, amounts and relative phases of the broad band temporal modulation in speech signals (Porter and Hogue, 1998).

Traditionally, the speech processes like speech articulation, prosody and voice have been examined through linear methods, that utilize descriptive statistics as well as parametric and nonparametric statistics. In voice, the unsteadiness in acoustic parameter eg., perturbation in fundamental frequency and amplitude provide an objective and quantitative measurement for assessment of variability. But it remains clear that the voice or speech contain many nonlinearities that are ignored in linear measures. Chaotic features of speech and possibly, variations in these chaotic features, may provide some information whether the system is healthy or not. Although linear methods do report intra-subject variability, they do not permit one to inspect the individual instances during which these variations occur, nor they reveal how they change over time. In contrast, nonlinear methods emphasize visualisation of these variability in the form of time series or phase plot representations. This qualitative information may be used towards the development of clinical procedures of characterising "regularities" and "irregularities" during normal and abnormal speech performances.

A number of studies have been carried out to detect the presence of nonlinearity in the vocal tract by fractal analysis, through examination of pitch periods and vocal fold synchronization. (Baken, 1990 ; Herzel et al. 1993). Herzel et al (1993) applied methods of nonlinear dynamics to the analysis of vocal disorders. Their results revealed different configurations of the acoustic measures for the dysphonias representing different etiologies. Thus it would be feasible to observe subtle qualitative changes in performance profiles which are not revealed by traditional linear measures. Thus far, only one study has reported the use of nonlinear methods to decide variability in rate of speech production. Hadden et al. (1997) examined intra-subject variability during repetitive production of a stimulus word in four speaking conditions. These included a spontaneous and three "driven" or altered speaking rates. The spontaneous condition served as a reference for observing the natural speaking rate, and three driven conditions served to alter the natural speaking rate. Phase plots and accumulated time series plots were utilised to display intra-subject variability.

Need for the study

There appears to be a paucity of applications that have involved nonlinear methods for examining aspects of speech articulation and prosody. Mostly, linear methods have been utilized to examine these speech processes which involved comparison of durational aspects of articulation and prosody between samples with normal and abnormal speech. Although linear methods do report intra- subject variability, they do not permit inspection of individual instances during which these variations occur, or how they change over time. Thus, it would be feasible to observe subtle qualitative changes in performance profiles using nonlinear methods which are not revealed by traditional linear measures.

Aim of the study

1. To establish method or procedure to visualize durational variability in the speech production, using non linear methods.
2. To obtain preliminary information regarding intra - subject variability in speaking rate over a period of time through use of non linear methods, in normal subjects.
3. To compare the durational variability in speech production,between normal and dysfluent speakers, using nonlinear methods.

HYPOTHESIS

1. There is no non linearity in the rate of speech production in normal subjects.
2. The non linearity in the durational variability cannot be visualised "qualitatively" using non linear methods.
3. There is no difference in the pattern of durational variability in the speech production of normal and dysfluent speakers.

Implication of the study

1. The study would introduce an option for visualizing variations in normal speech production and usage of this information toward the development of clinical procedures for characterizing "regularities and irregularities" during normal and abnormal speech performances.
2. Non linear techniques may reveal aspects of variability in speech motor performance not revealed by traditional measures. This may be valuable clinically in the diagnosis of both fluency disorders such as stuttering and neuromotor speech disorders such as verbal apraxia and dysarthria.
3. With nonlinear methods, it would be feasible to observe subtle qualitative changes in performance profiles and therefore faclitate differential diagnosis and charting of performance profiles among each of these speech disorders.

Limitation of the study

1. There is a need for gathering large numbers of data points for the identification of attractors and shifts in variability. This may be an impeding factor while testing clinical population.
2. The study has not considered the intra- subject variability across different speaking conditions.
3. The number of subjects for the study were limited to two normal and two dysfluent speakers.
4. The number of subjects were not uniformly distributed in terms of age and sex.

II. REVIEW OF LITERATURE

Speech is the audible manifestation of language. It is a complex motor act brought about by sophisticated and fine movements of the components of vocal tract and their complex interaction with vocal cord vibration. The speech results by the fine organization, coordination and modulation between the respiratory, phonatory, articulatory and resonatory systems. The faculty of language which forms the basis of communication by speech is known to be specific to humans. This biological innovation is superimposed on the primitive system of vocal communication of same kind as is used by various other species. Natural speech signals inevitably carry some paralinguistic and extralinguistic information in addition to their linguistic content. The acoustic properties of speech depends on physical properties of speaker's speech organ such as vocal fold mass and vocal tract length. The acoustic reflections of these variables, which are informative about age and sex of the speaker cannot be removed from the speech signal. It is not possible to produce speech without any personal quality. (Traunmuller, 1994)

When talking, a speaker produces a vocalization with acoustic properties which are primarily determined by physical shape of his vocal tract. In addition, they are influenced by such factors as emotions, attitudes or choice of vocal effort. Most of the conventional gestures of the speech code do not have an acoustic realization of their own, but they are realized by merely modifying the acoustic properties of a vocalization. This is how the prosodic features of speech are realized and how vowels, stops, nasals and laterals acquire their acoustic substance.

The extent to which speakers can modify their vocalizations is restrained in such a way that it is not possible for them to produce a spectral copy of the speech of any other speaker, eg., an attempt of an adult male to imitate the speech of a kindergarten child or viceversa. As a consequence of the large difference in vocal fold size and vocal tract length, there is very little overlap in the frequency ranges of fundamental frequency (Fo) and the formants between these two speaker categories. In addition to the effects of biological constraints on the frequency ranges of Fo and the the formants, they also set the upper limit to the speed with which the articulatory gestures can be executed. This affects speech rate and articulation. (Traunmuller, 1994) This can to some extent, be counteracted by an increase in articulatory effort and restructered neuromotor commands. (Lindblom, 1983)

Traditionally, the speech processes like speech articulation, prosody and voice have been examined through linear methods that utilize descriptive statistics as well as parametric and nonparametric statistics. Linear methods permit analysis of similarities and differences between sets of data. Often, these analyses involve comparisons of durational aspects of articulation and prosody between samples with normal and abnormal speech. (Hadden et a!, 1997). In voice, the unsteadiness in acoustic parameters eg., perturbation in fundamental frequency and amplitude provide an objective and quantitative measurement for assessment of vocal fold pathologies.

Pitch perturbation or jitter is defined as cycle-to-cycle variation in fundamental frequency and amplitude perturbation or shimmer is defined as cycle-to-cycle variation in amplitude.

These, usually small perturbation in frequency and spectral contents from period to period are important for the judgement of character of voice and as an indication of pathological changes in the larynx. If the degree of perturbation is high enough to be perceived as separate feature, the voice is usually described as hoarse, harsh or rough. Jitter and shimmer measurements, made by comparing the durations and amplitudes of neighboring periods have been used by many investigations to study this phenomenon. Studies have indicated that pitch and amplitude perturbations have been affected by variables such as age, sex, vowels intensity and frequency. (Linville, 1988; Orlikoff & Baken 1990). In some cases, perceived hoarseness is highly correlated with jitter and shimmer measurements (Askenfelt and Hammarberg, 1986) but it was easy to find voices where this correlation was very low or even negative. (Gauffin et al 1996). This indicates that methods, using period-to-period variability as a way to rate perceptual voice qualities may fail (Gauffin et al, 1996).

Thus, clinicians and voice researchers have been dissatisfied with acoustic analysis. It is clear that acoustic signal carries an enormous amount of information, but a well trained ear still detects a great deal more than it has been able to measure routinely (Sataloff, 1996). Sataloff (1996), believed that this is the function of the equipment and strategies used to measure acoustic features of voice. Although, enhancing the sophistication of analysis, using the current methodologies probably would not solve the whole problem, but it would certainly help. It appears clear that voice contains many nonlinearities that are ignored in linear measures. Chaotic features of voice and possibly variations in chaotic features of voice may provide some information that has eluded us so far (Sataloff, 1996).

Morever, all biological systems including speech, are complex and nonlinear in their response - greater stimulus does not simply increase the magnitude of the response but may bring about a qualitative change in its nature. The combination of nonlinear dynamics and fractal geometry has considerable potential for explaining many biological phenomena, a number of which are of particular importance in physiology or medicine. It has been found for example, that strange attractors are associated with Electroencephalographic activity and that their change, and their associated dimension are altered in response to alteration of consciousness level, cognitive activity of the brain or the presentation of stimuli (Rapp et al, 1990, Samar and Rosenberg, 1990, Freeman, 1990) Principles of nonlinear dynamics have been applied to the study of the cardiovascular, pulmonary and nervous systems. Goldberger and his collaborators (Goldberger, 1990a; Goldberger and West, 1990 ;Nelson, West and Goldberger, 1990; Goldberger and West 1992) proposed that the heart and other physiological systems may behave most erratically when they are young and healthy. Increasingly regular behaviour of the different physiological systems sometimes accompanies aging and disease, while irregular and unpredictable behaviour is an important feature of health. This notion has led physiologists to examine periodic behaviour in physiological systems as a potential indicator for developing sickness or decaying health (Hadden et al, 1997). Chaos theory has been described relative to senescence. Such applications have involved observations of dendrite loss and reduced neural branching, decrease in heart rate variability, decreased in electroenceophalographic evoked potentials. (Goldberger, Rigney and West, 1990 ; Smith and Denny 1990 ; Lipsitz and Goldberger, 1992).

Similarly, human speech is a combination of phase-locked, harmonic voiced vowel sounds and near chaotic unvoiced stops and consonants, produced in rapid time-sequence. The same is true of the sounds produced by many other animals, although there are cases in which the vocal sound is both voiced and chaotic at the same time. The complexity of this behaviour presents a rich field for study.

NONLINEARITY AND CHAOS

Π αυα ρει (Everything flows). This is the word of Herakleitos, an ancient Greek scientist (Kirk, Raven & Shofield, 1983). In nature, nothing is strictly stable nor periodic. Any phenomenon exhibits motion and its fluctuation. To scale the extent of fluctuation, the notion of chaos is useful both in principle and in practice.

According to Batterman (1993), chaos is a feature that reflects the dynamics of a system whose future behaviour is unpredictable or random.

Chaos lies between regular and random. "Regular" state means there is no fluctuation, whereas the random state means there is no rule, but there is only probability.

Choas theory postulates that a system which displays periodicity can be driven to a point at which apparent randomness can be observed. Other systems exhibit chaotic behaviour without imposition to any of their parameters. The latter systems are known as "chaotic or nonlinear dynamic systems" (Batterman, 1993). The apparent randomness may, according to chaos theory still reflect patterns of activity that are disguised because of their complexity (Hadden et al., 1997). Chaos is also defined as a condition of a system with a trajectory manifesting a random like behaviour although the system is deterministic. The term "deterministic" means that the output of the system is completely described by a rule that can be expressed by a notation such as a mathematical function (Kakita and Okamoto, 1996). Another significant characteristic of chaos is that chaos is very sensitive to the initial condition. That means that, once one knows the initial state of an attractors, the future behaviour of the system will be completely predictable. However, if a different initial state is chosen, even if it is very close to the "original" initial state, the future behaviour can be entirely different (Kakita and Okamoto, 1996).

