SPEECH MOTOR CONTROL AND STUTTERING: A COMPUTATIONAL MODEL OF ADAPTIVE SENSORY-MOTOR PROCESSING

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ABSTRACT - A theoretical account of stuttering is presented in which an inadequacy of neuronal resources for sensory-motor information processing is seen as the basis of the disorder. It is proposed that stutterers are deficient in the processing resources normally responsible for determining and adaptively maintaining the internal models which subserve speech production. A general description of such computational processes is detailed in the form of circuitry for an adaptive controller which can calibrate itself to control any variable, nonlinear, dynamic, multiple input, multiple output system.

INTRODUCTION

Today the weight of research evidence indicates that stuttering is a disorder mediated both by genetic and environmental factors (Andrews, Craig, Feyer, Hoddinott, Howie & Neilson, 1983). Former theories which attributed stuttering to learning or to neurosis gained much of their perceived validity because of the well documented variability of fluency and the readiness with which stuttering can be behaviourally modified. These aspects of stuttering can now be incorporated in a theoretical account which attributes the basic deficit to inadequate resources for sensory-motor information processing.

The idea that stuttering arises from a defect in sensory-motor integration can be traced some decades back when it was popular to view the speech production process as a servosystem dependent on auditory and kinaesthetic feedback (Fairbanks, 1954; Yates, 1963). The possibility of a link between pathological stuttering and the 'pseudostuttering' induced by delayed auditory feedback was compelling and a considerable literature developed within this framework. But despite this effort the nature of the 'perceptual defect' (Cherry & Sayers, 1956) presumed to underlie the disorder remained elusive. Consequently, when feedback models of speech control fell from favour in the early 1970s, the search for the cause of stuttering moved largely elsewhere (see Neilson & Neilson, 1985).

Having established for ourselves by means of auditory-motor tracking experiments that a model of speech production as an error-correcting servosystem did not seem viable, we nevertheless continued to investigate the sensory-motor integration capabilities of stutterers. By calculating transfer functions between the input and output signals in tracking tests we were able to compare the performance characteristics of stutterers and nonstutterers when tracking auditory or visual stimuli. The finding that stutterers as a group performed significantly less well on auditory tasks in terms of gain, phase, coherence and remnant measures, yet performed comparably on visual tasks (Neilson, 1980) led us to a new theoretical position. In essence this is as follows: We see the speech production system as an adaptive control process and we propose that stutterers are deficient in the processing resources normally responsible for determining and adaptively maintaining the relationship between the multiple sensory and motor signals which subserve speech production.

ADAPTIVE MODEL THEORY

In regarding the speech production system as an adaptive controller we see it as possessing computational circuitry capable of determining inverse models of the steps through which a set of motor commands is transformed into the acoustic signal that is speech. This derives from the more general representation of adaptive sensory-motor control depicted in Figure 1.

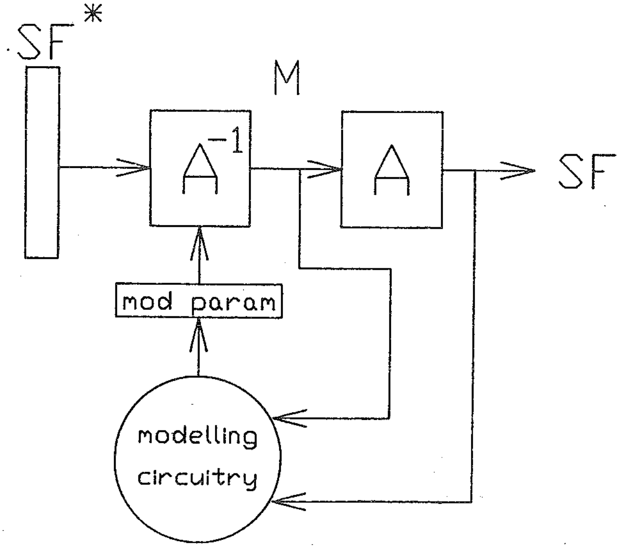

Figure 1. Adaptive sensory-motor control.

This figure illustrates the basic postulate of the adaptive model theory (Neilson, O'Dwyer, & Neilson, 1986); namely, that the central nervous system (CNS) contains the necessary neuronal circuitry to monitor continuously the outgoing motor commands (M) and their resulting sensory consequences (SF) and to compute, store in memory and adaptively maintain the accuracy of a set of model parameters describing the inverse relationship between them. Any change in the input-output response characteristics (A) of the controlled system leads automatically to an adaptive recalibration of the inverse internal model (1/A). Provided the internal model remains accurate, the actual sensory consequences (SF) will reproduce the intended sensory consequences (SF*). Although depicted simply in the diagram, the system represented by A is potentially multiple input, multiple output, dynamic, nonlinear and variable.

The ability of humans to form inverse internal models as depicted in Figure 1 is attested to by a variety of evidence, for example, from studies of adaptation to sensory rearrangement or gravitational change. But undoubtedly the most extensive mathematical data comes from studies of the adaptability of the human operator in the control of man-machine systems. Figure 2 gives a more detailed representation of adaptive model theory applied to the human operator engaged in a tracking task.

