

Converging evidence in support of common dynamical principles for speech and movement coordination

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KELSO, J. A. SCOTT, AND BETTY TULLER. *Converging evidence in support of common dynamical principles for speech and movement coordination*. Am. J. Physiol. 246 (Regulatory Integrative Comp. Physiol. 15): R928-R935, 1984.—We suggest that a principled analysis of language and action should begin with an understanding of the rate-dependent, dynamical processes that underlie their implementation. Here we present a summary of our ongoing speech production research, which reveals some striking similarities with other work on limb movements. Four design themes emerge for articulatory systems: 1) they are functionally rather than anatomically specific in the way they work; 2) they exhibit equifinality and in doing so fall under the generic category of a dynamical system called *point attractor*; 3) across transformations they preserve a relationally invariant topology; and 4) this, combined with their stable cyclic nature, suggests that they can function as nonlinear, limit cycle oscillators (*periodic attractors*). This brief inventory of regularities, though not meant to be inclusive, hints strongly that speech and other movements share a common, dynamical mode of operation.

topology; limit cycle; equifinality; functional organization; nonlinear oscillation

OUR WORK HAS BEEN and is directed toward understanding control and coordination in complex systems composed of many degrees of freedom. In brief, we want to determine how order and regularity arise in systems whose component structures are nonhomogenous. In a nontrivial sense we view the task as one of understanding the emergence of (kinetic) form, since we take our inspiration from the Soviet physiologist Bernstein who viewed movement "as a living morphological object" (4, p. 68). Both of us have chosen speech production as paradigmatic of the problem, for even the "simplest" of speech gestures requires cooperation among respiratory, laryngeal, and supralaryngeal structures. Nature has solved this coordination problem, but science is a long way from doing so.

At the Lake Arrowhead Conference the participants spent a good deal of time discussing properties that language and movement may have in common. This issue and many others (e.g., origins, neural bases, and development) are addressed in several of the papers (cf. 3, 38, 53, 62). Our aim is a bit more parochial. We wish to present briefly four sets of findings that relate the pro-

duction of speech to the control and coordination of other activities such as reaching and locomoting. We feel that these observations suggest rather strongly that speech and other motor skills share a similar dynamical organization. We hasten to add that this claim is far from universally accepted; in fact, at a recent conference on speech motor control in Stockholm it constituted a major source of controversy (cf. 32), although in his concluding remarks, the Nobel Laureate Ragnar Granit remarked provocatively, "The motor marionette is what neurophysiology has in common with speech motricity" (28, p. 271). The problem as we see it, however, is to unpack the "motor marionette," indeed it is to strip away, as much as possible, the puppeteer pulling the strings.

In short, we resist any tendency to assume that the order and regularity we observe when people talk or move about in their environment is contained in, or prescribed by, some device (such as the programs and reference levels common in machine-type theories) that embodies said order and regularity. Rather we wish to understand the generation of pattern and form without assuming a priori that there is a *generator* which possesses some kind of representation, neural or mental, of the pattern before it appears. This strategy applies as much to language as to action. Taking such a strategy seriously means, first and foremost, a commitment to understanding the rate-dependent, dynamical processes that underlie the *implementation* of language and action. In adopting this stance we do not mean to reject entirely the abstract, symbolic mode of operation that seems to be a hallmark of language and action. But Nature employs the symbolic mode of operation only minimally (cf. 38), and so, at least for us, a *principled analysis of language and action must begin with an account of the dynamics of speech and movement*. Like several of the participants, as well as others, notably Pattee (60, 61), we wonder how it might be that discrete, rate-independent symbol strings could arise from dynamical, biological processes (cf. 55). As far as language and action are concerned, we feel that until the latter have been explored more fully the question is moot. Here we simply present some recent results which, when interpreted from a dynamical perspective, suggest that there are common principles governing speech and other movements.