In the study of chaotic systems, numeric values assigned to its examined variables are plotted as coordinates in an imaginary space called "phase space". Phase space, therefore establishes a dimension for each of the examined variables. During nonlinear analysis, point at which the variables interact is not fixed across time, the point moves about dynamically in phase space. As points move around in phase space, some will travel repeatedly to particular regions. These regions have structured geometric forms, and because they attract points are called "attractors" (Hadden et al 1997).

Attractors embody the behaviours of a system qualitatively. If a system exhibits simple change, its attractors is a simple geometric form. In a chaotic system the movement of a given point may appear to be random and this may result in generating "strange attractors" (chaotic attractors are also called strange attractors because of the unpredictable nature of the output). Strange attractors are represented as multidimensional patterns that arise from an infinitely long line in a finite space. The geometric form that emerges is called a "fractal". A characteristic property of a fractal involves an infinitely long line that never intersects itself. Computer graphics have made it feasible to paint a picture of chaotic behaviour through fractals. These irregular patterns simulate shapes that occur in nature and are used in studying chaotic systems across disciplines (Stewart, 1992). Phase space representation technique tracks the values of independent variables that change with time. The number and type of independent variable depends on the system. For many complex systems, all the independent variables cannot be readily identified or measured. For such systems phase space representations can be plotted using the method of delay maps. For the simplest delay map, each point of graph corresponds to the value of some variable at a given time plotted against the value of that same variable after a fixed time delay. A series of these points at successive times outline a curve, or trajectory that describes the system's evolution. (Goldberger et al, 1990).

The term "fractal dimension" is used to represent the degree of the structure's irregularity (irregularity is different from variation). This notion is applied to the attractors generating the fluctuation. The value of the fractal dimension is generally a non integral number. Eg. "Lorenz attractor" which is a chaotic attractor having the dimension of 2.1 (Kakita and Okamoto, 1996).

Tools of analysis of non linear dynamics may allow one to summarise many of the dynamic properties of a system that are comprehensible at a glance.

The "logistic equation" [$x_n = r\ (x_{n-1})\ (1-x_{n-1})$] represents a purely deterministic system that has unpredictable outputs. But even the erratic outputs are clearly not random. So the system is said to be chaotic. Any system is potentially chaotic if :

a) It is deterministic and non linear

b) It shows sudden qualitative changes in its output, that it demonstrates bifurcations (the system may exhibit, at certain parameter values, nonperiodic behaviour that appears as intermittent bursts of irregularity or transients or the output may be exquisitely dependent on initial condition and tiny parameters changes. Eg, Infinitesimal differences in 'r' of the logistic equation may result in enormous differences in regularity of the output.

c) Its representation in phase space shows fractal properties.

There are a number of ways to estimate the fractal dimension of natural structures (Barnsley 1988 ; Farmer, Ott and Yorke, 1983 ; Froehling et al, 1981 ; Farmer, 1982 ; Grassberger, 1986). What that dimension represents is the degree of the subjects irregularity. Irregularity is different from variability. Eg the completely regular function F(x) = sin x has a very distinct variability, which could be expressed as the standard deviation of F(x). But a plot of the points F (x) is not at all self similar and on measurement its dimension would be 1 indicating that is really is a line (Titze et al, 1993).

Nonlinear Dynamical Systems in Speech Production

Listeners report, they hear speech as an ordered sequence of segments which linguists call phones, syllables and morphemes. Speakers in a complementary way, perceive their own behaviours as the production of these segments. The lack of correspondence between physical and psychological segments particularly at the level of phones is the fundamental problem in speech research (Porter and Hogue, 1998). The same intended or perceived phone can be associated with manifestly different acoustic segments, whereas the same acoustic segment can be associated with different phones. (Delattre, Liberman and Cooper, 1955, Fant, 1960). Attempts to untangle this lack of correspondence problem dates very old. A new approach based on nonlinear dynamical systems (NDS), may provide a basis for understanding how speakers and listener's nervous systems naturally specify the correspondence between sound and phone. It must involve nonlinear processes which relate psychological segments to their manifold manifestations in speech gestures and acoustics. Nonlinear processes abound in speech, from those involved in the coupled oscillatory modes of the vocal folds, to the acoustic filtering of the vocal tract, and to the travelling waves in the cochlea. Speech researchers have recently broadened the application of NDS, however to include systems that are neither directly accessible nor easily understood in physical terms, viz., the biophysical and biopsychological systems involved in articulation and perception.

Adopting a nonlinear, dynamic systems approach to speech, conflicts with some fundamental assumptions and models of the classical approaches in speech research. These assumptions include top-down/bottom-up notions of perception and the servo-system concepts of motor control. Those classic approaches take a basically linear, information processing approach, and accommodate nonlinearities with the introduction of executive functions, arbitrary mappings, and/or probabilistic and stochastic processes. However, even though these approaches have had some success in, for example, computer speech recognition and text-to-speech conversion, they do not enjoy application in understanding many aspects of natural, human perception and production, particularly the understanding of pathology (Tuller & Kelso, 1993). This observation points mainaly that the application of NDS theory to speech involves a significant change in the conceptual paradigms and assumptions traditionally brought to speech research.

It is assumed that the biobehavioural acts of speech communication involve nonlinear, dynamic, self-organizing systems (Nicolis & Prigogine 1989). In discussing such systems, terminology of "synergetic systems", for speech and nonspeech motor behavior is used. It is assumed that both the perception and production of speech involve synergetic systems which intrinsically reduce a large number of degrees of freedom to a relatively few "order parameters" (Haken, 1983; Kelso, 1995). Order parameters specify the task-relevant states of a system, remaining invariant over a wide range of values of system "control parameters", and changing when the system state changes. Control parameters (which may be order parameters for other levels of description), are system variables which are found to vary more slowly than order parameters, to move the system into and out of its states. In the case of speech, order parameters are presumed to represent speech-message-specific aspects of production and perception, whereas control parameters represent communicatively non-specific aspects. It is further assumed that listeners ordinarily hear what their interlocutors intend and that these shared intents are represented in terms of order parameters defined over large collection cf "control parameters". By "speaker's intents" one refers to those psychologically specified segments which, when combined in different ways, convey meanings.

These assumptions are complementary to those of a "direct perception/ action" point of view as originally proposed by Gibson (1966, 1979) and subsequently argued by others (e.g., Kugler & Turvey, 1987; Porter, 1986, 1987; Turvey, 1977). That view emphasizes how biological systems naturally self-organize in order to allow organism to sense and respond in adaptive ways. Adopting a synergetic-systems approach is, thus, based in general biology; in particular, it is presumed that the human communication system evolved to exploit the self-organizing characteristics of the motor systems of the mouth, throat, and auditory system in such a way as to make phonetic correspondence between speaker and listener both natural and direct. Such a direct view is the logical consequence of a conclusion that speech perception and production are self-organized, nonlinear, dynamical systems.

PHONATORY SYSTEM DYNAMICS

Phonation is the process of generating sound via the vocal folds (glottis), either through oscillation of the folds or through partial closure of the folds to produce a turbulent flow, as in whispering. Similar sound-generating systems exist in organisms other than humans and are often used for communication. Thus it is possible to study some aspects of phonation using nonhuman species; it would appear that sound communication using the larynx and associated structures has a deep/ evolutionary basis.

Phonation can be modeled as a triangular or trapezoidal acoustic waveform (rich in harmonics) plus a degree of waveform asymmetry and/or stochastic "jitter" which provide a more "natural sounding" voice. This method is often used in speech synthesis. Only two or three parameters (frequency, amplitude, jitter) may be necessary to reasonably approximate biological output. These parameters do not convey much of the biological mechanism itself, however, abnormal phonation can be simulated using the parameters but without obvious benefit in understanding pathology (Ishizaka & Isshiki. 1976).

A greater degree of verisimilitude can be obtained using complex-system models of the biophysical structure of the folds themselves. In the most sophisticated of these models, vocal folds are approximated by finite elements simulations of the vocal fold tissue and include representations of mucosa, ligaments, and muscle. These models provide a large number of parameters which can be adjusted to produce model behavior nearly identical to that observed in biological preparations. The sophisticated models of the glottis, as useful as they are for understanding component's contributions are not particularly helpful in understanding the overall behavioral domain of fold activity. That is, these models are "over specified" in the sense that a great many different configurations of parameters and components may be expected to produce nearly the same behavior. This is the same problem which confounds the biologist when attempting to relate small details of a system to its broader function. It is in addressing this problem that NDS theory can be of particular help.

Clearly, the complexities of phonation, including a range of normal and abnormal modes, suggest a nonlinear, dynamic system which might be understood in terms of a relatively few order parameters. Confirmation of this expectation was provided in a series of investigations of Titze (1992 and his colleagues (e.g., Titze, Baken, & Herzel 1992). Phonatory output from both real speakers and models were subjected to conventional spectra and pitch extraction methods, and analyzed for autocorrelation, fractal dimension and Lyapunov exponents. The analyses suggested a system dimension of about 4.0 which indicates that four parameters could be used to describe the behavior of the system. Titze et al, (1992) report this result to be consistent with empirical exraction of a similar number of orthogonal components for long periods of phonation. The results also clearly reveal evidence of frequency jumps (period doubling), two frequency or amplitude modulated (AM) modes (toroidal attractor structure) and bursts of instability (intermitency and choas) (Herzel & Knudsen, 1995). Important transitions between these modes could be characterized by utilizing a two degree of freedom model, one parameter representing pressure and the other representing stiffness or elasticity. This simplified model displayed critical behavior transitions of self-sustained oscillations via a Hopf bifurcation and a period-doubling path to chaos. Additional NDS features included hysteresis and fluctuation sensitivity (Herzel, 1993). Combined, the results suggest the domain of vocal fold behaviour may potentially be captured in terms of a few parameters such as pressure and elasticity, together with factors related to vocal fold asymmetry (most dramatically present in some paralytic dysphonias) and vocal tract coupling (Herzel, 1993). It thus appears, from an NDS perspective, that vocal fold oscillation is an emergent behavior, characterized by the order parameters of pressure, elasticity and few others. An important NDS aspect illustrated in the phonation studies in the order parameter of oscillation rate emerges as a result of process intrinsic to the nonlinear, dynamic glottal system. That is, the oscillation rate is not extrinsically specified.

There are numerous attempts to relate perceptual categories such as "roughness of voice" to perturbation measures from acoustic analysis (Hirano et al, 1986 ; Kreiman Gerrat and Precoda, 1990). However, results were less than successful. A few investigators found a strong correlation between roughness scores and correlated fluctuations of periods and amplitudes (Hillenbrand, 1988). These findings suggest that widely used jitter and shimmer calculations that measure only the amount of perturbations (but not its correlations) are not sufficient to quantify roughness. The theory of coupled nonlinear oscillators predicts that the following phenomena should appear at the borderline of parameter region corresponding to normal phonation. Subharmonic vocalization (appearance of spectral peaks at Fo/2, Fo/3 and its multiples), beating like low frequency modulations, and low-dimensional chaos with a continuum of spectral components. Acoustic signals from voice patients indeed show often sudden jumps to subharmonic regimes (period doubling or tripling) and low frequency modulations (tori) (Titze et al, 1993 ; Herzel et al, 1994).