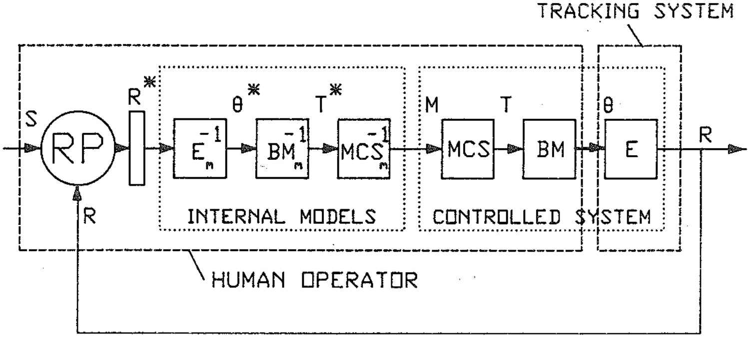

Figure 2. Adaptive control theory representation of a tracking task.

The controlled system and controller are basically as in Figure 1 but each is now represented as three substages connected in cascade, these being the muscle control system (MCS) which transforms the outgoing motor commands signals (M) into muscle tension signals (T), the biomechanics (BM) which transform the muscle tension signals into body movement signals (θ), and the external system (E) which transforms body movement signals into response feedback (R) from the tracking task. Each substage is regarded as a multiple input, multiple output, dynamic, nonlinear, variable system which must be modelled adaptively within the CNS. The corresponding internal models (1/MCS, 1/BM, and 1/E) are computed from available sensory and motor information and maintained in inverse form to allow a desired response R* to be transformed into the requisite motor commands. Any alteration in the characteristics of MCS, BM, or E will require an appropriate adaptive alteration of the corresponding inverse model if R is remain identical to R*.

As well as indicating the distinction between the internal model substages which comprise the adaptive controller and the substages which comprise the controlled system, Figure 2 is also partitioned to show the human operator as distinct from the external system. It is well established that an operator's input-output characteristics will adapt according to the dynamic characteristics of the external system in use. McRuer and Krendel (1974) employed tracking systems with different characteristics (gain, gain plus integrator, gain plus double integrator, gain plus integrator plus first order lag filter) and found the form of the operator's experimentally measured open loop transfer function to be invariant and insensitive to changes in the response characteristics of the tracking task. In other words, the human operator compensates for the dynamic responsiveness of the tracking system by forming an inverse internal model of that system, just as proposed in the adaptive model theory.

Returning now to consider the speech production system in terms of Figure 2 it will be apparent that the problem of transforming a changing vocal tract shape into a changing speech signal exactly parallels the problem of transforming a body movement into the movement of a tracking response marker. So, just as in tracking, an inverse internal model of the vocal tract to speech signal characteristics must be formed and maintained adaptively. It should now be clearer as to why we see deficiency in this ability as underlying stuttering, given the finding that stutterers perform poorly on auditory tracking tasks.

NEURAL CIRCUITRY FOR ADAPTIVE MODELLING

Having postulated that stutterers have inadequate neuronal resources for determining and maintaining the adaptive models subserving speech production, it is necessary to consider how such models might be computed, stored and deployed within the CNS. The following figures give an overview of one possible means, a full account of which can be found in Neilson, O'Dwyer, & Neilson (1986). The circuitry depicted here applies only to a single input, single output system but readily expands by adding further similar modules. Essentially therefore, we are describing a neuronally based design for a distributed parallel processor which will serve as an adaptive controller able to calibrate itself to control any variable, nonlinear, dynamic, multiple input, multiple output system. The processor involves both cortical and cerebellar neural circuits and is consistent with known anatomy and physiology.

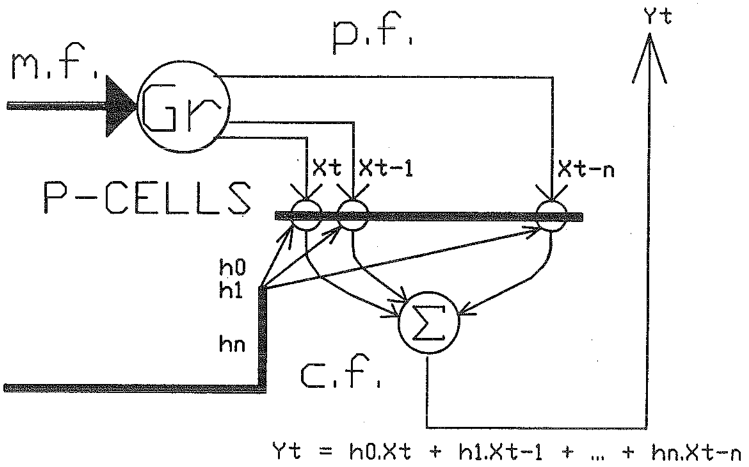

Figure 3. Cerebellar circuit as an adaptive filter.