I. ON THE FUNCTIONAL (NOT ANATOMIC) SPECIFICITY OF MOTOR SYSTEMS

For some time it has seemed to us (and others; e.g., 10, 29, 74, 81) that it is extremely unlikely that the degrees of freedom of *any* articulatory system are individually regulated during purposive activity (as the marionette image or earlier keyboard metaphors might suggest; for discussion, see Ref. 82). Instead, in many multijoint movements, ensembles of muscles and joints exhibit a unitary structuring—a preservation of internal relations among muscles and kinematic components of a particular task that is stable across scalar changes in such parameters as rate and force (e.g., Refs. 47 and 48; see Refs. 22 and 40 for reviews and sect. III for details regarding the form the internal “topology” takes). For us then the significant units of control and coordination are *functional* groupings of muscles and joints (which the Russians call functional synergies and we call coordinative structures) constrained to act as a unit to accomplish a task. One of our goals has been to try to ground this claim firmly and at the same time contrast it with notions that “units of action” consist of anatomic arrangements such as hard-wired reflex connections or servomechanisms (see, e.g., Gallistel’s “new synthesis” of action and commentaries, Ref. 24; see also Ref. 46). Biological systems, as emphasized by Iberall and Yates (e.g., 36, 37, 87, 88), are not “hard wired, hard geared, or hard molded,” though in exhibiting the functions they do, they might appear to be so. But for us at least, biological things share no genuine likeness to machines; instead they organize themselves to meet task demands with whatever components are available to them.

How might one establish the “soft,” functional nature of muscle-joint linkages composed of many degrees of freedom? One way is to poke them around, perturb them, and then examine how the potentially free variables reconfigure themselves. An instructive experiment on speech by Folkins and Abbs (19) loaded the jaw unexpectedly during the closure movement for the first /p/ in the utterance “a /hae 'paep/ again.” Lip closure was attained in all cases, apparently by exaggerated displacements and velocities of the lip-closing gestures, particularly of the upper lip. Although the interpretation of this result has been uneven [initially accounted for by online feedback processing (19) and later as supporting open-loop feedforward control processes (1)], its impact for us as a paradigm is that anatomic structures not directly coupled to the perturbed articulator are those that compensate. The lips and the jaw in this case seem to constitute a functional unit, an “equation of constraint” as it were (68); when one part is altered, other distally linked parts automatically adapt to preserve the constraint. To us these data can hardly be accounted for by either complete preplanning (open-loop control) or fixed input-output feedback loops. But to show that, we need to demonstrate that the pattern of coupling among the articulators observed in response to the *same* perturbation shifts with the functional requirements of the act. For example, coordinative structure theory would predict that if the jaw is halted in its raising action during the

transition into the final /b/ in /baeb/, then the lips will compensate but the tongue will not. In contrast, for a different utterance such as /baez/ the tongue will perform the primary compensation and not the lips. In short, the effects will not be fixed in reaction to the perturbation; rather the pattern of coordination will be functionally specific to the requirements of the spoken act.

Our data (51, 50) bear this prediction out. In one experiment, a load (5.88 N, 1.5 s duration) was applied to the subject’s jaw unexpectedly (on 20% of the trials) via a direct-current brushless torque motor. Movement was monitored by an optical tracking system (modified Selspot) that detected infrared light-emitting diodes attached to the subject’s lips and jaw at the midline. In addition, electromyograph (EMG) potentials from lip and tongue muscles were obtained from paint-on and Lipolar hooked wire electrodes, respectively.

The movement results were clear. The upper and lower lips preserve the timing of closure for the final /b/ in /baeb/ in the perturbed condition [like Folkins and Abbs’ data (19)] by increasing their displacement and velocity. But this is not a fixed, “triggered reaction” on the part of the lips to jaw perturbations. When the jaw is perturbed in exactly the same place, but this time /z/ friction is required as in /baez/, there is no active lip compensation. Instead, because the jaw is lower than usual, the tongue moves further (as manifested in highly amplified tongue muscle activity) to achieve the tongue-palate relationship appropriate to friction. Like the lips in /baeb/, the tongue in /baez/ responds remarkably quickly and is time locked to the torque applied to the jaw (15- to 30-ms latency).