Thus, the connection of nonlinear phenomena to results of the psychoacoustic and perturbation analysis become obvious. Subharmonics and modulations induce correlated fluctuations of pitch and amplitudes that were found to correlate to roughness scores. Subharmonics plus modulation frequencies often occur in the frequency range below 70 Hz which gives the impression of roughness according to psychoacoustic theory (Herzel, 1996).

In the case of the human vocal system, nonlinearity is encountered in the vocal cord vibrations themselves, in the aerodynamics of the flow through the vocal fold opening and in the interaction between these two quantities. (Fletcher, 1996). This highly nonlinear part of the vocal system is coupled to passive and very nearly linear multimode vocal tract resonators both downstream and upstream from the glottis, and these interact with the motion and flow mechanics of vocal folds. (Fletcher, 1996). Titze et al (1993) have speculated on the possible contributions of irregularity in vocal fold vibration.

1) Unsteadiness in muscle contractions in the laryngeal and respiratory system. In particular the incomplete summation of muscle twitches in an attempt to form a "smooth tetanus" brings about a fundamental frequency jitter (Baer, 1981b ; Titze, 1991).
2) Turbulence in the glottal airstream.
3) Vortex shedding and instability in the jet emerging from the glottis. The jet may flip flop from side to side, even if turbulence does not exist.

4) Asymmetry in the mechanical or geometrical properties of the two vocal folds. Usually a dominant oscillation mode exists due to synchronization of two similar oscillators by the airflow, but excessive asymmetry may cause desynchronization.
5) Nonlinearity in the mechanical properties of vocalfold tissue (the constitutive equation) and the pressure-flow relations. Non-linearities complicate the mode structure of the vibrating system.
6) Coupling between the vocal folds and the vocal tract. Acoustic pressures in the subglottal and supraglottal region may play a part in driving the vocal folds. If these pressures change dynamically, oscillation may be perturbed.
7) Mucous riding on the surface of vocal fold tissue. The mucous could reorient itself from cycle to cycle, causing disturbances in the vibration pattern.

Several of these sources of irregularity can exist in combination with others. Some of them, like mucous and air turbulence may result in high dimensionality chaos; others, like left right asymmetry may lead to low dimensionality chaos.

Thus, the vocal folds with glottal airflow, constitute a nonlinear oscillating system. This system is amenable to nonlinear dynamics analysis, which can provide an entirely different perspective on the underlying basis of phonatory function.

Isshiki and Ishizaka (1976), in an early modeling study showed that asymmetry of vocal fold vibration yielded subharmonic structure. Herzel and coworkers (Herzel et al 1991; Mende, Herzel and Wermke, 1990), had undertaken preliminary examination of the cries of newborn infants and had found numerous bifurcations in the sound pressure signal, including period doubling and sudden transitions to aperiodicity. Their analysis of these phenomena strongly suggested the presence of low dimensional choas and they established the consistency of these phenomena with two mass models of the vocal folds. A more intensive modeling experience of Awrajcewicz (1990) examined the trajectory of the vocal folds and supported the findings of Herzel et al (1991). It would appear, then, that the vocal folds are in principle, capable of chaotic behaviour.

Baken (1990) had undertaken a preliminary examination of the fractal dimension (D_F) of normal vocal fundamental frequency (F_o) and amplitude using a box counting algorithm for estimation of D_F He found that a data record of sequential period values had a D_F of 1.46 which was unaffected by speaker sex or by mean vocal F_o. D_F was at least weakly correlated to measures of vocal variability such as relative average perturbation or shimmer. This study demonstrated that fractal geometry can be useful for measuring irregularity of vocal fold oscillation independent of oscillatory variability which are denoted by jitter and shimmer. Baken (1990) in an exploratory and informal examination of vocal F_o and amplitude in cases of several different types of vocal disorders, demonstrated that the fractal dimension is often different from normal, but the differences do not seem related to traditional categories of laryngeal disorders.

Herzel et al (1993) applied methods of nonlinear dynamics to the analysis of vocal disorders. Their results revealed different configurations of the acoustic measures for the dysphonias representing different etiologies. Such differences were discussed as support for chaotic findings in the following parameters; desynchronised motion of the left and right vocal folds, interaction of true and false folds, and interaction of vocal fold vibrations with sub and supraglottal resource.

RESPIRATORY SYSTEM DYNAMICS

Respiration is a nonlinear dynamic system of considerable complexity. The magnitude and rate of inspiration-expiration cycles vary with physiological levels of blood oxygen and CO_2 as well as other factors such as airway resistance (Grassino & Goldman, 1986). Variation in magnitude and/or rate of inspiration/expiration involve coordinated activity of dozens of chest and abdominal muscles and can be accompanied by variation in muscles in the bronchi and supraglottal airways which change airway resistance. The dynamic, self-organized nature of ordinary respiration has been demonstrated in a number of studies (e.g., Sammon & Bruce, 1991). Fewer studies have examined the dynamical systems aspects of respiration during speech, although many studies have described its variation among different types of speaking tasks (e.g., Davis, Bartlett, & Luschei, 1992; Hixon, 1987 ; Stathopolous et al., 1991).

In speech tasks, a critical value of transglottal pressure is required before the vocal folds display self-sustained oscillation. Generation of other vocal tract noise sources (such as for fricatives like/s/) also involves critical pressure values. These pressures originate in the respiratory system. The critical pressures are maintained throughout utterances in spite of continuous variations in airway resistance and air flow due to the movements of the articulators. Respiratory flow patterns also vary systematically during speech. The nearly regular and equal-length inspiration/expiration flows of quiet breathing are replaced by cycles consisting of quick, high flow inspirations followed by low flow expirations of varying lengths. The timing of inspirations varies with the intensity of speech, the type of phonetic segment, and whether speech is voiced or whispered (Stathopolous et al., 1991), presumably because of changes in vocal tract resistance and related factors. Since the system also meets blood gas exchange needs during speech,the speaking-breathing system displays truly remarkable, self organized flexibility across many variables.

VOCAL TRACT DYNAM ICS

The Dynamics of Cavities

Speech primarily involves movement of the lips, jaw, tongue, and velum. The movements of these articulators vary in size of vocal tract cavities and can also impede air flow by producing either complete or partial constrictions. The articulators are biophyscially (and non linearly) coupled to some extent and are, consequently, mutually constrained to some (as yet not completely specified) degree. Positioning the tongue tip forward in the tract, for example, produces a complementary positioning of he tongue base away from the pharyngeal wall. The lower lip and tongue vertical position are partly dependent upon jaw position.

The sounds of speech are produced when sound (and air) travels through the cavities produced by these ariticulators. The sound source may be phonation or turbulent noice produced by air moving through a constriction (for example, for /s/). The flow of air and sound is usually towards the lips, with occasional detours through the nasal cavities (if the velum is open). The nasal and oral cavities act as acoustic filters which shape the source spectrum as a function of cavity size. Because of the natural, physical, sequential order of cavities from source to lips, the final spectral shape of the speech output is a nonlinear function of the source spectrum and the spectral characteristics of the acoustically coupled cavities. The same cavity size at one point in the tract might, therefore have a somewhat different effect on the final spectrum depending upon the filtering produced by subsequent and prior cavities.

Thus, speech production is nonlinear both in terms of the articulator's positions and movements (and, hence, the pattern of cavity shapes) and in terms of the acoustic filtering produced by the flow-based sequential dependence of the cavities. In the context of the presumption that such a mutually constrained, nonlinear, biological system would naturally be self-orgainzed. It can be supposed that certain configurations of articulators would dominate in speech and that those patterns would reflect physical and biological optimization.

Stevens (1989), using a simple model of coupled acoustic cavities of the vocal tract, compared the spectral outputs of a wide range of possible patterns of cavities excited by a glottal source. He related spectral peaks (designated F1,F2 & F3) to the relative size of anterior and posterior cavities. Stevens (1989), varied the cavity size in a natural, dependent way (eg as the anterior cavity was increased the posterior was decreased). He found such a continuous variation in cavity size to result in a discontinuous nonlinear change in formats. In some regions, small changes in cavity size produced large changes in formants whereas, in other regions, large changes had relatively small effects. Stevens (1989) referred to the sudden changes as quantal effects to suggest that some configurations represented "stable orbits" between which the spectral patterns jumped. Steven's (1989) results, suggest that some articulator configurations represent more articulo-acoustically stable modes, whereas others represent regions of enhanced sensitivity to perturbations. The stable modes are "optimal configuration " of cavities in terms of physical, acoustic characteristics of the system. Interestingly, spectral shapes associated with the stable regions are also those shapes most commonly seen for vowels of natural language (Lindblom, 1986). The spectral shapes may also be those most perceptually discriminable, suggesting that the articulo-acoustic system is "optimal" in terms of a wide range of acoustic, articulatory, physiological and communicative variables (Carre' Lindblom and MacNeilage, 1995; Mryati, Carre and Guerin, 1988).

THE DYNAMICS OF ARTICULATORS

Speech involves a complex and rapid coordination of many muscles and muscle groups. The biomechanical linkages of articulators may constrain to some degree, the possible configurations and sequences of articulatory gestures (Porter and Hogue, 1998). Motor systems produce behaviours of great variety and complexity. It has long been observed that it is unlikely to be purely the result of biomechanical linkages. It has also been observed, however, that it is unlikely to be the result of external (i.e., central) imposition of temporal patterns on a large collection of independent (peripheral) motor elements (Bernstein, 1967; Lashley, 1951). There are such a large number of motor elements involved in even simple actions, that it is unreasonable to suppose a central "executive" could control all the degrees of freedom at the rate required. In addition, the details of execution of a motor task can be modified very rapidly and accurately to complete tasks in spite of changes in context. The rapidity of the adjustments precludes complex central processing, suggesting instead, considerable autonomous organization of collections of motor elements (Porter and Hogue, 1998).

The organizational structure of collections of motor elements has all the hallmarks of a self organized, nonlinear dynamic system Reorganizations have also been observed in speech, eg., lip closure (as in/ba/) usually involves coordinated upward movements of the lower lip and jaw. If a barrier to jaw upward movements is introduced after the start of the gesture, however the lip closure will be completed using a downward movement of the upper lip, a gesture not ordinarily employed in the task (Folkins and Abbs, 1975). Comparable reorganizations are seen in other speech tasks (eg. Abbs and Gracco, 1984, Kelso et al, 1984). From a synergistic systems perspective, these results suggest that speech communication tasks are specified in terms of order parameters at the level of articulatory gesture coordination. The motor system under intentional constraints appears to capture in its modes of organization the same sort of ordered behaviours as seen in complex systems operating under purely physical constraints (Kugler & Turvey, 1987).