Figure 3 depicts present and past values of an input signal Xt,Xt-1,...,Xt-n read from a short-term memory buffer in the cerebral cortex and connected via mossy fibres, granule cells and parallel fibres to a row of Purkinje cells in the cerebellar cortex. The gains of the P cells are set to the weights h0,h1,...,hn retrieved from a memory buffer in association cortex via the inferior olive and climbing fibres. The axons of the P cells converge on to target neurons in the cerebellar nucleus where their signals add. Thus the output signal Yt relayed to the rest of the brain from the cerebellar nucleus can be expressed as

$$Yt = h0.Xt + h1.Xt-1 + \ldots + hn.Xt-n$$

This is equivalent to the output of a digital filter which has input-output characteristics described by the impulse response function weights h0,h1,...,hn. The mossy fibre input signal Xt is convolved with the impulse response function set via the climbing fibre input to give the output signal Yt. Thus this cerebellar circuit functions as an adaptive linear filter. If the impulse response function weights h0,h1,...,hn from association cortex had been computed to describe the dynamic relationship between sensory and/or motor signals Xt and Yt, then the adaptive filter in Figure 3 would represent an internal model of that relationship.

It happens that the impulse response function weights describing a linear dynamic relationship between two signals Xt and Yt can be computed easily by crosscorrelation if the input signal Xt is a Gaussian white noise signal because in this case the impulse response function weights equal the crosscorrelations divided by the variance of Xt. The values of crosscorrelations at different lags can be computed in parallel by using many multipliers and averaging filters in conjunction with a short-term memory buffer acting like a bucket-brigade delay line to supply delayed values of the input signal. The neuronal circuitry of the cerebral cortex appears well suited to such computations.

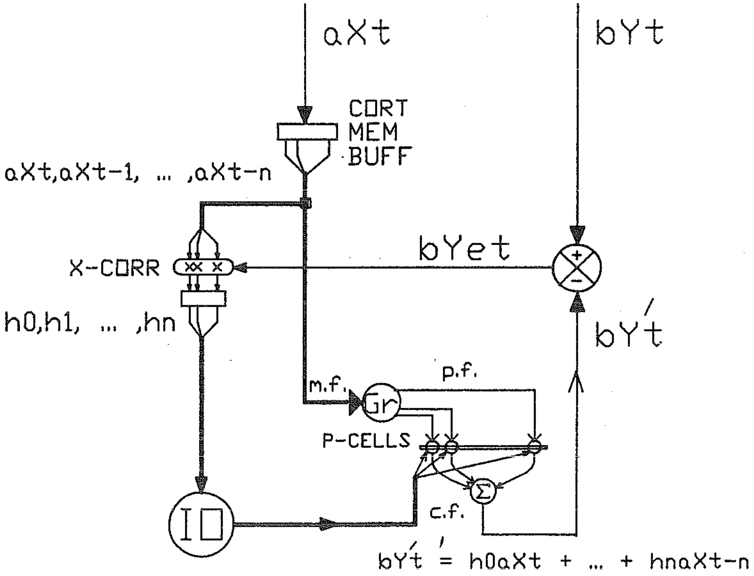

Figure 4. Basic circuit for adaptive modelling.

The circuit shown in Figure 4 employs distributed parallel processing to compute, store and adaptively maintain the accuracy of the relationship between signals Xt and Yt. First the signals are prewhitened, becoming aXt and bYt (this operation is not shown in the figure but leaves the relationship between the signals unchanged). Present and past values aXt,aXt-1,...,aXt-n are read in parallel from a short-term memory buffer in cortex and are convolved with impulse response weights h0,h1,...,hn as described in Figure 3. These are then output from the cerebellar nucleus as the signal bY't which is fed back to a cortex and compared with the signal bYt. This produces the discrepancy signal bYet = bYt - bYt'. If h0,h1,...,hn accurately describe the dynamic relationship between Xt and Yt, the discrepancy signal bYet will either be zero or else will equal fluctuations in bYt not linearly crosscorrelated with aXt. In either case, when bYet is crosscorrelated with aXt, by means of the the parallel crosscorrelator (X-CORR), the outputs will be zero. But if h0,h1,...,hn do not accurately describe the relationship between Xt and Yt, bYet will contain a component which IS crosscorrelated with aXt. The outputs from X-CORR in this case will be nonzero and, when added to the memory buffer which stores the impulse response functions weights h0,h1,...,hn, will change the values of those weights. Importantly, since the crosscorrelation function between a white noise input signal and the output signal of a linear system is proportional to the impulse response function, it follows that the changes in the weights ho,h1,...,hn (normalized by the variance of input aXt) will be precisely the adjustments required to correct them. Thus any change in the dynamic relationship between Xt and Yt will lead automatically to an adaptive recalibration of the stored impulse response function weights describing that relationship. Herein lies a feasible mechanism for computing, storing and adaptively maintaining the internal models subserving sensory-motor control.

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