The coordinative patterns we observe in these speech experiments are highly distinctive and anything but inflexible. In this they parallel work on other movements such as cat locomotion. For example, when light touch or a weak electrical shock is applied to the cat’s paw during the flexion phase of the step cycle, an abrupt withdrawal reaction occurs—as if the cat were trying to lift its leg over an obstacle. When the *same* stimulus is applied during the stance phase of the cycle, the flexion response (which would make the animal fall over) is inhibited and the cat reacts with enhanced extension (20). Just as these reactions are nonstereotypic and functionally suited to the requirements of locomotion, so the patterns we have observed are fashioned to meet the linguistic requirements of the spoken act in unique and specific ways. The flexible patterning observed in response to perturbations in different phonetic contexts strongly speaks against either a fixed response organization (of a reflex or servo type) or a completely preprogrammed mode of control. Rather we are talking about a softly coupled system of articulators constrained to act temporarily in a unitary fashion. The cooperativity evident in the tongue-jaw-lip ensemble is specific not to any particular articulatory target configuration but to the production of the required sound. *The relationship is many to one; there is no isomorphism between the exact state of the articulators and the utterance produced.* As we will suggest next, the latter constitutes an *attractor field* (in the nomenclature of dynamical systems theory,

see Refs. 2 and 66) to which articulatory trajectories converge, regardless of contextual variation (and the multiple meanings of words?).

II. ON THE EQUIFINALITY PROPERTY OF MOTOR SYSTEMS

The spatiotemporal adjustments that occur in structures (often far removed from the structure perturbed) are constrained by the task performed. Seen in another light, they guarantee the task's accomplishment provided that biomechanical limits are not exceeded. This phenomenon of "goal" achievement in spite of ever-changing postural and biomechanical rearrangements and through a wide variety of kinematic trajectories has been called motor equivalence (33) or equifinality (5).

We have observed equifinality in our studies of limb-targeting behavior in single degree-of-freedom movements. Briefly we have shown that a given target angle can be achieved despite changes in initial conditions of the limb and despite unforeseen perturbations to the movement trajectory imposed en route to the target. This is the case in functionally deafferented humans (39, 42, 67) and individuals who have had the joint capsules of the index finger surgically removed, thus eliminating the seat of joint mechanoreceptors (43). Very similar findings have been reported in normal and deafferented monkeys for both head (7) and arm movements (64). Interestingly a recent paper by Poizner et al. (63) shows how "final position control" is exploited by the linguistic system of American Sign Language, both in its lexical structure and its grammar.

Recently we have examined the production of the vowels /i/, /a/, and /u/ in isolation and in a dynamical speech context (e.g., "its a peep again"). In one condition the vowels were produced normally; in another rather extreme manipulation we altered artificially the normal configuration of the articulators by fixing the mandible using a bite block and at the same time removed as much tactile, proprioceptive, and auditory information as possible. The temporomandibular joint was anesthetized bilaterally; tactile information from oral mucosa was reduced by application of topical anesthetic (to the extent of, in some cases, eliminating the gag reflex), and audition was masked by white noise (49). Though we recognize that it was probably impossible to deprive the subject completely of sensory information, the level of performance was nevertheless quite remarkable. Measuring the vowel's acoustic spectrum at the first glottal pitch pulse, we found (in 5 naive subjects) no differences between normal and deprived conditions in the values of the first and second formant frequencies. Thus, in spite of the changed articulator geometry and rather drastic sensory reduction, the vocal tract accommodated to produce a normal acoustic output. Cinefluorographic work has shown that the new articulatory configuration (often involving changes in tongue and pharynx shape) preserves regions of maximum constriction between, say, the tongue and the palate for the vowel /i/ (25). In addition, we have recently shown in an x-ray study of bite-block speech that compensatory movements occur

in a similar fashion for one adventitiously and two congenitally deaf subjects (83).

What kind of system is defined when elements of the motor apparatus cooperate in an apparently complex manner to exhibit equifinality? Rosen (66) suggests a strategy for dealing with complexity that has received only spasmodic use over the years by physiology and neuroscience, in spite of its effectiveness historically in other scientific domains. In brief, he argues that modeling complex behavior involves abstracting what the system's *functional organization* is rather than (or at least before) focusing on its material structure. Often complex systems have a propensity for turning themselves into rather simple, special-purpose devices to meet functional requirements.