Kelso (1995), using limb coordination task included the manipulation of the absolute rate-of movement control parameter, which takes the system through its various modes of behaviours. On the other hand, it is the phase (relative timing) which serves as an order parameter and captures both the qualitative changes in behavioral pattern and the instabilities seen in nonlinear, dynamic systems. The importance of this observation for motor system in general and speech in particular, is that whereas the temporal demands of the task may be viewed as extrinsic to the system, the actual manifestation of temporal structure in particular relative phase, is an intrinsic consequence of the organization of the system. Thus, the sequence of behaviour components (represented by the order parameter phase) is intrinsic to execution and is not explicitly imposed on the movements.

Stetson (1951), observed that production and perception of certain syllables change suddenly as speaking rate increases. The speakers were asked to repeat syllables such as/ip/at faster and faster rates. He observed that the syllables appeared to change from /ip/ to /pi/ at high rates, inspite of speakers clear intent to produce/ip/. No comparable effect was observed for repetitions of syllables of the /pi/ form. Stetson (1951), argued that the perceived shift in phonetic structure was the result of a constraint on the coordination of vocal tract movements and respiratory activity which allows symmetrical coordination of vowels and consonants at low rates but precluded vowel-to-consonant sequencing at high rates.

Tuller and Kelso (1990,1991) discovered that the shift from vowel consonant to consonant-vowel reflected a phasing constraints on articulation. At low rates, the phase relation of phonation onset for the vowel and lip movement for the consonant is stable as rate increases and remains appropriate for the/ip/syllable. At the critical rate, however, there is an abrupt shift to the phasing appropriate for the/pi/syllable. These results suggest that relative phase in speech, as in other movement tasks may be an order parameters. Relative phasing also displays stability for the phonetic feature VOT i.e., VOT as a relative portion of syllable-duration, remains the same over differences in syllable duration introduced by differences in speech rate (Fowler, 1980; Kelso, Saltzman and Tuller 1986; Port and Dalby 1982).

The constancy of relative phasing is not restricted to particular syllable types nor to VOT. Constancies in absolute and relative durations have been observed in a number of articulation studies (Kent and Moll, 1972 ; Lofqvist and Yoshioka, 1981). In one series of studies, the effect of speaking rate, syllable stress and phonetic segment type were investigated for utterances of the CV1 # CV2 C type (Tuller, Kelso and Harris, 1982). Of particular interest was the relative timing of the consonant and vowel gestures across the boundary (#). Tuller et al (1982) report that the relative time between the vowel and the consonant gestures across the boundary was found to bear a constant relation to the time between vowel gestures. This constancy was maintained inspite of the very large variations in absolute durations of utterances components which accompanied changes in speech rate and syllabic stress. Thus the relative timing constancy observed for simpler syllables such as /pi/ extends to the organization of more complex segments even across boundaries between syllables.

The same syllable, relative timing Constances also appear in languages other than English and which differ from English in their general temporal structure (French and Japanese), suggesting that the same sort of intrinsically timed, nonlinear system is involved (e.g., Port, Cummins, & Gasser 1995; Vatikiotis-Bateson & Kelso, 1993).

On the basis of the results summarized above, it seems reasonable to conclude that one order parameter for speech is relative phase and that this order parameter captures the communication task-relevant aspects of the sequntial order of elements. Relative phase also appears to be a characteristic of articulatory organization which may be revealed by auditory/ perceptual processes. It thus meets the criteria for communication-specific order parameter by capturing patterns of organization in production, in acoustics, and in perception. In this regard relative phase is defined at the task-level, not at the gesture level. Constraints at the gesture level would specify the actual durations of gestural components, the regularities of which would be captured in gesture-level order parameters.

With the exception of a few features like VOT, an order parameter of relative phase does not provide an account of differences in phonetic segment identify, either in terms of general segment type (consonants and vowels) or among segments of particular type (e.g., stop vs. approximate consonants, or labial vs velar stops). Other aspects of vocal tract dynamics must be examined to discover the order parameters related to communicatively relevant segment features and identities.

Consonant and vowel gestures, both, change with speaking rate and syllabic stress. Gestures tend to become shorter in duration and to be some what less stable in absolute positioning in rapid, unstressed speech (Guenther, 1995). Overall, consonants display much less variability than vowels, however. In rapid, unstressed speech segments, for example tongue gestures for vowels can become very much shorter (50% or more) and gestures for the different vowels tend to become more alike in absolute positioning both in the anteroposterior and vertical displacements (the later tending to vary least) (Perkell & Nelson, 1985). Consonant durations, on the other hand, tend to decline by 20% or less and consonants rarely fail to achieve either the appropriate degree or placement of constriction (e.g., van Son & Pols, 1995). Vowels, thus tend to appear as reduction in duration, coupled with smaller inter-vowel positioning differences, whereas consonant gestures tend to appear with more nearly preserved temporal and positional aspects.

The relative constancy of consonantal gesture durations also appears as a regular relation between the amount of displacement required of the articulator and the peak velocity of the articulator movement. That is, at the level of the phonetic segment, consonants involving a particular articulator movement, e.g., tongue tip to alveolar ridge for /d/, end to have nearly constant durations regardless of the vocalic context and hence, the amount of displacement necessary to produce the constriction. In this example, the displacement necessary would be smaller if the vowel which is produced before or after /d/ required the tongue to be in an anterior as constrasted with posterior position. Stated differently, the peak velocity of consonant gestures tends to bear a constant relation to the distance travelled (displacement) such that the slope of the velocity vs. displacement regression line is constant.

Other data reveal that different types of consonants (e.g., stops and approximates) appear to have somewhat different durations and different velocity/displacement slopes (Kuehn & Moll 1976); in addition, velocity/ displacement slopes for all consonants can vary with stress and speaking rate (Kelso et al., 1985; Kuehn & Moll, 1976; Ostry & Munhall, 1985; Vatikiotis-Bateson & Kelso, 1993). This suggests that in addition to equilibrium position, the "stiffness" of the "spring" component of the gestures might be an order parameter at the gesture level for consonants.

Vowels "reduce" in duration, and their tongue positions become more alike when in rapid speech and/or in unstressed syllables. Peak velocities of vowel movements do not, consequently, show the same constant relation to displacement shown by consonants and do not, therefore, appear to have the same gesture-level order parameters.

In a preliminary investigation, Hadden et al (1997) performed a pilot study to examine the rate of repetitive speech production through use of nonlinear methods. Durational measures were obtained from a normal subject who was required to produce a stimulus word (/papa.p/) in four speaking conditions ; normal, controlled normal, accelerated and controlled accelerated. Phase plots and accumulated time series plots were utilised to display intra-subject variability. Attractors were observed in each of the four phase plots and of particular interest was the direction of their shift for different speaking conditions. The accumulated time series plots also revealed patterns of intra-subject variability across time. These two forms of nonlinear representation successfully characterised qualitative changes within, and across, the four speaking conditions. The observed spectral distributions and patterns of variability have implications for differentiating normal from abnormal speaking conditions.

NEURAL CONTROL

When controlling a linear system, one has simply to set the values of controlling parameters, such as muscular tensions and blowing pressures, and then allow sufficient time for the system to settle into equilibrium. This time is controlled by the system Q value and is typically a few tens of cycles of the fundamental oscillation. In the control of a nonlinear system, on the other hand, attention must be paid not just to the final state but also to the trajectory in parameter space by which that state is approached, since the final oscillation regime can be a function of system history.

A deterministicaly chaotic system has two important properties. The first, is that its trajectory in phase goes close to every possible point on the attractor and thus to every possible regime of oscillation, usually within rather few cycles on the basic oscillation. The second, is that the future behavior of the trajectory, and thus the form of the future oscillation, can be influenced to an extremely large extent by a very small change in the parameters of the system. Together, these two facts mean that any desired mode can be stabilized, at least in principle, by repeated application of very small corrections to the system parameters. They also mean that, if one wishes to change the regime of oscillation, then one just needs to let the system run autonomously for a short time until its trajectory brings it close to a point on the orbit one wishes to choose, when a small correction can stabilize this new regime. The control is exercised by a human neural system. Such a neural system behaves as an elaboration of the simple neural networks.

Each element of the system mimics a neuron, in that it has several input connections and a single output, and has only two output states, "on" and "off". Whether a neuron is in the on or the off state is determined by a weighted average of the on or the off signals applied to its inputs, the weighting factors for the input links being important parameters of the network. The elements are arranged in at least three layers and there is a great deal of interconnectivity between them. The neurons of the lowest layer sense the physical state of the system at some instant and each turns on or off depending upon the stimulus it receives. The outputs of this layer feed to the second "hidden" layer and turn its elements on or off depending upon the weightings assigned to the network links. The outputs of the elements of the second layer now pass on to the third layer and similarly determine its pattern of on and off states. There is thus a wave of "neural" activity that passes through the system from its first to its third layer, and the process is repeated many times each second as the state of the system changes.

The third layer is the output layer of the network, and its pattern of on/off states directly controls muscular actuators that influence the state of the system. The elements of the neural network are highly nonlinear in their response - a small change in the input states can flip a neuron from its off state to its on state. The network as a whole is nonlinear in a very more subtle and complex way, and its outputs are not simple functions of its inputs (Fletcher, 1996).

Neural networks "learn" by modifying the weights assigned to their internal synaptic connections so as to reinforce desired outputs and inhibit those that are undesired. In this way, they can maintain a system in a desired state, which may be either constant or else varying in time in a regular manner. The same approach can be applied to system trajectories. The time varying weighting parameters corresponding to the desired trajectory

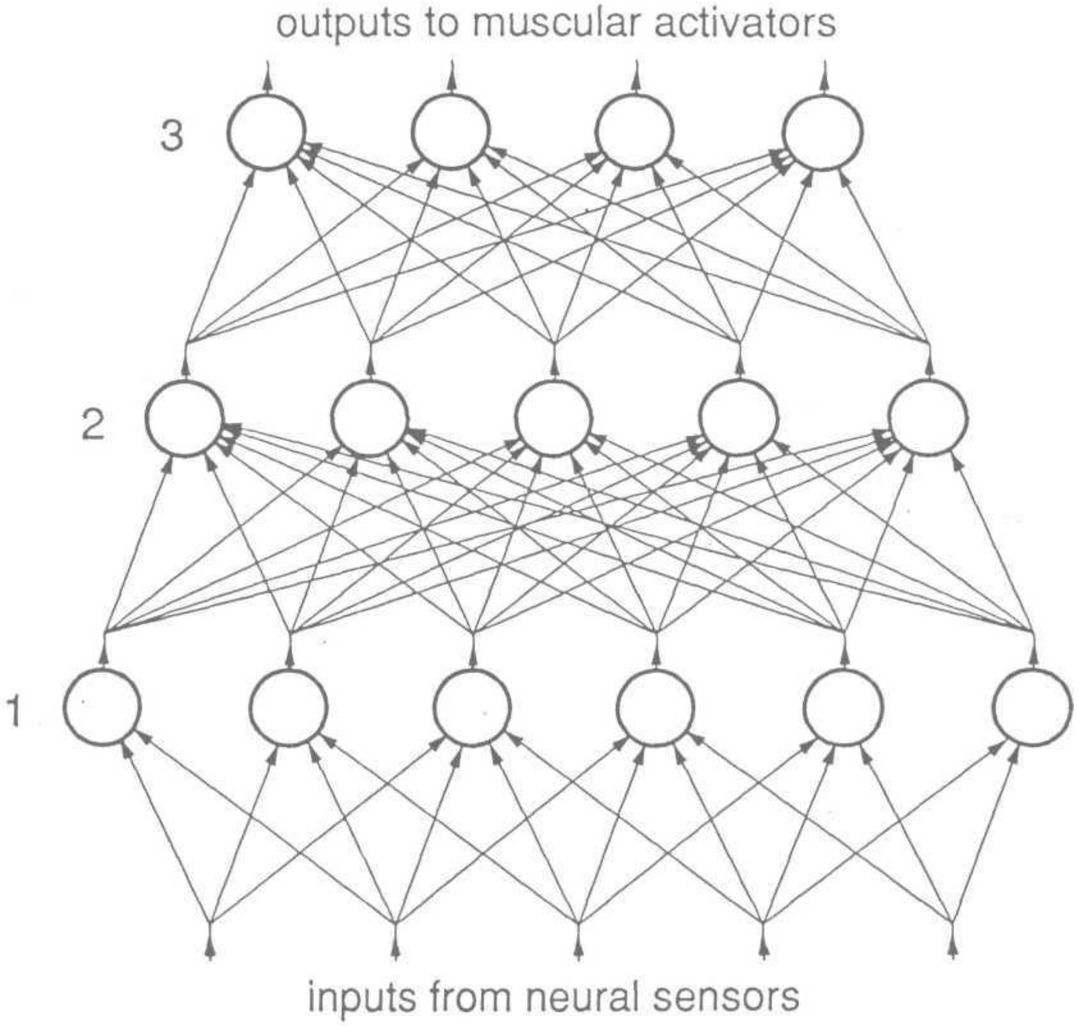


Figure **A** : Representation of the schema of a simple neural network.

are stored somewhere outside the network and then passed to it in sequence. This is quite clearly, closely related to the way in which humans learn complex tasks-first learn to maintain steady states such as vowel sounds and then to combine them to produce desired outputs such as phonemes and then words.

The nonlinearity of the system is responsible for the richness of vocal sounds and it is also responsible for the fact that these sounds generally have regularly repeating waveforms and thus harmonic spectra. The nonlinearity locks the behavior of the system into one of a number of regimes of autonomous oscillation, which can then be controlled as stable entities. At the same time, nonlinearity allows the possibility of more complex and even chaotic behavior, and it is generally the objective of the neural control system to avoid these.

A recognition of the nature of the neural control system, and its simplified modeling as a neural network, displays one the role of both imitative practice and conscious thought in achieving both routine vocal utterances and special vocal effects. Certainly, this approach has been exploited by evolutionary processes in natural childhood development (Fletcher, 1996).

Thus, nonlinear, dynamical system behaviors and principles are represented in speech production and perception at several levels of system behavior. Consequently, non linear methods of analysis would be more suitable to provide "qualitative" information about the speech system. Thus far, there appears to be a paucity of application that have involved nonlinear methods for examining aspects of speech articulation and prosody. Traditionally these two speech processes have been examined through linear methods which involved comparisons of durational aspects of articulation and prosody, between samples with normal and abnormal speech. Although, linear methods do report intra-subject variability in duration, they do not permit one to inspect the individual instances during which these variations occur; nor they reveal how they change over time (Hadden et al., 1997). In contrast, nonlinear methods emphasize visualization of durational variability. Thus, preliminary information regarding intra subject variability in speaking rate through use of nonlinear methods is required. Nonlinear techniques may reveal aspects of variability in speech motor performance not revealed by traditional linear measures. For example application of this informations or methods the study the behaviour of rate of speech in fluency disorders may throw more light on the abnormal aspects, than it is presently known. Therefore the present study is also planned to note the intra-subject variability in the rate of speech production in normals and pattern observed in dysfluent subjects.

III. METHODOLOGY

Aim of the study

1. To establish a method or procedure to visualise durational variability in speech production, using non linear methods.
2. To obtain preliminary information regarding intra-subject variability in speaking rate over a period of time, through use of non linear methods, in normal subjects.
3. To compare the durational variability in speech production,between normal and dysfluent speakers,using nonlinear methods.

a) Criteria for Subject Selection

Normal Group :

Two subjects, one female (subject 1) and one male (subject 2) within the age range 18-25 years were selected for testing. The subjects had no past history of smoking, respiratory disease or vocal tract pathology. There was no history of hearing loss or any speech and language problem reported by the subjects. The mother tongue of both the subjects was Hindi.

Dysfluent group

Two male subjects (subjects 3 and 4), in the age range of 18-30 years were selected for testing. Subject 3 had "mild" degree of stuttering as assessed by the Stuttering Severity Index. His mother tongue was Malyalam. He had attended therapy for two sessions.

Subject 4 had "moderate" degree of stuttering based on SSI results. He had also attended therapy for one session. His mother tongue was Kannada. Both the subjects had no past history of smoking, respiratory disease or vocal tract pathology.

b) Experimental Stimulus

A bisyllabic reduplicated word "pop-pop" (/papa:p/) was chosen. The stimulus was nonmeaningful in the native languages of the subjects. The syllables chosen occur frequently in all languages. Reduplicated words allow for easy extraction of durational measure. Morever, phoneme /p/ is easily extracted. Release of a pressure consonant such as /p/ is easy to observe and thus used frequently for durational measurements. The vowel /a/ is an unobstrusive vowel in terms of airflow impedance.

The two syllables of stimulus word were equally stressed. This was attested through visual examination of respective amplitude profiles and syllable durations.

c) Testing condition :

The testing was carried out in a sound treated room in the morning. The subjects were alert and relaxed with no anxiety or fatigue. The subjects were made to sit comfortably in a chair with backrest. They were unaware of the purpose of the study. The stimulus word was visually represented in a written format in a "3x5" index card to cue the subject to maintain a consistent output. Instructions were repeated after a set of every 5 consecutive trials.

d) Instruction to the subject

"When you are ready, repeatedly say the word on the card "pop-pop" at a comfortable rate untill you get a hand signal to stop".

e) Instrumentation

1. Digital audio tape recorder (Sony Audio Taperecorder)
2. Dynamic Microphone (Philips)
3. Kay Elemetrics DSP sonagraph (model 5500) interfaced with a personal computer for analysis of speech production.
4. NCSS software package.
5. SPSS software package.

f) Experimental Procedure

The subject 1, was asked to produce the stimulus word "pop - pop" total 1050 times in a single session. The subject was told to produce a set 21 consecutive productions. A total of 50 such sets were produced with a 1 minute rest between each set of 21 consecutive productions to allow coordination of respiratory and speech performance successive utterance. Subject 2 (normal male) and the dysfluent subject 3 were asked to produce the set of 21 consecutive stimulus productions, 20 times yielding 420 utterences each. The number of production was reduced from 50 to 20 as the subjects were unable to produce the utterences without getting fatigued. The spontaneous rate of speech could not be maintained in this case.

All elicited productions were audio tape recorded on a digital tape recorder (model Sony stero deck TC - FX 170) using Philips microphone. The microphone was placed on the table top approximately 15 cm from the subjects' mouth. Supraaural earphones were worn by the subjects through out the experiment. After each set of 21 productions the tester raised the hand and the subject ceased production of the stimulus word. This protocol was maintained untill all the productions were recorded.

Data organization and Representation

The audiotaped productions were fed into channel fo the DSP sonagraph (model 5500) to observe an analog display of the production on the monitor. There was a split screen display of both waveform and wideband spectrogram.

The input specifications included

Frequency range - 8 kHz

Channel memory size - 38 seconds

Analysis option	:	spectrographic/waveform/amplitude combination display
Time axis	:	200 ms (0.002 sec)

Analysis was done sequentially from one utterance to another. The curson was set at the burst release of the first /p/ of each bisyllabic production till the burst release of the first /p/ of the successive utterance. The digitised duration (in ms) between consecutive cursor settings was noted and tabulated (figures A and B). Each set of 21 consecutive utterance yielded 20 durational measures. A file was created in NCSS software package for each of 20 durational measures. The durational measures extracted from the 50 sets of 21 productions each, yielded 1000 data points for subject 1. For subjects 2 and 3, total number of 400 data points were obtained each from the 20 sets of stimulus production. A transformational analysis was done on the tabulated durational values to obtain the cumulative value. This was done by adding each durational measure to the subsequent measure the cumulative value. This was also stored in a separate file.

Data Representation : Accumulated time series plot

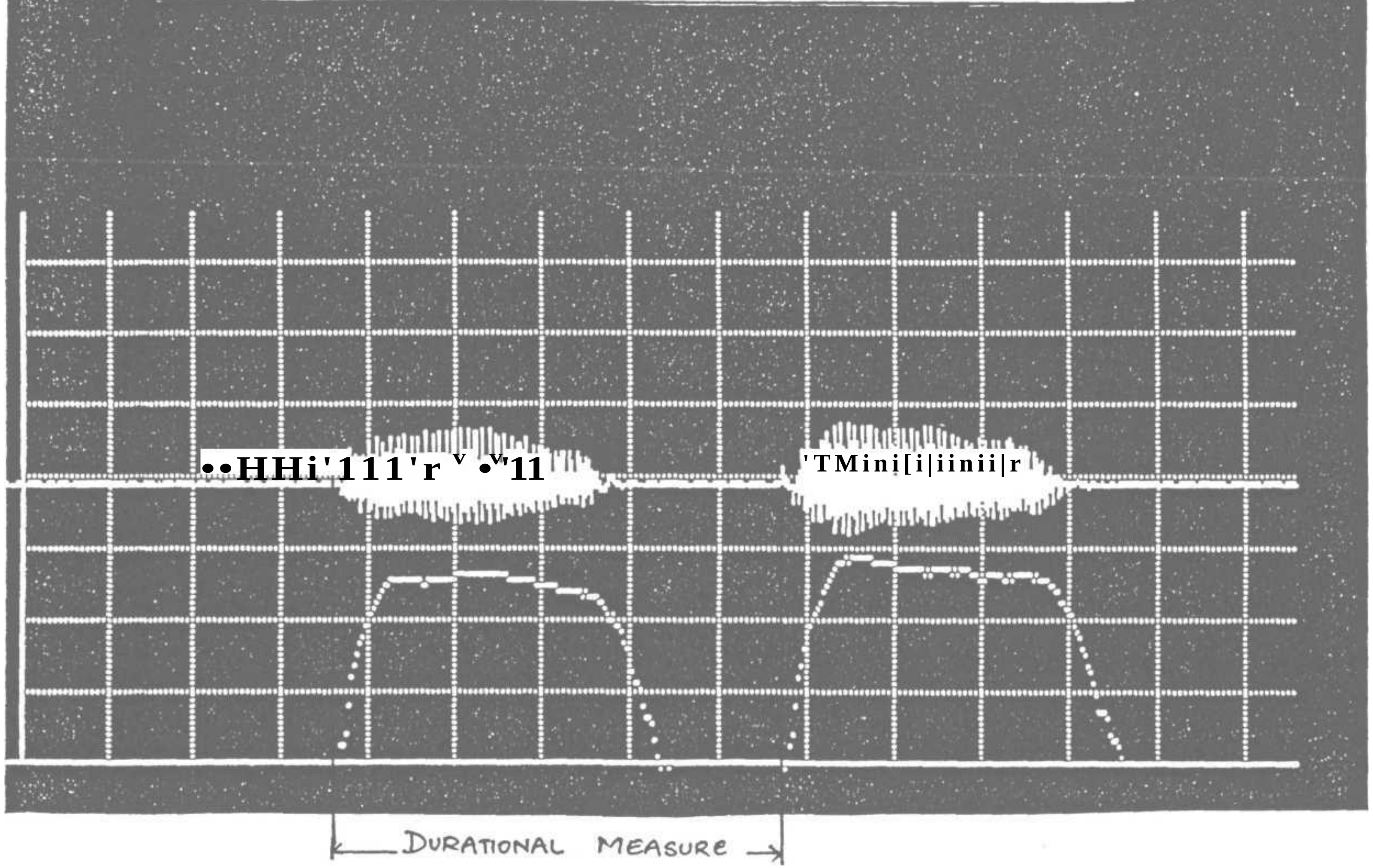
The data was fed into SPSS software package software to obtain the graphical representations. The accumulated time data (generated by adding each durational measure to the subsequent measure in the list of data points) was plotted against the X-axis. The Y-axis was represented by actual durational measures for these data points.