There is now a good deal of support for the notion that "targeting" movements are controlled by an organization dynamically similar to a (nonlinear) mass-spring system (e.g., 15, 16, 39, 44). Such systems are intrinsically self-equilibrating in the sense that the "end point" or the "target" of the system is achieved regardless of initial conditions. For us the appeal of this model is that the target is not achieved by conventional closed-loop control with its processes of feedback, error detection, and comparison. Instead it arises as an equilibrium operating point determined by the system's dynamical parameters (e.g., mass and stiffness). Kinematic variations in displacement, velocity, and trajectory are *consequences* of the parameters specified, not "controlled" variables (see Ref. 73 and commentaries). Importantly kinematics (or dynamics for that matter) are nowhere represented in the system, and sensory feedback, at least in the conventional, computational sense is not required (cf. 18). We are not saying that information is unimportant for the regulation and control of movement but that it is unlikely to be provided in terms of receptor codes specific to the movement's kinematic dimensions (cf. 43). Rather, as proposed by Kugler et al. (54), a conception of information is required that is unique and specific to the state of the system's dynamics, given perhaps geometrically in the form of gradients and equilibrium points in a potential energy manifold (see also 34). This is admittedly a very general description that has yet to be fully explored; it follows Thom's (75) view of information as *topologically specified* in the system's dynamical qualities and offers an alternative to simplistic coding schemes in which receptor signals on a signal dimension are fed back to a set point. In fact, we have questioned all along [as have others, such as Weiner (85) in his last paper; Refs. 12, 22, 36, 44, 54, and 87] the appropriateness of the set-point concept in biological processes.

We should stress again one very important point that can be misinterpreted (e.g., 6, 72). The role of the mass-spring model of equifinality as we propose it is to characterize an *abstract functional organization* not a unique mechanism. As we have emphasized here, it accounts for the qualitative dynamical behavior of a wide variety of materially different systems. As a style of description it has more in common with say Gibbs' phase rule for lawfully describing the behavior of matter as it undergoes changes in phase (e.g., from liquid to gas, *regardless* of

chemical composition) than it has in common with say the details of an isolated muscle's length-tension curve. The approach here is truly dynamic: complex systems—in performing goal-directed functions—can behave as abstract, task-defined special-purpose devices such as a mass spring. Dynamicists classify such devices as belonging generically to a taxonomic category called *point attractors*. We think and have preliminary evidence showing that when point attractor dynamics are expressed in task rather than articulatory coordinates, the degrees of freedom at the muscle-joint level can be wrapped up in those situations when the system displays equifinality (Ref. 69 and Saltzman and Kelso, unpublished observations).

III. ON THE TOPOLOGICAL NATURE OF MOTOR SYSTEMS

Bernstein (4) placed great emphasis on the predominance of topological categories over metric ones in biological processes. He states, "The totality of the topological and metrical characteristics of the relations between movements and external space can be generalized under the term *motor field*," and further, "The immediate task of physiology is to analyse the properties of this field" (4, p. 48).

In our experiments and our analyses of others' experiments we have asked What variables, or relations among variables, are preserved in the face of relevant transformations? What, if anything, remains invariant across metric change? These questions are motivated by an approach to living systems proposed by Gelfand and Tsetlin (26) in their theory of well-organized functions. For Gelfand and Tsetlin, as for Bernstein, control and coordination are completely described by so-called non-essential ("control") variables that can effect scalar changes in the values of the function without annihilating its internal structure or topological character. The internal topology is determined by so-called "essential" variables, which elsewhere we have linked with the term coordination (54).

In a wide variety of activities including locomotion, handwriting, postural balance, and interlimb coordination (see Refs. 40 and 70 for reviews) we have observed a *stable temporal patterning* (among muscle activities or kinematic events) across scalar changes in absolute magnitude of EMG activity or kinematic components. The temporal stability often takes the form of a phase constancy among cooperating muscles as a kinematic parameter is systematically changed. Large variations in handwriting speed, for example, do not alter the intrinsic phasing among tangential velocity peaks (84), and, though the magnitude of acceleration pulses is much greater for a word written large than small, the timing is the same (35). In short, the "topology" is a temporal one.

We believe that this invariant temporal structure is a fundamental "signature" of coordinated activity, including, perhaps, the production of speech. Of course, finding any kind of invariant in speech, temporal or otherwise, has been notoriously difficult. Early work at Haskins Laboratories (e.g., 56a, 58) underscored the problem in both the acoustic and physiological domain; supraseg-

mental variables (e.g., prosodic variations and changes in speaking rate), as well as contextual (coarticulatory) effects, were shown to affect the acoustic and physiological realization of the segment. For example, when a consonant-vowel-consonant syllable is spoken with primary stress, the muscle activity associated with production of the vowel is of longer duration and greater amplitude than it would be in an unstressed environment. The acoustic duration of the stressed vowel is also longer and the formant frequencies more extreme than when the same vowel is produced without primary stress. Thus, although the metrics of speech shift constantly, segmental identity is somehow preserved. How can this be?

In our work (77, 78) we hoped that by applying two transformations believed to be particularly important for speech—changing syllable stress and speaking rate—we might uncover motor variables, or relations among variables, that remain unaltered. We approached the problem initially by examining EMG and acoustic recordings of speakers' productions of utterances in which syllable stress and speaking rate were orthogonally varied. Native speakers of English produced two-syllable utterances of the form pV1pV2p, where the vowel (V1 or V2) was either /i/ (as in "peep") or /a/ (as in "pop"). Each utterance was spoken with primary stress placed on either the first or second syllable. The subjects read lists of these utterances at two self-selected speaking rates, slow (conversational) and fast.

EMG recordings were obtained from five muscles known to be active during production of the speech sounds we used. Orbicularis oris participates in bringing the lips together for /p/. Genioglossus bunches the main body of the tongue and brings it forward for the production of the vowel /i/. The anterior belly of digastric and the inferior head of lateral pterygoid are associated with jaw lowering during speech, whereas medial pterygoid acts to raise the jaw (76).

When subjects increased speaking rate or decreased syllable stress, the acoustic duration of their utterances decreased as expected and the magnitude and duration of activity in individual muscles changed markedly. In general, EMG activity was of longer duration and greater magnitude for production of stressed than unstressed syllables. EMG activity was of shorter duration or increased amplitude in syllables spoken quickly compared with those spoken slowly.

To evaluate possible phasing relations among muscle events that might be stable across such large individual variations, we looked at period durations (e.g., between the onsets of muscle activity for V1 and V2) and latencies of corresponding consonant events relative to such periods. We examined all possible muscle combinations across each of the four speaking conditions (i.e., conversational or fast rate with first or second syllable stressed). One very consistent result emerged, namely, an invariant linear relationship between duration of the vowel cycle (onset of muscle activity for V1 to onset of muscle activity for V2) and the latency between V1 onset and the intervening consonant. Thus *timing of consonant production relative to vowel production was invariant over substantial changes in the period of the vowel cycle*. New

kinematic results in which articulatory movements corresponding to vowel and consonant gestures were examined have confirmed this result (79), implicating a functionally significant vowel-to-vowel cyclicity in English (see also Ref. 21).

In short, these data not only provide evidence for relational invariance in timing among articulatory events in speech but also share a close correspondence to results obtained in many motor activities. To use Winfree's (86) term, the preservation of "temporal morphology" across scalar variation may be a design feature of all motor systems and may be Nature's way of solving the problem of coordinating complex systems, like speech, whose degrees of freedom are many. It will not be lost on the reader that this design may arise from the (thermodynamic) requirement that biological systems, to persist, must be cyclic in nature. In our final comment, we turn to a discussion of the fundamental rhythmicity that characterizes many articulatory activities and perhaps even language itself (see also Ref. 53).

IV. ON THE FUNDAMENTAL CYCLICITY OF MOTOR SYSTEMS

The ubiquitous cyclicity in biological processes at many scales of analysis needs little comment here (see Ref. 86 for a good review). As for the neural basis of rhythmic motor behavior, Delcomyn remarks that the big questions no longer concern central vs. peripheral control but rather what kind of oscillatory processes are involved and how they interact to effect coordination in an animal. He goes on to say, "Recognition that systems of oscillators are universal will lead to a better understanding of motor control . . . and . . . bring neuroscientists much closer to the goal of understanding how nervous systems function" (13, p. 498). Similarly, Grillner (30, 31), among others (52), has argued that rhythmic generation in locomotion, respiration, and mastication share a common neural design logic.