The subjects "mean spontaneous speaking" rate was computed by dividing 21 production by the time taken to produce them. This computation was performed for every fifth set of 21 production. The computed value for the subjects' mean speaking rate was;

Subject 1 : 1.23 words per second.
Subject 2 : 1.01 words per second.
Subject 3 : 1.21 words per second.

The graphical representation of accumulated time series was then analysed for variation in the rate of speech production. The accumulated time series graph of the normal speaker's production was compared with that of the dysfluent speaker's. The data from the speech production of subject 4 (dysfluent speaker) was discarded as the subject had difficulty in initiation of speech. He also exhibited hard articulatory contacts and blocks in his speech utterances. Since, he was unable to maintain consistent speech output the data could not be used for analysis.

Figure B : Waveform display and cursor placements for the analysis of durational measures in the speech production sample of normal subject using the DSP sonagraph.



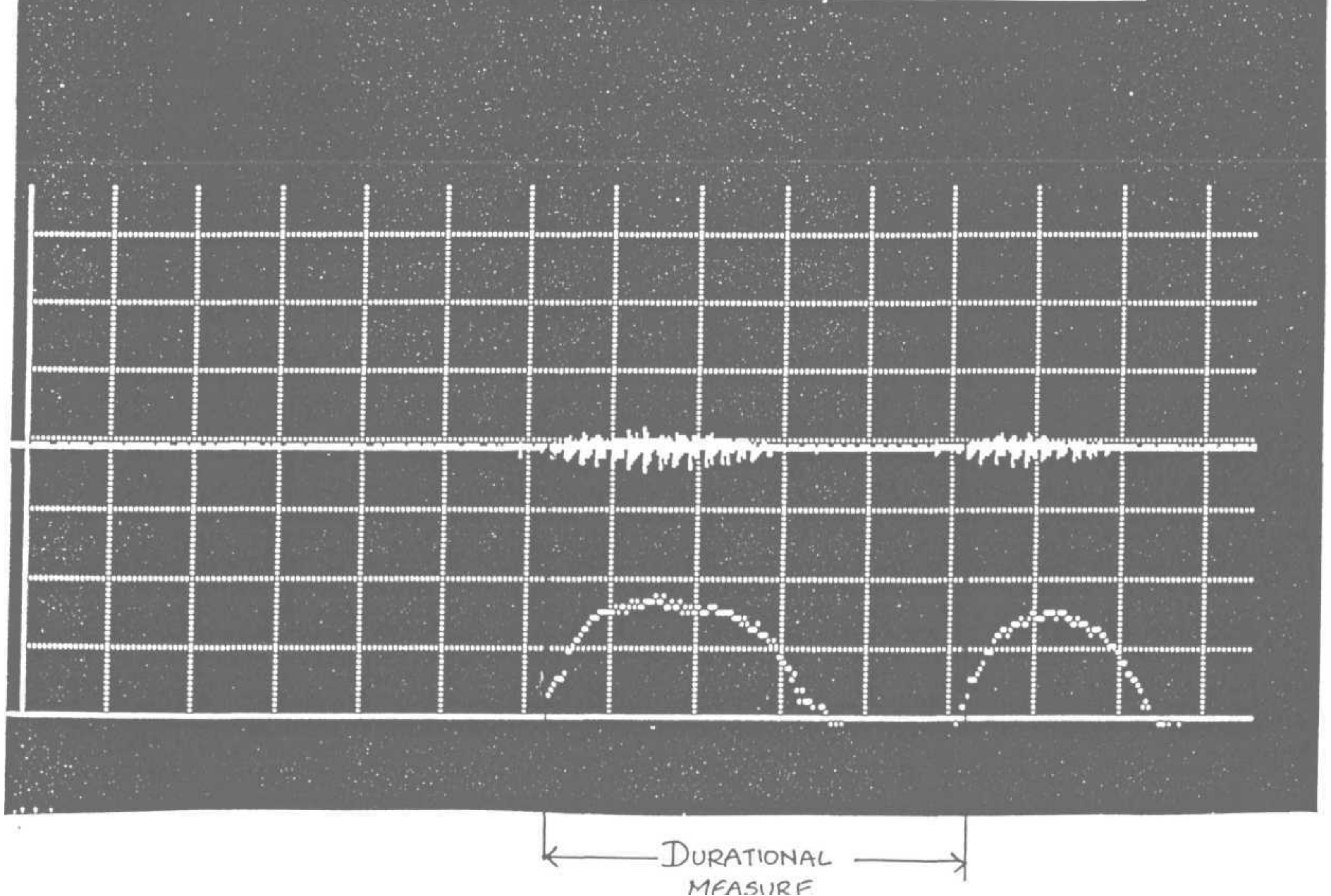


Figure C : Waveform display and cursor placements for the analysis of durational measure in the speech production sample of dysfluent speaker using the DSP sonagraph.

IV. RESULTS AND DISCUSSION

The aim of the present study was to :

1. To establish method or procedure to visualize durational variability in speech production, using non linear methods.
2. To obtain preliminary information regarding intra - subject variability in speaking rate over a period of timethrough use of non linear methods, in normal subjects.
3. To compare the durational variability in speech production,between normal and dysfluent speakers,using nonlinear methods.

RESULTS

The data were plotted sequentially in accumulated time series plots. These were generated by adding each durational measure to the subsequent measure in the original list of data points. This was plotted against the x-axis. Its y-axis was represented by the actual durational measures of the data points.

Besides, the graphical representation, computation of the range and mean values for each set of 21 utterences where determined. For subject 1, these values were calculated for every fifth set of utterence.

The subjects' "mean spontaneous speaking rate" was also calculated by dividing 21 production by the time taken to produce them. This was performed for every fifth set of 21 production. The results were :

Subject 1 : 1.23 words per seconds
Subject 2 : 1.01 words per seconds
Subject 3 : 1.21 words per seconds

The tables 1a, 1b and 1c represent the maximum, minimum the range and mean values of each set consisting of 21 consecutive productions in subject 1 (normal), subject 2 (normal) and subject 3 (dysfluent).

Figure 1. Illustrates the durational measure across accumulated time for subject 1. The sharp spikes denote the variability on both sides of the central tendency. The plot demonstrates an overall pattern of decreasing variability over time. The periodic variations or spikes are more dispersed and of larger durations in the beginning of time series than towards the end. The plot also demonstrates variations that appear to be periodic and of both longer and shorter durations than central tendency.

Moreover, the variability shows slight upward incline of the central tendency in the initial utterances. A slight downward decline is seen in the middle portion of the plot and there is again a very small incline in the last portion of the graphical representation.

Figure 2 : Illustrates the durational measure across accumulated time the subject 2. This would compare with the initial portion of the Figure 1. (as only 400 data points from 20 sets of production were computed). There is an increased variability in the initial and final portions of the graph. This is

also reflected in the range values (between 0.3 to 0.4) for these sets of utterance. There is a steep the decline in the durational measure in the middle portion of the graph. The variations from the central tendency are also reduced in this portion. The periodic variations (spikes) are less dispersed and of shorter duration as compared to the variations in the beginning and the end.

Figure 3 : Illustrates the durational measure across accumulated time for the dysfluent speaker (subject 3). On comparing, figure 3, with the initial portion of figure 1, it is observed that the plot demonstrates an overall pattern of decreasing variability over time. The periodic variations are less dispersed and of smaller duration in the figure 3 than in the figures 1 and 2. The plot demonstrates variations that appear to be periodic and are of both longer and shorter duration than the central tendency. Two to three sharp spikes are observed in the initial portion of the plot. Moreover, the variability shows a clear upward incline of the central tendency. This is also seen in the initial portion of figure 1 but in figure 3, this include is steeper. This is also reflected in the range values (Table 1a, 1b and 1c). Though, there is a progressive increase in the mean value of the consecutive sets of production, the range is considerably lesser than that in subjects 1 and 2. This collaborates with the information derived from the graph.

Table 1a

Sets	Maximum	Minimum	Range	Mean
1	1.044	0.9875	0.0565	1.050
5	1.231	1.000	0.231	1.284
10	1.031	0.9375	0.935	1.067
15	1.006	0.9687	0.0373	1.068
20	1.031	0.9812	0.0498	1.088
25	0.5812	0.8625	0.2813	1.701
30	0.5312	0.5875	0.0563	0.565
35	0.55	0.7437	1.937	0.6321
40	0.6625	0.8123	0.015	0.7312
45	0.625	0.8937	0.2687	0.7493
50	0.7250	0.8438	0.1188	0.7824

Table 1a : Represents the maximum, minimum, range and mean values of the durational variability in every fifth set of speech production for normal subject 1.

Table 1b

Sets	Maximum	Minimum	Range	Mean
1	1.231	0.8625	0.3685	0.844
2	1.106	0.7750	0.331	0.82
3	1.278	0.8406	0.437	0.94
4	1.244	0.9437	0.3003	1.064
5	1.266	0.9779	0.2881	1.05
6	1.325	1.025	0.3	1.08
7	1.281	1.159	0.122	1.42
8	1.436	0.9124	0.523	1.22
9	1.375	1.00	0.37	1.18
10	1.391	1.166	0.225	1.23
11	1.156	0.825	0.331	0.90
12	1.3	0.8937	0.4063	0.95
13	0.8875	0.7813	0.1062	0.79
14	0.85	0.7562	0.0938	0.74
15	0.9187	0.7625	0.1562	0.85
16	0.9875	0.8250	0.1625	0.83
17	1.119	0.875	0.244	0.86
18	1.019	0.8812	0.1378	0.94
19	1.369	1.087	0.282	1.2
20	1.394	1.125	0.269	1.3

Table 1b : Represents the maximum, minimum, range and mean values of the durational variability in all twenty sets of speech production for normal subject 2.

Table 1c

Sets	Maximum	Minimum	Range	Mean
1	0.6817	0.5437	0.138	0.55
2	0.850	0.5125	0.3373	0.55
3	0.8187	0.6563	0.1624	0.7
4	0.7812	0.5125	0.2687	0.64
5	0.7937	0.65	0.1437	0.67
6	0.8625	0.7437	0.1188	0.75
7	0.8375	0.7562	0.0813	0.73
8	0.9063	0.7687	0.1376	0.88
9	0.8937	0.7625	0.1312	0.79
10	0.9562	0.8062	0.15	0.83
11	0.9187	0.7812	0.1375	0.83
12	1.050	0.8187	0.2313	0.91
13	0.9937	0.8375	0.1562	0.86
14	1.063	0.8750	0.188	0.94
15	0.9937	0.8562	0.0875	0.82
16	1.019	0.8812	0.1378	0.9
17	1.069	0.9187	0.1503	0.093
18	1.062	0.9125	0.1495	0.92
19	1.069	0.9187	0.1503	0.95
20	1.188	1.037	0.151	1.08

Table 1c : Represents the maximum, minimum, range and mean values of the durational variability in all twenty sets of speech production for dysfluent subject 3.

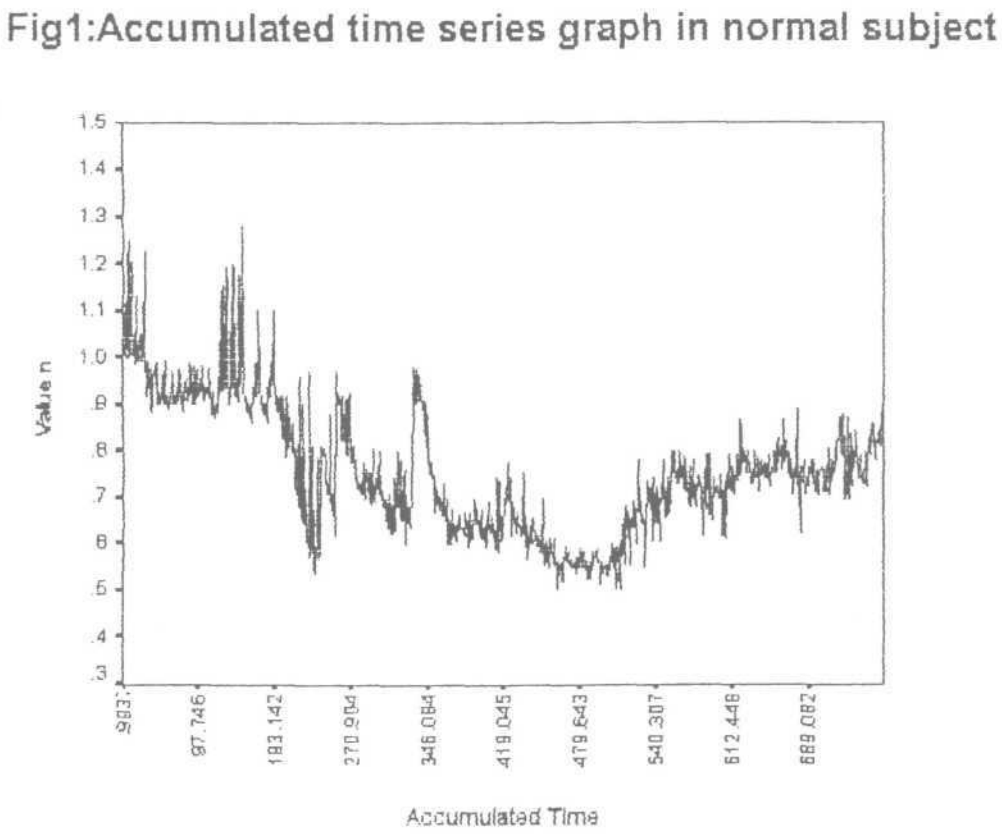


Figure 1: Accumulated time series plot for rate of speech production in normal subject 1. n denotes duration in seconds and accumulated time was derived from n, n+1, n+2.........n+100.

Fig. 2 : Accumulated time series graph in normal subject 2

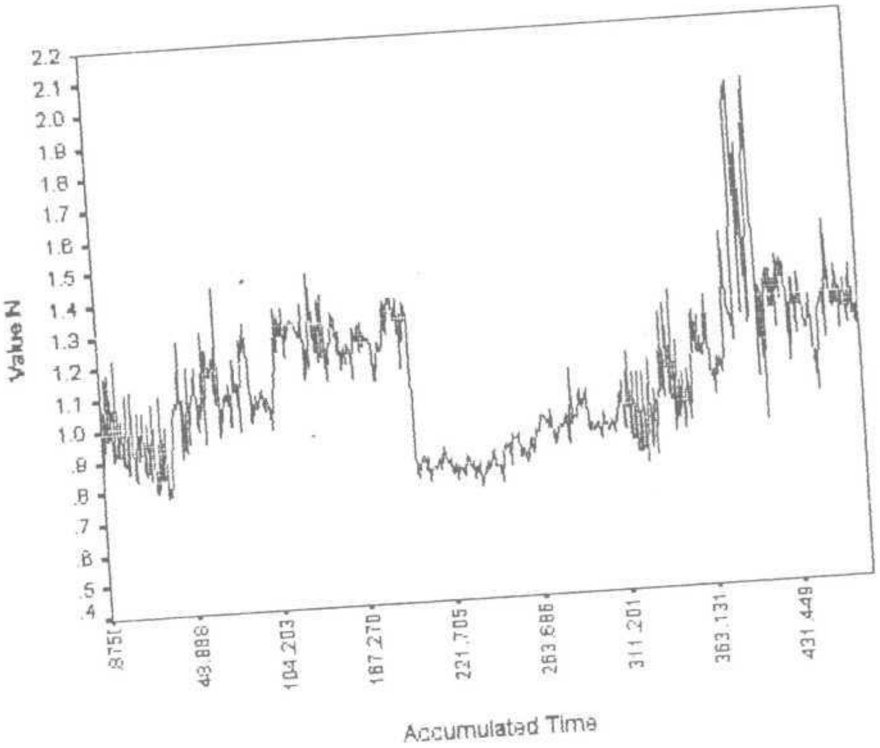


Figure 2: Accumulated time series plot for rate of speech production in normal subject 2. n denotes duration in seconds and accumulated time was derived from n, n+1, n+2,........n+1000.

Fig. 3 : Accumulated time series graph in dysfluent subject

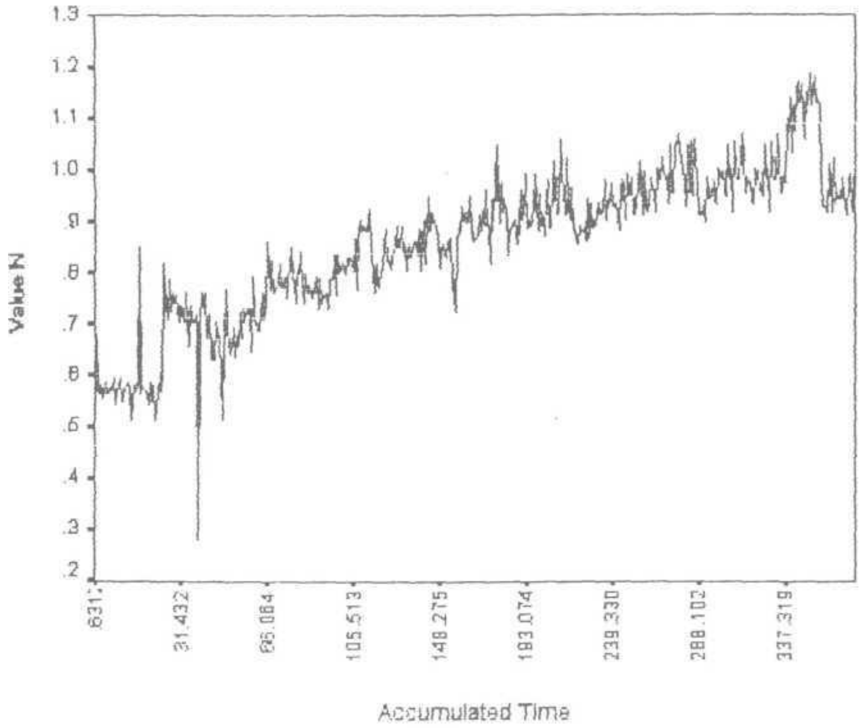


Figure 3 : Accumulated time series plot for rate of speech production in dysfluent subject 3. n denotes duration in seconds and accumulated time was derived from n, n+1, n+2,........n+100.

Discussion : Accumulated Time Series representation for normal subjects:

This data supports the findings of Hadden et al (1997) study where a similar trend in variability was seen for spontaneous rate of speech. The accumulated time series plot displays the temporal history of utterance durations across productions. Conceptually, this reflects utterance duration perturbation or patterns of variability. The plot displays the pattern of variability in speech production rate over a period of time. Since the number of data points is large, the changes in durational measures reflect a detailed information on how these variations occur and how they change over time. Tuller et al (1982) have also reported that, though there were large variations in absolute duration of utterance component which accompanied changes in speech rate and syllable stress, while, there was a constant relationship between the vowel and consonant gesture across boundary to the time between vowel gestures. (CV1 # CV2 C type).

Hadden et al (1997), have also reported a decrease in variability across time, in the latter segment of the accumulated time series plot for spontaneous rate condition.

Morever, behaviour is an important feature of health. Thus, an increasingly periodic behaviour in physiological system serves as a potential indicator for developing sickness or decaying health. In Hadden et al (1997) study, the "driven" or conditions with altered speaking rates displayed an increasing regularity with a pattern of variability, that inconsistently but gradually decreased over time.

In the present study, figure 2 and the initial portion of the accumulated time series plot, of the utterance of the subject 1 reflects greater variability with time. This may be explained by the fact, that the subjects had been instructed to produce the utterance in the "natural spontaneous rate" of speech. Since, the system had been in a healthy, physiologically balanced state, the increased variability reflects the state. The slight upward incline of the central tendency at this stage may hint that the subject's speech system was seeking some "regularity".

In addition, the figure 1 time series plot for the experiment, shows less variability in the latter segment of the series. This suggests that there was less intra-subject variability across consecutive productions as compared to the initial state of the system. This may be explained by the learning effect and fatigue of the system. Fletcher (1996), had suggested that the speech control is exercised by human neural system. Such a neural system behaves as an elaboration of the simple neural networks. Neural networks "learn" by modifying the weights assigned to their internal synaptic connections so as to reinforce desired outputs and inhibit those that are undesired. In this way, they can maintain a system in a desired state, which may be either constant or else varying in time in a regular manner The nonlineairty locks the behaviours of the system into one of a number regimes of autonomous oscillations which can thus be controlled as stable entities. As suggested by Fletcher (1996), the recognition of nature of neural control system shows the role of both imitative practice and conscious thought in achieving both routine utterances and special vocal effects.