Though speech certainly uses many of the same body parts as chewing, its rhythmic basis is much less secure in spite of the fact that linguists have long claimed languages to be rhythmic and people perceive them to be so. Moreover the timing data (see sect. III) was also suggestive of some basic rhythmic structure underlying the maintenance of temporal order across transformation. Lenneberg (56) reviewed some indirect evidence on psychological and physiological "clocks" that led him to posit a basic speech periodicity of 6 ± 1 cycles/s. To test the idea, Lenneberg suggested monitoring by computer some easily isolable speech event associated with syllable onset and plotting its frequency distribution over an extended period of running speech. The suggestion was taken up seriously by Ohala (59), who measured some 10,000 successive jaw-opening gestures during a 1.5-h reading period but to little avail: an extremely wide variance band accompanied a dominant but ill-defined periodicity of 250 ms. According to Ohala, his findings gave "no support to the claim that there is any isochronic principle underlying speech, at least the speech of this particular speaker" (59, p. 434), who, parenthetically,

was himself. In addition, there have been many acoustic studies of speech rhythm, most of which have reported large departures from measured isochrony (see Ref. 21 for review and also a fresh look on the issue).

Part of the problem in establishing the existence of an articulatory rhythm rests (as it apparently does in the acoustic domain as well; Ref. 23) on the measurement process. Speech production is inherently multidimensional; during running speech, different articulators are involved to different degrees and the temporal overlap, "coarticulation," among articulators is considerable. Confronted with so many cooccurring events, there is little chance of identifying a basic rhythm, even though our perceptual impressions lead us to suppose that there is one.

We have adopted an experimental paradigm that may provide some insight (41). Briefly, we asked subjects to speak "reiterantly," that is, to substitute the syllable /ba/ or /ma/ for the real syllable in an utterance yet maintain the utterance's normal prosodic structure. Thus "When the sunlight strikes raindrops in the air" would be produced "ba ba ba ba ba ba ba ba ba" where italics indicate an idealized (and simplified) stress pattern. A previous acoustic study by Liberman and Streeter (57) found that the segmental makeup of target utterances had little or no effect on the duration of the substituted nonsense syllables, which were principally determined by stress and constituent structure. For example, the acoustic duration of reiterant syllables in "cunning scholars deciphered the tablets" was identical to "thirteen teachers were furloughed in August."

The benefit of the reiterant technique is that the removal of segmental factors (besides having minimal effects on the metric pattern) allows one to measure the movements of the *primary* articulators, in our case the lips and jaw involved in /ba/ and /ma/. Figure 1 (left panel) shows displacement-time profiles of the jaw and lower lip plus jaw for one such sentence. Although there are clear effects of stress on the space-time behavior of articulatory gestures (e.g., a tendency for large amplitudes and longer durations for stressed syllables), the overall periodicity is very stable indeed. Coefficients of variation in cycle duration (lip closure to lip closure or jaw opening to jaw opening) were in the region of 15–20%. This relatively narrow band variance concentrated around a cyclicity of approximately 5 Hz contrasts sharply with Ohala's earlier work (59), which for reasons discussed previously was probably subject to contaminating factors. When segmental variation is removed and measurements confined to the action of primary articulators, it is possible to identify (as we have here we think, for the first time) an articulatory cyclicity in its "purest" form. Clearly the periodicity we observe is not *perfectly* isochronous: unless one were dealing with an ideal totally conservative harmonic oscillator (which exists only in textbooks), one would not expect it to be. Nevertheless, as shown in phase-portrait form in Fig. 1 (right panel), the trajectories do exhibit stable orbits and single-peaked velocity profiles regardless of stress and rate variations and small changes in initial conditions. (There are, in fact, some interesting differences in the microstructure