The reduction in variability could also be possible due to the 'fatigue' experienced by the subjects speech system. The subject 1, had to produce 50 trials of 21 utterances in one session. Even though, a 1 minute rest time was imposed between each trial (set of 21 consecutive productions) to allow the subject to coordinate the respiratory and speech performances, fatigue of the system could not be controlled. As discussed earlier, as the systems moves towards a more unhealthy physiologicallly unsuitable mode there is a decrease in variability. This is reflects in the time series plot. In figure 2, the reduction in central tendency, in the middle part can be explained by the fact that the subject had suddenly increased the rate of speech production, during sets 13 and 14 (mean values 0.79 and 0.74 respectively). With repeated instructions, subject reattempted to maintain the spontaneous rate of utterance in the subsequent sets of utterances. The alteration in the speaking rate from the spontaneous rates is reflected in the pattern of lesser variability during this period. Though, this behaviour was methodologically and desired, its supports the findings of Hadden et al. (1997), who reported a decrease in variability in 'driven' conditions. Morever, as the number of sets of utterance was reduced, the effect of fatigue is not visible in the end of the plot. Hence, a pattern of increased variability associated with normal physiological function can be visualised.

On comparing, the variability in speech production of dysfluent speaker (figure 3) with that in normal subjects (Figures 1 and 2), it is evident that there is lesser variability in the pathological condition than in the normals. The mean spontaneous speaking rate of the dysfluent speaker (1.225 words per seconds), was considerability more than subject 2 (1.01 words per second) but was comparable with that of subject 1 (1.21 words per second). The sharp spikes seen in the initial portion of the plot correspond to the articulatory blocks encountered by the patients during the production which increased duration of utterance. Morever, it was difficult to place the cursor accurately as the release burst for /p/ was not very clear. The sharp incline in central tendency is also different from that of the normals. Like in the figure 1, the system may be seeking "regularity" but it is greater and steeper than that seen in the normal subject for comparable time. Though the computed data, (Table 1a, 1b and 1c), is able to provide some information about the range of variability within a set of utterance, it does not provide sufficient information about the variability across different sets which can be obtained from the nonlinear graphical representation. The nonlinearity of the system is better and more comprehensively visualized using nonlinear methods than that possible in the statistical method.

As suggested by many investigators (Goldberger, 1990a ; Goldberger and West, 1990; Nelson ; West & Goldberger, 1990), the speech and other physiological systems may behave most erratically when they are young and healthy. Increasingly regular behaviour of the different physiological systems sometimes reflect againg and disease or a nonnatural state of the system. While irregular and unpredictable behaviour reflects a healthy system.

Thus, chaotic dynamics in the speech system has profound implications in terms of evolutionary biology. Such dynamics offer many functional advantages. Chaotic systems operate under a wide range of conditions and are therefore adaptable and flexible. This plasticity allows systems to cope with the exigencies of an unpredictable and changing environment. Fractal structures by virtue of their redundancy and irregularity are robust and resistant to injury. Thus, the flexibility and strength of irregular fractal structures and the adaptability and robustness of systems that exhibit apparently chaotic behaviour its important.

Thus, by using, nonlinear techniques, aspects of variability in speech moter performance can be visualized which reflect the basic nonlinearity of the system itself. This may not be possible using only linear methods.

In the present study, an attempt has been made to study the durational variability using nonlinear methods in the speech of normal speakers and to compare this information with that in pathological group (dysfluent speakers). The information from the study cannot be generalized as all the variables, including individual variations, are either difficult to control, or not sufficiently explored. More research in these lines is required to expand the knowledge about the nonlinearity in speech production of normals itself before it can be used as a tool for clinical diagnosis. Morever, the procedural difficulty while collecting a large data from speech impaired individuals, makes the task more cumbersome. Individuals with moderate to severe degree of speech impairment may not be able provide a large and consistent speech output (as in the case of subject 4). The study, suggests that there is nonlinearity in the durational parameters of speech production which is reflected in its variability. The pattern of variability can be visualized in greater detail using nonlinear methods like time series graph to provide 'qualitative' information about this nonlinearity than traditional linear methods. There is also a distinct difference between the pattern of durational variability in normal speakers and that in dysfluent speakers. Nonlinear method may be more sensitive than linear methods to study these variabilities. Based on these findings, the formulated hypothesis can be rejected.

Thus, it can be concluded that nonlinear dynamical methods can be used for studying variability in the speech production. The established procedure demonstrates ;

1. There is nonlinearity in the rate of speech production in normal speakers.
2. This nonlinearity can be visualized qualitatively to provide information about the speech system.
3. Non linear methods may be more sensitive than the traditional linear methods to explain the changes occuring in a relatively nonlinear speech system.
4. The variability in durational aspects of speech production is more in normal healthy physiological systems than in 'driven' or pathological conditions.
5. This procedure can be used to study the variability in the durational parameter of speech production in dysfluent speakers.
6. Dysfluent speakers exhibit less variability in their speech production than the normal speakers.

7. This procedure requires further modifications to include severely speech impaired population as they are unable to provide large speech samples for analysis.

V . SUMMARY AND CONCLUSIONS

The present investigation was carried out with the aim of :

1. Establishing a method or procedure to visualize durational variability in speech production, using non linear methods.
2. Obtaining preliminary information regarding intra - subject variability in speaking rate over a period of time through use of non linear methods, in normal subjects.
3. Comparing the durational variability in speech production, between normal and dysfluent speakers, using nonlinear methods.

Two normal subjects (one male and one female), were selected for testing. One dysfluent speaker (mild degree of stuttering) was selected to represent the pathological population. The age range of all the subjects was within 18 to 25 years. There was no meaningful representation of the stimulus material in the mother tongue of the subjects.

The stimulus material consisted of a bi-syllabic reduplicated word "pop-pop" (/papa:p/). The two syllables of the stimulus words were equally stressed. This was a tested through visual examination of the amplitude profiles and syllable duration. The testing was carried out in a sound treated room in the morning hours. The subjects were alert and relaxed with no anxiety or fatigue. The subject were instructed to repeatedly say the word "pop-pop" at a comfortable rate until they received a hand signal to stop. The normal female subject (subject 1) was asked to produce the stimulus words 1050 times in a single session. A total of 50 sets consisting of 21 consecutive productions of the stimulus words were produced with 1 minute rest between each set of 21 productions. Subject 2 (normal, male) and subject 3 (dysfluent, male) were told to produce only 20 sets of 21 consecutive productions.

All elicited productions were audio tape recorded on a digital tape recorder (model Sony stereo deck TC-FX170) using a Philips dynamic microphone placed 15 cm away from the subjects' mouth. Supra aural earphones were worn by the subjects through out the experiment.

The audiotaped productions were fed into channel 1 of the DSP sonagraph (model 5500) to observe an analog display.

The input specifications included :

Frequency range - 8kHz
Channel memory size - 38 seconds
Analysis format - spectrographic /waveform/ amplitude combination display
Time Axis - 200 ms (0.002 sec)

Analysis was done sequentially from one utterances to another. The cursor was set at the burst release of the first /p/ of each bisyllabic production till the burst release of the first /p/ of the following utterance. The digitised duration (in ms) of consecutive cursor settings was noted and tabulated. A file was created in NCSS Software package for each set of 20 durational measures. A transformational analysis was done on the tabulated durational values from all the sets to obtain the cumulative value. This was done by adding each durational measures to the subsequent measure.

The data was stored and fed into SPSS software package to obtain the graphical representation. The X- axis was represented by the accumulated time data and the Y-axis was represented by the actual durational measures for the data points.

The range and mean values of each set of the stimulus production were also computed. Fa **subject 1,** every fifth set was considered for this computation. The subject mean spontaneous speaking rate was also computed by dividing the 21 production by the time taken to produce them. The accumulated time series graphs for subjects 1, 2 and 3 were plotted and analysed. In **figure 1**, sharp spikes denoting variability on both sides of the central tendency were observed. An overall pattern of decreasing variability was seen. The periodic variations were more in the beginning than in the end. The variability showed slight upward inclined in the initial utterances. In **figure 2** there was an increased variability in the initial and final portions of the graph. There was a steep decline in the middle portion of the graph which had lesser variability. This corresponded with the change in rate of speech by the subject. In **figure, 3** there was lesser variability in comparison of the other two figures for normal subjects. Two to three sharp spikes were observed in the initial portion of the plot which corresponded to the articulatory blocks in the speech output. There was sharp upward incline of the central tendency observed. These findings correlated with the range and mean values. Greater variability in the time series plot would display a more normal physiological condition. The effect of fatigue and learning resulted in decreased variability. For the dysfluent speakers, the variability was much lesser than the other two normal subjects.

Thus, using these nonlinear methods, its possible to visualise the variability in the durational aspect of speech production in both normal and pathological population. There is decreased variability for pathological population as well as in those conditions where the speech system is in the 'driven' (as in altered speaking rates) condition. The nonlinear methods are better indicators of this 'qualitative' change. Using this procedure, further research can be carried out, to study the variability and nonlinearity in the speech system more extensively.

It can be concluded that nonlinear dynamical methods can be used for studying variability in the speech production. The established procedure demonstrates ;

1. There is nonlinearity in the rate of speech production in normal speakers.
2. This nonlinearity can be visualized qualitatively to provide information about the speech system.
3. Non linear methods may be more sensitive than the traditional linear methods to explain the changes occuring in a relatively nonlinear speech system.

4. The variability in durational aspects of speech production is more in normal healthy physiological systems than in 'driven' or pathological conditions.
5. This procedure can be used to study the variability in the durational parameter of speech production in dysfluent speakers.
6. Dysfluent speakers exhibit less variability in their speech production than the normal speakers.
7. This procedure requires further modifications to include severely speech impaired population as they are unable to provide large speech samples for analysis.

Implications for further Research

1. A more extensive study would introduce an option for visualizing variations in normal speech production and usage of this information toward the development of clinical procedures for characterizing "regularities and irregularities" during normal and abnormal speech performances.
2. Non linear techniques may reveal aspects of variability in speech motor performance not revealed by traditional measures. This may be valuable clinically in the diagnosis of both fluency disorders such as stuttering and neuromotor speech disorders such as verbal apraxia and dysarthria.
3. With nonlinear methods, it would be feasible to observe subtle qualitative changes in performance profiles and therefore faclitate differential

diagnosis and charting of performance profiles among each of these speech disorders.

4. More research is requires to study the different variables which affect the physiology of the speech system both in normals and in abnormal population.
5. Variables such as sex, age and other individual variations could be controlled to gain greater insight about the variation in speech production.

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APPENDIX

	n	n1
1	.9937	.9937
2	.8837	1.8874
3	1.0250	3.0124
4	1.0120	4.0244
5	1.0190	5.0434
6	1.0000	6.0434
7	1.2250	7.2684
S	1.0440	8.3124
9	1.0000	9.3124
10	1.2500	10.5624
11	1.0060	11.5684
12	1.0250	12.5634
13	1.2080	13.7994
14	1.0680	14.8684
15	1.0250	15.8934
16	1.0180	16.9124
17	.9875	17.8999
18	.9875	18.8874
19	1.1310	20.0184
20	1.0310	21.0464

Table 4. : Sample data of durational measure and accumulated time measure of one set of the speech production sample of normal subject 1.

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