REITERANT SPEECH /ba/

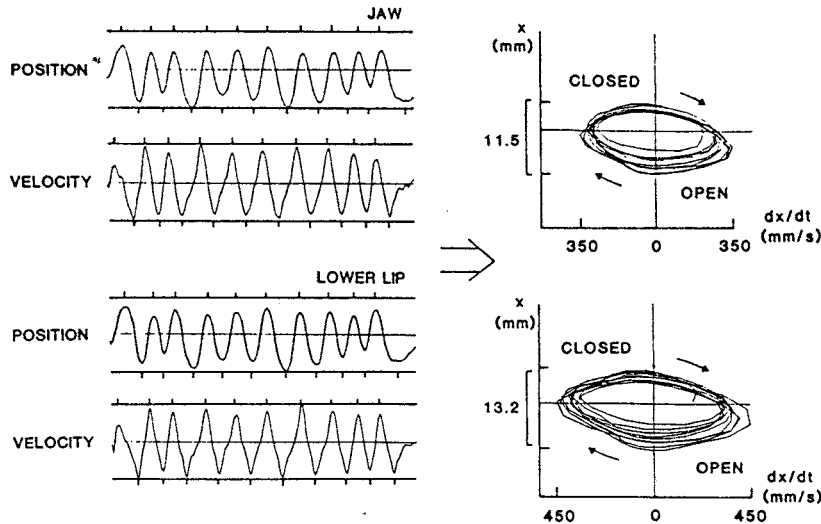


FIG. 1. *Left*: position-time and corresponding velocity-time profiles of jaw and lower lip (plus jaw) of "When the sunlight strikes raindrops in the air" spoken reiterantly with syllable /ba/ interjected for real syllables (see text for details). *Right*: phase portraits corresponding to articulatory profiles shown on left. Closed, portion of trajectory in which articulator is moving into and out of closure for bilabial consonant. Open, vocalic portion of syllable.

of the stressed and unstressed syllables when viewed on the phase plane, which space does not permit us to discuss here.) These trajectories describe the behavior of the articulatory system for this task: their topology is characteristic of nonlinear, limit cycle oscillations which are the only predicted temporal stability for biological processes (37, 88). In a limit cycle, any dissipative losses that occur during a cycle are precisely compensated for by a forcing function (an "escapement" pulse) which in the case of speech is precisely tuned to the required stress level. As suggested for locomotion (71), we might expect each cycle to be instituted *de novo* in speech to satisfy local phonetic and more global, suprasegmental constraints.

Elsewhere we have identified muscle linkages in general with nonlinear oscillatory processes (see sect. III) and demonstrated their entrainment properties both within (45) and across anatomically separate subsystems (52). By this reasoning, which is consistent with homeokinetic theory, any persistent motion must exhibit limit-cycling behavior (54). Speech cannot be granted exempt status. An ensemble of functioning muscles is first and foremost a "thermodynamic engine" (9, 54) whose dissipative cyclic motions are sustained through the capability to draw on a source of potential energy. Thus such functional units not only share common sources of afferent and efferent information (10) but a vascular, metabolic network as well (9).

Though we have yet to test this idea, we might expect a complex system like speech to consist of different nested periodicities; the cycling we have observed here, for example, may well be coupled to the respiratory cycle in a harmonically related fashion, just as the locomotory motions of many animals are (11). Indeed, in a preliminary study of continuous limb movements in which the subject chooses a preferred frequency and amplitude and we record movements over an extended period of time (≈ 90 s), spectral analysis reveals two dominant peaks—one at the preferred frequency (≈ 2 Hz) and the other at ≈ 0.25 Hz, corresponding to the respiration rate. In this case, as in speech, shorter-term cyclicities may cohere

under a longer-term power cycle such as the inspiration-expiration-inspiration cycle.

The present data on speech then, combined with evidence from many other motor activities, are strongly suggestive of a temporal organization of the limit cycle type. We have begun to identify the cyclicities and to show that they can be functionally significant, following the methods of biospectroscopy (8). A good beginning has been made with physiological tremor (27).

CONCLUSIONS

We recognize that this inventory of parallels between speech and other motor behaviors is incomplete. We have omitted, for example, any detailed discussion of coarticulation, which recent evidence suggests is a faculty not restricted to human speech. Thus the grooming behavior of mice can be modified by its relation to actions that occur before or after it in an overall sequence (17). Motor marionette theories, which posit a discrete organization of elements of behavior, do not handle such findings very well. We recognize also that our results may indicate only analogies and that the stronger claim—that they arise from common dynamical principles—is very risky. But it is precisely these functional similarities that exist in structurally very different systems that allow us to identify them as belonging to the same set. The regularities we see in speech and movement and the laws that underlie them may have more in common than the particular structures that embody the laws. Indeed the strategy adopted here—of identifying functional organizations common to materially very different systems—was central to Rashevsky's (65) early attempts at formulating the field of relational biology and remains at the core of dynamical systems theory (e.g., 2, 66). The same sentiment has recently been expressed by Eigen and Winkler (14, p. 252). Our tentative but nontrivial claim then is that speech and other articulator movements are dynamically alike with respect to the way they are controlled and coordinated.

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